Navigation in VR for visual analytics using the latest consumer-grade hardware

by

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Abstract

The Virtual Reality (VR) hardware market has been evolving rapidly since 2016. Consumer-level VR headsets or HMDs (head-mounted display), such as HTC Vive, have become more affordable and accessible during the last few years. As the hardware specifications improve, a greater level of immersion will be able to be achieved. This trend is paving the way for exciting new opportunities in the software market for exploiting the new possibilities afforded by these interactive display systems. One new avenue of design research in this space is immersive analytics, which refers to data visualization using immersive technologies. Many design challenges remain in such VR-based platforms such as user navigation and interface design. My research re-examines the validity of existing navigation techniques and VR interface design by building and testing an immersive data visualization environment using the latest VR hardware and software packages.

Keywords: Immersive Analytics, Virtual Reality, Navigation, 3D Visualization

Acknowledgements

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1. Introduction

1.1 Background

Nowadays, government and IT companies are collecting massive amounts of data every second. As urban dwellers, data-driven technologies power our everyday activities and shape social behaviors. The ability to extract intelligence and insights from very large and complex data become crucial to the decision-making process of different organizations. Visual analytics serves as a necessary tool in coping with the challenges of processing and presenting those data.

Visual analytics is "the science of analytical reasoning facilitated by interactive visual interfaces" (Cook and Thomas, 2005, p. 4). Keim et al. (2008b) defines visual analytics as "an iterative process that involves information gathering, data preprocessing, knowledge representation, interaction and decision-making" (p. 77). It has a wide influence in multiple fields, such as information analytics, scientific analysis, statistical analysis, cognitive science, data management, and so forth (Keim et al., 2008b). Thus, the interactive interfaces being employed plays an important role in the process.

Aside from the continuous development of desktop-based visual analytics systems, we have seen an advance in immersive display technologies and non-conventional input devices. For immersive display systems, the virtual reality (VR) hardware market has been evolving rapidly since 2016. VR headsets or HMDs (head-mounted display) have become more affordable and accessible as a consumer-grade technology. For input devices, novel input methods such as touch-based, voice-based,

gesture-based, and even multisensory devices have become integrated into everyday and business scenarios. As hardware constraints (e.g. latency, resolution, field of view, input accuracy) are overcome, the development of next-generation immersive visual analytics applications become more viable. However, researchers at Monash University (Chandler et al., 2015) have identified that previous studies on 3D user interfaces have been only focussed on low-level improvement such as making head-tracking more reliable. More attention should be brought into establishing a systematic method when developing immersive visual analysis applications. They named this new research direction Immersive Analytics, which refers to visual analytics based on VR and augmented reality (AR) environments as well as non-conventional interfaces (Chandler et al., 2015).
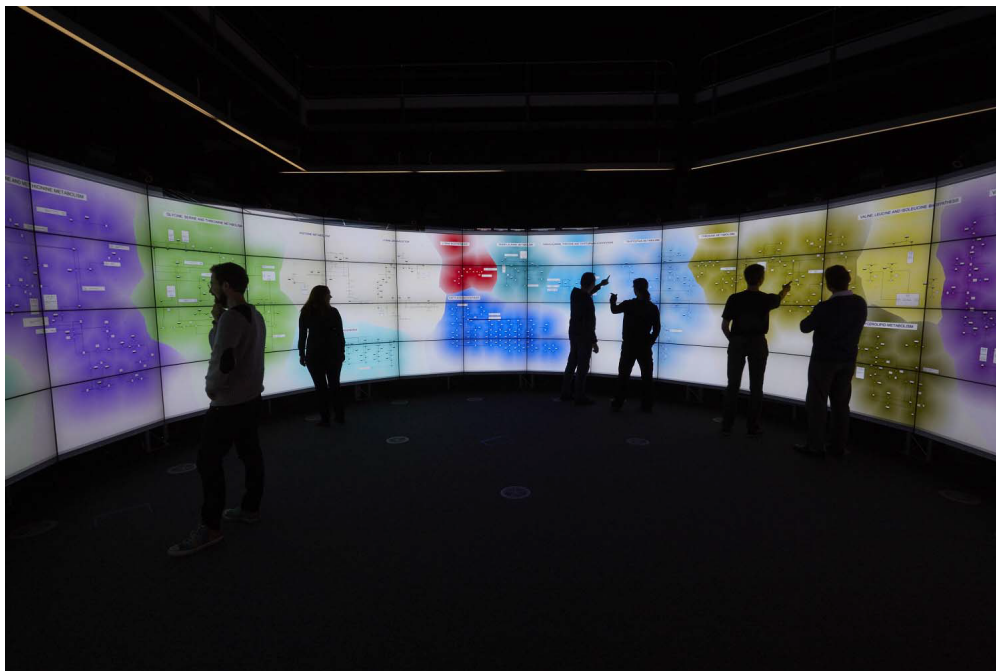
Figure 1.1: Monash CAVE2 immersive visualization facility (Chandler et al., 2015)

Recently, there has been several academic and commercial projects that center around immersive data visualization. In terms of academic projects, Donalek et al. (2014) explored immersive VR as a scientific data visualization platform by developing a data visualizer. Moran et al. (2015) visualized Twitter[1] data on a 3D model of MIT's campus with VR integration. For commercial projects, LumaPie, the winning team of the "Big Data VR Challenge" organized by Epic Games[2] in 2015, created a VR visualization of health data from 14,000 residents of the city of Bristol (Maddix, 2015). Nirvaniq Labs[3], a Toronto-based virtual and augmented reality studio, created a demo of data visualization of Canada's energy demand in VR (Nirvaniq Labs, 2016). CodeScience[4] also presented a prototype that visualizes business data for Salesforce[5] in VR (CodeScience, 2015). It should be noted that all of the projects above were developed with consumer-grade hardware, either Oculus Rift[6] or HTC Vive[7], and with game engines, such as Unity[8] or Unreal Engine[9].

Due to the novelty of immersive analytics, there are few studies focusing on interaction in VR specifically for visual analytics. There is a gap between the performance evaluation results derived from previous research and what could be achieved with the latest hardware. For that matter, recent VR applications built for

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[1] https://twitter.com/
[2] https://epicgames.com/
[3] https://nirvaniq.com/
[4] https://www.codescience.com/
[5] https://www.salesforce.com
[6] https://www.oculus.com/
[7] https://www.vive.com/ca/
[8] https://unity3d.com/
[9] https://www.unrealengine.com/

analytics are still going through a process of establishing design guidelines for

numerous aspects, such as input methods, interaction techniques, and user interface

design. Navigation, for instance, is an essential interaction in immersive environments.

It facilitates a user's ability to understand content and space from different angles and

hierarchies. Travel, as part of navigation, creates a sense of presence in the virtual

space (Bowman et al., 1998). To navigate through an immersive data visualization

environment can refer to navigating 2D/3D contents through a graphical user interface

or navigating in 3D space. For instance, switching between occluded graphs or 3D

visualizations is navigating the content, while flying through a virtual city is navigating in

space.

The overarching goal of this project is to develop a set of design guidelines,

specifically on the navigation support in immersive analytics. An immersive data

visualization environment, consisting of a 2D map of Toronto overlaid with custom data

visualization and integrated with the latest VR hardware and software packages, is built

and tested with expert users. The underlying data set being used is Toronto's

recreational courses historical data (City of Toronto, 2017). It is multivariate and has a

spatial dimension. The data is visualized as 3D geometric shapes or objects across the

map based on the locations of community centres. Multiple travel techniques such as

teleportation and custom zoom are implemented and evaluated. Although the

prototype contains abstract data visualization, its primary focus is on user navigation

between content and space that supports data analysis. This work will contribute to

the standardization of interaction and user interface design of visual analysis

applications employing immersive consumer-grade technologies.

1.2 Research Question

The primary research question this work attempts to address is:

How can users effectively navigate within an immersive data visualization environment?

Other questions that will help address the primary question include:

1. What design heuristics can be developed to aid in the development of an effective user interface in immersive analytic systems?

2. How do we design for complex navigation between 2D/3D content inside an immersive environment? How can this work support analytical tasks?

1.3 Theoretical Framework

In order to better explain the position of my research within a broader framework, I reference Creswell's (2013) research framework of four philosophical worldviews: postpositivism, constructivism, transformative, and pragmatism. I place my research in the pragmatism worldview. According to Creswell, "pragmatism arises out of actions, situations, and consequences rather than antecedent conditions (as in postpositivism)" (p. 10). In this worldview, researchers focus on problems and solutions rather than methods, and they are encouraged to use all approaches that are out there to understand the problem (Creswell, 2013). Creswell states that, "pragmatism provides a philosophical basis for research" (p. 11). Pragmatism also strongly promotes mixed methods research and the use of of both quantitative and qualitative data (Creswell, 2013). In comparison, postpositivism promotes the collection and analysis of quantitative data in controlled experiments in order to establish laws and theories, whereas constructivism advocates drawing conclusions from subjective experience (Creswell, 2013). In my work, I adopt the idea of using both quantitative and qualitative data to help me understand the variables that are affecting how users navigate in VR environment.

The theoretical foundation of my research is based upon the model of ecological psychology (Gibson, 1979) and the model of perceptual processing (Ware, 2013). In the following sections, I provide the basic definition and explanation of the relevance to my research questions.

Gibson's theoretical model of ecological psychology has had great influence on the theories of virtual realities as well as information visualization (McLellan, 1996; Ware, 2013). According to McLellan (1996),

> Ecological psychology is the psychology of the awareness and activities of individuals in an environment. This is a theory of perceptual systems based on direct perception of the environment (p. 476).

Based on Gibson's model (1979), "affordances" describe the unique physical properties of an object or environment and we as human perceive the possible interactions with objects and environments based on our understanding of those properties. For example, we perceive environment for exploring or navigating, surface for supporting, and so forth. McLellan (1996) describes that, "affordance perceptions allow learners to identify information through the recognition of relationships among objects or contextual conditions" (p. 476). In practice, McGreevy (1993) uses Gibson's theory of ecological psychology as the basis of his study in virtual reality as a tool for planetary exploration. McGreevy argues that the physical world offers a wider range of affordances than computer-generated scenes. In response to that, McLellan (1996) reasons:

> Although a virtual world may differ from the real world, virtual objects and environments must provide some measure of the affordances of the objects and environments depicted (standing in for the real world) in order to support natural vision (perceptualization) more fully (p. 477).

This process of exploring the affordances that virtual reality (VR) environment provides is reflected in my prototype and user testing.

In light of information visualization, Ware (2013) thinks the affordances theory is "attractive from the perspective of visualization" (p. 18) because they both imply actions. On the other hand, Ware argues that Gibson's direct perception approach may not be appropriate for explaining visualization concepts. Ware provides three reasons:

1. Even if perception of the environment is direct, computer-generated data visualization is indirect.

2. There are no clear physical affordances in any graphical user interface.

3. Gibson's rejection of visual mechanism is in conflict with most of vision research. (p. 19)

Ware constructs a principle by applying affordance theory into interface design: "a good interface has affordances that make the user's task easy" (p. 18). Ware thinks affordances theory is useful from a design perspective. In contrast, Norman (2013) sees affordances effective for interaction with physical objects, but confusing for virtual ones. I agree that with Norman's view because people have different experience with virtual interfaces and we as designers cannot assume they always recognize the same affordances. Nonetheless, during prototyping, I design the virtual environment and the user interface based on what affordances may best fit the tasks.

Because my research is concerned with visual analytics, I follow the model of perceptual processing. Ware (2013) defines it as "a simplified information processing model of human visual perception" (p. 20). It is a three-stage model. The first stage is a

passive process of extracting low-level information (Ware, 2013). The second stage, pattern perception, is slower and flexible (Ware, 2013). Goodale and Milner's (1992) two-system hypothesis best characterizes this stage (Ware, 2013). The theory states that one visual system, called "the action system," controls locomotion and action and the other, called "what system," controls symbolic object manipulation (Goodale and Milner, 1992). The final stage, sequential goal-directed processing, is at the highest level and handles visual queries (Ware, 2013).

For perceiving information in 3D space, Ware (2013) introduces depth cue theory. Depth cues are sources of information about 3D space for supporting accurate spatial judgment (Ware, 2013). Some commons cues are linear perspective, texture gradient, occlusion, shadows, motion parallax, stereoscopic depth, and so on (Ware, 2013). In my work, I consult this theory when designing the data visualization environment and analyzing user test data, particularly on interpretation of 3D visualizations.

Last but not least, I use VR technologies as a data visualization platform more than a communication platform. However, VR is capable of facilitating more natural communication between humans. In that regard, the Media Naturalness Theory (MNT) (Kock, 2004) plays an important role in supporting collaboration and communication in VR. MNT essentially states that there is a positive link between the naturalness of a communication medium and the cognitive efforts required to participate into an interaction using the medium.

1.4 Methodology

1.4.1 Purpose Statement

The mixed methods study will help evaluate the effectiveness of user navigation in an immersive data visualization environment. A convergent mixed method is used, a type of design in which qualitative and quantitative data are collected in parallel, analyzed separately, and then merged (Creswell, 2013). In particular, my research question is exploring how users effectively navigate an immersive data visualization environment. I assume that some navigation techniques are more effective than the others in different use case scenarios. However, it is not likely that one navigation technique is the most effective at all times because human perspective changes frequently when navigating. The effectiveness of user navigation may be influenced by a variety of internal (user) and external (environment) variables, such as real vs. virtual environment, types of tasks at hand, familiarity with the technology, usability of the interface, and so forth. In order to gain a more comprehensive understanding of those variables, I design navigational tasks in an immersive data visualization environment where each task is associated with a goal in the data analysis process. I collect performance metrics by observing how users carry out those tasks. The data being collected from pre- and post-test interviews as well as the "think aloud" process will explore the expert users' subjective experience in an immersive environment. In the following sections, I will briefly introduce the methodology and describe the use of the research method and design method in greater detail.

1.4.2 Research and Design Methodology

Mixed methods are also known as *integrating*, *synthesis*, *quantitative and qualitative methods*, *multimethod*, and *mixed methodology* (Creswell, 2013). Recent literature tends to use *mixed methods* (Creswell, 2013). According to Creswell (2013),

It can be seen as a new methodology originating around the late 1980s and early 1990s based on work from individuals in diverse fields such as evaluation, education, management, sociology, and health sciences. It has gone through several periods of development including the formative stage, the philosophical debates, the procedural developments, and more recently reflective positions (noting controversies and debates) and expansion into different disciplines and into many countries throughout the world (p. 217).

1.4.3 Rationale of choosing Mixed Methods

Mixed methods provides the opportunity for me to collect both quantitative and qualitative data of a specific VR application scenario. This data might be of values to several groups including researchers, business analysts, VR hardware manufacturer, VR developers, and so forth. Compiling both kinds of data gives me a more complete understanding of the research problem in the following ways:

- Comparing different perspectives from quantitative measures and qualitative feedback
- Validating conclusions by identifying inconsistencies in the findings
- Understanding individual's performance and perspective

1.4.4 Research Method

I employ ethnographic user research as the primary research method. More specifically, I adopt participant observation and interview during user testing. The interviews are divided into pre- and post-test interviews. I gather demographic information and experience and general perspective of tools and technologies from the participant during the pre-test interview. The post-test interview serves as a retrospective session in order for me to better understand the decision making process and behaviours of the participant for a given task. For participant observation, I videotape the participant and ask her to "think aloud" while she is carrying out the instructed tasks. This allows me to precisely collect quantitative data, such as the completion time of a task, by validating in the video footage and also to record conscious feedback from the participant.

In the early stage of literature review, I conducted expert interviews with two managers from the Parks, Forestry & Recreation Division of City of Toronto in order to get more information on the problem domain and on the context of the data set being used. Later, I conducted user tests on approximately eight expert users, who have been involved into data visualization and/or urban planning projects and have academic backgrounds out of Data Visualization, Urban Planning, Computer Science, Informatics, Experimental Psychology, and Knowledge Sharing. More details are discussed in User Testing.

1.4.5 Design Method

Since my research is computer technology-based, I adopt agile methods. Agile methods can be loosely defined as iterative and incremental software development processes to meet constantly changing requirement (Deuff and Cosquer, 2013). The agile method I adopt is Rapid Application Development (RAD), which is an iterative development process focussing more on prototyping with changing design specification (Martin, 1991). It is also characterized with smaller team with skilled developers and shorter time-span on planning (Beynon-Davies et al., 1999).

Following this process, I built a computer-based prototype incrementally and iteratively. At the first stage, I defined a list of software features that meet the task specification. The features that are essential for performing navigational tasks are put into higher priorities. I presented the first few iterations of prototype to my thesis advisors, faculty members and colleagues to get feedback on the visual design, the usability, as well as the relevance to my research questions. When the key features were in place, I immediately tested it with six users. I worked on the improvement of functionality and task specification iteratively until the end of this research project.

2. Literature Review

2.1 Overview

In this chapter, I start by reviewing the definition of visual analytics and immersive analytics and related works on immersive data visualization. I then review the adoption of consumer-grade VR technologies and investigate into navigation techniques in virtual reality environment (VRE). Finally, I wrap up with introducing relevant cognitive issues within VRE.

Before I start, there are a few core terms that have been used interchangeably in this paper, where they also have been used differently by several scholars:

1. Virtual Reality / Artificial Reality / Virtual Environment / Virtual Reality Environment / Immersive Environment / Immersive Virtual Reality / 3D Environment / Virtual 3D Environment

2. VR Headset / Head-mounted Display (HMD) / VR Goggle

To clarify, virtual reality, artificial reality, virtual reality environment, immersive environment, and immersive virtual reality refer explicitly to virtual environment enabled with head-mounted displays. Virtual environment, 3D environment, and virtual 3D environment are virtual 3D world that are viewed through a flat screen. They are not necessarily immersive depending on the display systems and input devices used. VR headset, head-mounted display, and VR goggle are the same thing. I use VR headset to explain my prototype and user testing process as it tends to be used by the public more recently.

2.2 Virtual Reality as Data Visualization Environment

The concept of virtual reality as data visualization environment is not new. Erickson (1986) sees artificial reality "differs only in degree from previous systems" (p. 9), particularly in the range of input and feedback options. Erickson argues that "artificial reality makes it easier to interact with visualization" (p. 9). There are both advantages and drawbacks in using virtual reality as a data visualization environment. The advantages are summarized as three key points:

1. Manipulating 3D images or objects can be taken in more natural forms or in the manipulate the interface to manipulate the data; the user need only manipulate the data directly" (Erickson, 1986, p. 10).

2. Artificial realities allow multiple users to interact simultaneously with the same visualization (Erickson, 1986).

3. Artificial realities support human/human interaction (Erickson, 1986).

Erickson addresses several constraints and problems after his experience with an immersive brain visualization in 1989. Some of the problems still exist in the latest virtual reality hardware. For instance, the cable of tethered head-mounted display may trap users around their legs. In terms of 3D navigation techniques, Erickson concludes:

The more natural a gesture is, and the more variations the system will tolerate in recognizing it, the easier it will be to do accidentally; the less natural a gesture is, and the more stringent the system is in recognizing it, the more difficult the gesture will be to perform (p. 13).

Another problem is the design of the interface metaphor, which may contradict with people's understanding about real objects and environments (Erickson, 1986). Finally, Erickson addresses the needs for third-person representations to prevent disorientation.

2.3 Visual Analytics

Visual analytics is "the science of analytical reasoning facilitated by interactive visual interfaces" (Cook and Thomas, 2005, p. 4). Keim et al. (2008b) defines visual analytics as "an iterative process that involves information gathering, data preprocessing, knowledge representation, interaction and decision-making" (p. 77). Visual analytics research is interdisciplinary and overlaps with areas such as visualization, data mining, data management, and cognitive science (Keim et al., 2008a). According to Keim et al., the goal of visual analytics is to "make our way of processing data and information transparent for an analytic discourse" (p. 155).

Keim et al. (2008a) also argue visual analytics is more than information visualization because it combines visualization, human factors, and data analysis. The challenge of visual analytics is to "identify the best automated algorithm for the analysis task at hand, identify its limits which can not be further automated, and then develop a tightly integrated solution with adequately integrates the best automated analysis algorithms with appropriate visualization and interaction techniques" (Keim et al., 2008a, p. 158). Keim et al. (2008a) also address that less emphasis has been put on studying user interaction on the data, which is crucial for

the improvement of analytical processes. In my work, I focus more on gathering data from user interaction.

2.4 Immersive Analytics

Visual analysis has been confined to desktop-based tools until the recent advances in various immersive technologies and multi-sensory interfaces. A new research direction emerges, named Immersive Analytics. It refers to visual analytics based on VR and AR environments as well as non-conventional interfaces (Chandler et al., 2015). Immersive analytics is multi-disciplinary and involves researchers from human-computer interaction, visual analytics, augmented reality, and scientific and information visualization (Chandler et al., 2015). Similar to visual analytics, it aims to "understand how (and whether) new interface and display technologies can be used to create a more immersive kind of data analysis and exploration" (Chandler et al., 2015, p. 6).

2.5 Related Works in Immersive Analytics

More academic research on virtual reality for visual analytics has been published recently as the hardware becomes more affordable and accessible to university researchers, scientists, as well as hobbyists.

Donalek et al. (2014) believe that immersive visualization, immersive virtual reality using abstract data visualization, can multiply the effectiveness of desktop visualization. Their team built an immersive astronomical data visualization environment

in Unity (game engine) that supports Oculus Rift VR headset and Leap Motion[10] sensor and Kinect[11]. As shown in Figure 2.1, a user can navigate through the visualized data space using hand motions, and perform clustering and selection to determine optimal mapping choices of data parameters on 2D interface. However, their work does not focus on the navigation techniques in data space and no evaluation is present yet to show the effectiveness of gesture-based navigation in data exploration.

Figure 2.1: iViz. A student navigating through the visualized data space, using the Oculus Rift VR headset and Leap Motion gesture control (Donalek et al, 2014).

Similar to Donalek et al., Moran et al.'s (2015) argument is that simulations and virtual reality together can lead to better discovery in spatial and geographical domains. Their study focuses on both visualization and interaction. They visualized Twitter[12] data and projected them onto a 3D map of MIT's campus, in Unity. They also use Oculus Rift VR headset and Leap Motion. Within the life-size virtual scene, a user can move

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[10] https://www.leapmotion.com/
[11] http://www.xbox.com/en-US/xbox-360/accessories/kinect
[12] https://twitter.com/

freely in all directions (i.e. x, y, and z axes). For navigation, they implemented a free-form camera and adjustable zooming in order to help reveal the overall framework and features of the dataset. Other features that support data analysis include selection by pointing and filtering, and dynamic queries using virtual keyboard input. Figure 2.2 shows that the player's hand is rendered in the simulated scene and tweet object selection using hand motions.
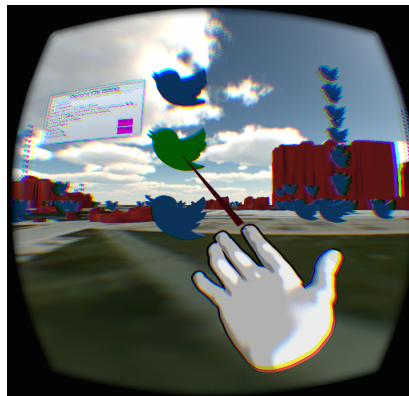
Figure 2.2: Interaction with Twitter data. View of selected tweet in virtual reality and selecting data using hand motions (Moran et al., 2015).

The winning team, LumaPie, at the Big Data VR Challenge built a VR visualization of a large set of health data in Unreal Engine (Maddix, 2015). The display system is Oculus Rift and the input device is Razor Hydra[13] controller. Since the dataset is not geospatial-based, the virtual scene is designed in a way that the user is surrounded by spirals arranged in arcs, where each geometry on the spiral is the representation of a person, as shown in Figure 2.3. Their project put more design considerations on interaction and 3D user interface design that supports visual analytics rather than navigation.

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[13] https://www.razerzone.com/ca-en/gaming-controllers/razer-hydra-portal-2-bundle

Figure 2.3: LumaPie's Big Data VR visualization (Stoll, 2015)

More recently, Simpson et al. (2016) built an immersive analytics prototype using Unity and HTC Vive to help with environmental decision-making and policy analysis for non-expert users. They argue that there are potential advantages of interpreting Dynamic Integrated Climate-Economy (DICE) model in an immersive context. They also suggest that there is a need for more evaluation of multidimensional immersive VR representations over 2D multidimensional representations. Since it is an ongoing work, no evaluation work has been done at the point of publication. It is either not clear that whether or not immersive VR is better than desktop-based paradigms in the context of environmental decision-making. Figure 2.4 shows the DICE workbench in VR view.
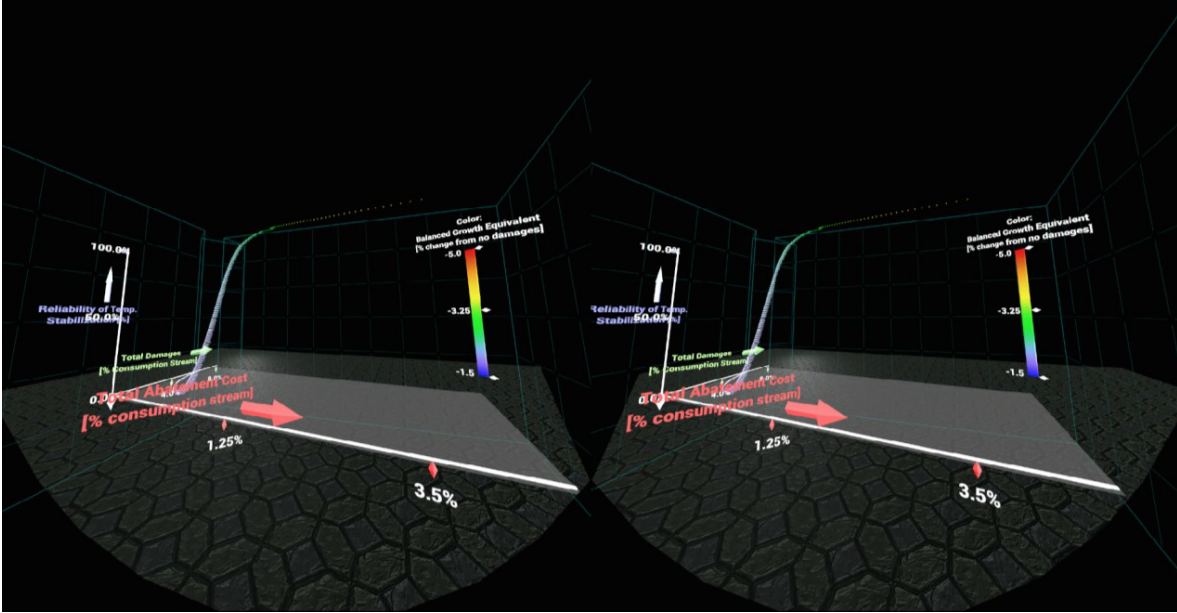
Figure 2.4: DICE workbench. A screenshot of the HTC Vive headset mirror illustrating the current state of the DICE workbench (Simpson et al., 2016).

None of the research discussed so far has tackled the effectiveness of user navigation in immersive visualization of data with spatial dimension. More recent research (Simpson et al., 2016) has started to apply room-scale VR like HTC Vive but no user study results are available at the point of review.

2.6 Adoption of Consumer-grade VR Hardware

Since the first head-mounted display (HMD) system was implemented by Ivan Sutherland in 1968, VR hardware has undergone tremendous changes. HMDs or VR headsets, like many devices designed for specific research in the laboratories, are not viable at the consumer level until Oculus Rift achieved some success in 2012.

Nowadays, when we mention "VR" in a daily conversation, we often paint a picture of a person wearing a VR headset and being immersed into a virtual world in

their head. To define it technologically, it consists of a collection of hardware, including computers, HMDs, headphones, and handheld controllers (Steuer, 1992). They can be generally grouped into two categories, tethered and mobile.

A tethered headset can also be called a high-immersion headset. It consists of a headset (with sensors) connected to an external system. It is superior to mobile headsets in the level of quality of the images being rendered and the capabilities of the controls. In comparison, mobile headset is simply a goggle that a mobile device that can fit into it. It has the advantage of accessibility and portability. HTC Vive, currently with the highest cost, has the largest maximum tracking area, resolution, and field of view. Although HTC Vive and Oculus are tethered at the point of review, the manufacturers are currently in the process of developing wireless solutions. A comparison between the specifications of the latest consumer-grade VR headsets can be found in Table A.1 Tethered VR Headset Comparison 2017 in Appendix A.

2.7 Navigation in Virtual Environment

Navigation is an essential interaction in immersive 3D environments. It facilitates a user's ability to understand the visual space and its content so the user knows where to go and how to carry out tasks. It is also important that an analyst can travel to a desired coordinate in virtual 3D space and locate a piece of data efficiently and accurately. Especially in a large and complex immersive environment such as an urban simulation, it takes more mental effort than moving around basic 3D geometries. If sufficient visual cues about the reference space are not provided or navigation

techniques are not chosen adequately, the user may get disoriented or confused (Bowman et al., 1997). This may hinder any analytical tasks from going forward.

Navigation in an immersive environment also has more options than in physical reality and often purposely neglects natural laws. In the real world, most people travel in terrestrial space on foot or by a vehicle. Although we have control over movement, speed, acceleration and orientation, they are constrained by physical laws. On the other hand, we gain more freedom in a virtual environment. For instance, we can ignore gravity and resistance force to gain more freedom in direction of travel or speed of travel. Navigation techniques in 3D space can also be applied into immersive environment. In the rest of this section, I review the definition of navigation and major works in VR navigation and travel techniques.

According to Herndon et al. (1994), "navigation is the planning and execution of travel through space, real or virtual, carried out with reference to external or internal representations of the space being traveled" (p. 38). They suggest that users must be able to control the navigation techniques at all times. They define a number of interaction tasks that are universal to 3D graphics applications:

- Object creation, model definition
- Object selection
- Object placement and editing: affine transformations (e.g., translate, rotate, scale, alignment, etc.); modifications to other parameters (e.g., color, shading, etc.)
- Viewpoint control

- Perception: extracting cognitive information from an environment

- Programming: defining behavior of objects and relationships between objects

  (Herndon et al.,1994, p. 37)

Additionally, a conceptual framework was proposed by Herndon et al. (1994) that classifies navigation into three categories, position-based, velocity-based, and acceleration-based. Position-based navigation "relies on external signals indicating position and orientation (e.g., in the form of signals from stationary landmarks)" (Herndon et al., 1994, p. 38). Velocity-based navigation "relies on external signals indicating speed and direction of travel" (Herndon et al., 1994, p. 38). Acceleration-based navigation depends on vestibular- or proprioceptive-based acceleration signals (Herndon et al., 1994). Herndon et al. suggest that visual position and velocity information is most important in effective navigation by humans. Common best practices that help users understand the environment include placing landmarks and horizons, putting textures on surfaces, and casting shadows (Herndon et al., 1994).

Mine (1995) introduces a framework for interaction techniques in virtual environment. In terms of controlling one's direction during traveling, there are ways that simply use body movement (hand-directed and gaze-directed), rely on input devices (physical and virtual controls), and ways that are influenced by the environment (object driven and goal driven) (Mine, 1995). For speed and acceleration control techniques, Mine introduces constant speed, constant acceleration, hand controlled, external physical controls, and virtual controls. Mine suggests that the most natural way to move through virtual environment is to map movement in physical reality.

However, the problem of physical movement is that it is limited by the capability of the tracking system. The size of an application's virtual space is likely to exceed the size of tracking area, as illustrated in Figure 2.5. Mine also discusses implementation strategies in related to navigation in 3D space. Mine proposes to constrain the types of motion by the user. The larger number of degrees of freedom, the more difficult to re-orient oneself (Mine, 1995). Finally, Mine suggests that letting the system take control of the user's motion is acceptable in some scenarios. Such scenarios can be found in the guided tour mode in Google Earth VR[14].
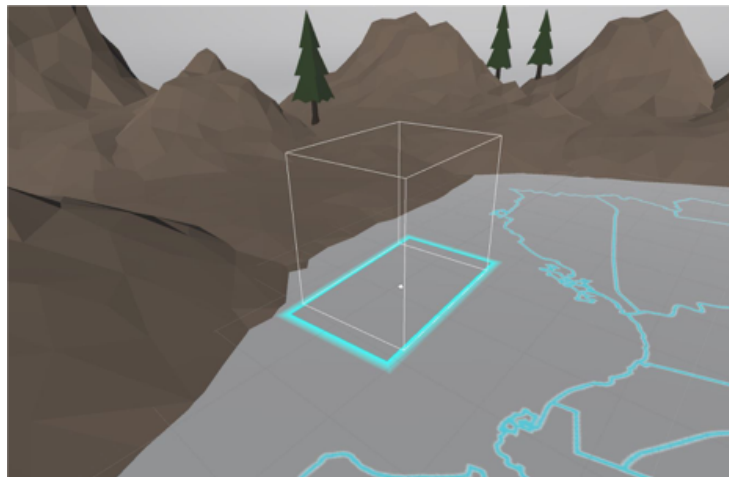
Figure 2.5: HTC Vive Chaperone bound. An example of the virtual environment is larger than the physical tracking area. The light blue box denotes the physical tracking area.

Bowman et al. (1998) define navigation as *travel* and *wayfinding*. Travel is the control of user viewpoint motion through a virtual environment (Bowman et al., 1998). Wayfinding is the cognitive process of determining a path based on visual cues and knowledge of the environment (Bowman et al., 1998). Bowman et al. (1999) argue that

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[14] https://vr.google.com/earth/

the method of travel may have an affect on the ability to perform wayfinding tasks and on a user's spatial orientation. Bowman et al. (1997) evaluate first-person travel techniques in an immersive virtual environment using head-mounted displays. Test results show "pointing" techniques are more effective than "gaze-directed" steering techniques in a relative motion task and teleportation (the user is instantly teleported to a target location) causes disorientation (Bowman et al., 1997). Teleportation is correlated with increased disorientation (Bowman et al., 1997). "Users may become disoriented because of improper motion cues, lack of-control over travel, or exposure to large velocities or accelerations" (Bowman et al., 1997, p. 50).

In order to design a travel technique, one can choose a method from each of the three branches of the taxonomy (see Figure 2.6) (Bowman et al., 1997). Bowman et al. also propose a list of quality factors that represents specific attributes of effectiveness for travel techniques, speed, accuracy, spatial awareness, ease of learning, ease of use, information gathering, presence, and user comfort. Within the eight factors, speed and accuracy are quantifiable while the others are inherently subjective (Bowman et al., 1997). Later, Bowman et al. (1998) expand the framework by including variables related to task, environment, user, and system characteristics. Bowman et al.'s (1999) experiment of virtual travel techniques comparison on spatial orientation has shown that performance depends not only on the travel technique, environment, and task, but also on the sophistication of the user. However, the pointing technique used in user tasks led to limited performance due to the cognitive load it induces and the failure of users to recognize important strategies (Bowman et al.'s, 1999).

```
                    ┌── Gaze-directed steering
                    │
                    ├── Pointing/gesture steering (including props)
  Direction/Target   │
  Selection   ───────┤                      ┌─ Lists (e.g. menus)
                    ├── Discrete selection ──┤
                    │                      └─ Environmental/direct
                    └── 2D pointing            targets (objects in the
                                               virtual world)

                    ┌── Constant velocity/acceleration
                    │
                    ├── Gesture-based (including props)
  Velocity/Acceleration │                      ┌─ Discrete (1 of N)
  Selection   ───────┤── Explicit selection ──┤
                    │                      └─ Continuous range
                    ├── User/environment scaling
                    │
                    └── Automatic/adaptive

                    ┌── Constant travel/no input
                    │
  Input Conditions ─┤── Continuous input
                    │
                    ├── Start and stop inputs
                    │
                    └── Automatic start or stop
```

Figure 2.6: Taxonomy of virtual travel techniques (Bowman et al., 1997)

A few other works investigated into travelling in VR environment from different perspectives. Pausch et al. (1995) tested World-in-Miniature (WIM), a hand-held miniature 3D map, as a navigation tool in VR. In the experiments, users see both the immersive world and a manipulable God's eye view of the world (Pausch et al., 1995). As a user moves her avatar, she flies in the virtual world (Pausch et al., 1995). Pausch et al. found that flying the user is confusing because the user's focus of attention is in the miniature instead of the full scale virtual world. Chance et al. (1998) conducted experiments on travelling in virtual mazes using three modes, Walk, Visual Turn, and Real Turn. Walk was physical walking with room-scale tracking (Chance et al., 1998). Visual Turn was using a joystick to control turning (Chance et al., 1998). Real Turn was a mix of both (Chance et al., 1998). The results showed that the degree of motion sickness depended upon travel mode, where the real walking mode has the lowest

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incidence among the three (Chance et al., 1998). In terms of subjective presence in immersive virtual environment, Usoh et al. (1999) found that real walking as a locomotion is significantly better than virtual walking and flying for exploring human-scale spaces. Usoh et al. addressed the necessity to replace head-mounted display cables with wireless links.

2.8 Cognitive issues

Understanding the cognitive issues behind virtual reality is essential in designing virtual reality applications (McLellan, 1998). Because cognition is a broad topic and this paper only concerns with navigational perspective of VR, only spatial perception in virtual environment will be discussed.

2.8.1 Navigation Loop

Ware (2013) explains:

Viewpoint navigation is important in visualization when the data is mapped into an extended and detailed 3D space. Viewpoint navigation is cognitively complex, encompassing theories of path finding and map use, cognitive spatial metaphors, and issues related to direct manipulation and visual feedback (p. 353).

Navigation loop explains how the spatial data model of the visualization system is interpreted by the user and becomes encoded in the user's memory, either in working or long-term memory (Ware, 2013). In my work, I base my task design on this

concept where I present different data mappings between different set of tasks so that users will not be able to memorize the spatial data model.

2.8.1.1 Navigation Metaphors

Based on Ware's (2013) definition, "interaction metaphors are cognitive models for interaction that can profoundly influence the design of interfaces to data spaces" (p. 355). Navigation metaphors have two kinds of constraints, cognitive and physical limitation (Ware, 2013). The first constraint refers to the prediction of system behavior given different kinds of input actions by the user (Ware, 2013). The second constraint indicates the easiness of some physical actions (Ware, 2013). Ware introduces four classes of navigation metaphors associated with the view point control in virtual 3D scenes:

1. World-in-hand

2. Eyeball-in-hand

3. Walking

4. Flying

Among the four classes, the first one does not provide affordances for navigating long distances such as over a map (Ware, 2013). The second model is known as the least effective one due to its physical affordances (Ware, 2013). The third model is more natural but the affordances, such as of walking in place, are still restrictive (Ware, 2013). The fourth model offers more flexibility (Ware, 2013). Ware proposes that the optimal navigation method depends on the nature of the task. For example, walking may be sufficient for completing room-scale tasks.

2.8.1.2 Frame of Reference / Views

Frame of reference can be interpreted as another perspective of the world (Ware, 2013). It is classified into egocentric and exocentric. The egocentric frame of reference is our subjective view of the world, whereas the exocentric frame of reference means external view (Ware, 2013). Examples of external views include,

- Another person's view

- Over-the-shoulder view

- God's-eye view / Bird's eye view

- Wingman's view

However, in immersive virtual reality, there is only egocentric frame of reference since the user is wearing a VR headset and the virtual camera is always attached to the user's head. From a first-person perspective, bird's eye view may be achieved through letting the user navigate to a higher position in space or moving the world away from the user.

2.8.3 3D vs. 2D

Although 3D display seems 'cooler' than 2D display, it is not necessarily it is more effective in interpreting data. Ware (2013) suggests that it is necessary to consider the subtasks when weighing between 3D vs. 2D display. Ware argues that many 3D navigation methods are slower than 2D counterparts and accessing to massive amount of information in 3D can be inefficient. Specifically, 2D views are better at showing precise relationships and 3D views are better used to gain a

qualitative understanding of the data (Springmeyer et al., 1992). However, Munzner (2014) argues that 3D is beneficial in understanding the 3D geometric structure of objects or scenes. Munzner asserts that "in almost all of these cases, a 3D view with interactive navigation controls to set the 3D viewpoint will allow users to construct a useful mental model of dataset structure more quickly than simply using several 2D axis-aligned views" (p. 124).

In terms of retrieving data from static perspective spatial organizations, Cockburn and McKenzie (2002)'s experiment shows that user performance degraded in both physical and virtual scenarios as their freedom to locate items in the third dimension increased. 3D interfaces are also said to be more "cluttered" and less efficient by the users (Cockburn and McKenzie, 2002). However, it is unclear that it is the same case for larger data sets (over 100 data items) (Cockburn and McKenzie, 2002). In a later study, Cockburn (2004) argues that 3D effects make no difference to the effectiveness of spatial memory in monocular static displays. Even with virtual reality, it remains unclear that 3D would give spatial memory advantages or not (Cockburn, 2004).

3. Prototype

3.1 Overview

This chapter is devoted to the process of prototyping. I start with discussing the general development process and hardware and software specification. Then I discuss the use of the data set. Finally, I dive into the development of three major iterations of the prototype.

3.2 Development Process

In this section, I briefly describe my development process. The prototyping process was an iterative process of designing, implementing and testing. In every major iteration, I defined a list of functions or specifications. When I had a stable build, I showed it to advisors and colleagues so that I can improve the prototype with their feedbacks. For the last three iterations, I improved the prototype based on expert users' comments.

Since the development takes place on a game engine, the workflow is very similar to video game development. For the majority of the time, I focussed on functional design and implementation that would fulfill the user testing requirement. I scripted the data processing and modelling, the rendering of the virtual environment, and the interaction mechanism. I also used and modified existing open-source plugins and projects to meet my own needs. On the other hand, I made minimum efforts on aesthetics because it is less essential in achieving my research outcomes. For instance,

rather than creating a function or a 3D asset from scratch, I used free and pre-made assets.

3.3 Hardware Specification

After some research on the VR hardware products, I purchased the latest commercial VR headset, HTC Vive. The hardware specification of HTC Vive can be found in Table A.1 Tethered VR Headset Comparison 2017 in Appendix A. There are several reasons that I chose it over Oculus Rift:

- It has a larger tracking area, 15 feet x 15 feet. Presumably users can move around more freely.

- It has a Chaperone safety system, casting virtual boundaries that represent physical play area. This minimizes the risk of colliding with objects in physical environment.

- It is supported by both the Unity and Valve Developer Community[15]. There are potentially more plugins to be utilized.

There are three limitations associated with HTC Vive. One is that the resolution is not perfect and can still cause legibility issues. Another limitation is maximum tracking distance. When a user is doing physical walking with HTC Vive headset, the size of the tracking area is limited to up to 15 x 15 feet. The last one is that the cord attached to the headset may limit the user's head rotation or trapping the user's legs.

VR development relies on high-end hardware configurations because 3D

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[15] https://developer.valvesoftware.com/wiki/Steam

rendering is expensive performance-wise. HTC Vive also requires a constant frame rate

of 90 fps. So I had to configure a high-end desktop PC for development and for user

testing. The hardware specification of my development environment can be found in

Table A.2 Hardware Specification in Appendix A.

3.4 Software Specification

I leverage free commercial game engines and software plugins that support VR

development as well as other open-source projects as the development environment

for my VR application. Unreal Engine and Unity are known as dominant immersive VR

platforms due to their seamless integration with the latest VR headsets such as Oculus

Rift and HTC Vive. I use Unity as my development platform because its online

marketplace offers a great amount of free and paid assets and plugins that allows me

to quickly build mockups. As a developer, I am also more familiar with the workflow in

Unity. I use open-source Unity libraries such as VRTK[16], data processing tools such as

Tableau[17], and map services such as Mapbox[18]. Finally, I use Github[19] to store and

manage all the source code. A full list of the software used can be found in Table A.2

Development Software Specification in Appendix A.

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[16] https://github.com/thestonefox/VRTK
[17] https://www.tableau.com
[18] https://www.mapbox.com/
[19] https://github.com/

3.5 Use of the Data set

I use City of Toronto's recreational courses historical data 2015 (City of Toronto, 2017) as the primary data source of the VR application. The data set is owned and released by the Parks, Forestry, and Recreation Division as open data. The source of the data is the City of Toronto Recreation Management System. Hence, it is accessible to the general public. It contains data on courses of recreational programs offered by the City of Toronto. Courses with certain number of classes are running under different types of programs at multiple community centres across the city. They can be grouped by program types, age groups, locations, sessions, and so on. With the data, analysts can gather insights of patterns of utilization of courses at community centres across Toronto. The insights help managers better plan out the programming at different facilities across the city. I decide to use the data set because it has a spatial dimension or it is geographically distributed, which makes it a perfect candidate for mapping out in the immersive virtual environment.

In my VR application, I encode a subset of the attributes in the data visualization, including Location (community centre) Name, Average Utilization Rate, Total Visits, Total Course Waitlist, and Latitude and Longitude. Utilization Rate is percentage of actual registrations to maximum allowed number of registrations (capacity). Average Utilization Rate is the sum of utilization rate of courses divided by the number of courses at a community centre. Total Visits is the sum of the total number of participants visits. Total Course Waitlist is the sum of number of clients waitlisted for course. Latitude and Longitude are converted from the postal codes.

In the raw data set, there are 72448 courses running in 495 distinctive locations. Thus, it is not effective to visualize every single course on a limited visual space, such as on a map. I segment the data by applying a list of filters to produce smaller sample of the original data set. Then I calculate aggregate information of a community centre in each sample. Data Processing discusses the process in detail.

3.5.1 Data Processing

I took the following steps to convert the raw data set into data that can be easily loaded, modelled, and visualized in the application:

1. **Segmentation**. I loaded the entire data set into Tableau and applied filters to extract smaller subset of data sets. The filters include Registration Sessions (seasons), Course Type (registered/regular or drop-in courses), and Sub Section (age category).

2. **Aggregation**. I created aggregated data using Tableau's built-in functions on attributes (see Figure 3.1). Alternatively, querying data in a database system is more efficient.

3. **Validation and Correction**. Postal codes in several courses in the raw data set was incorrect. I validated their locations in Google Maps[20] and corrected them in Excel.

4. **Conversion of latitude and longitude**. Geographic coordinates (latitude and longitude) were not present in the original data set. I extracted all the distinctive postal codes and converted them to coordinates using batchcoordinates[21].

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[20] https://www.google.ca/maps
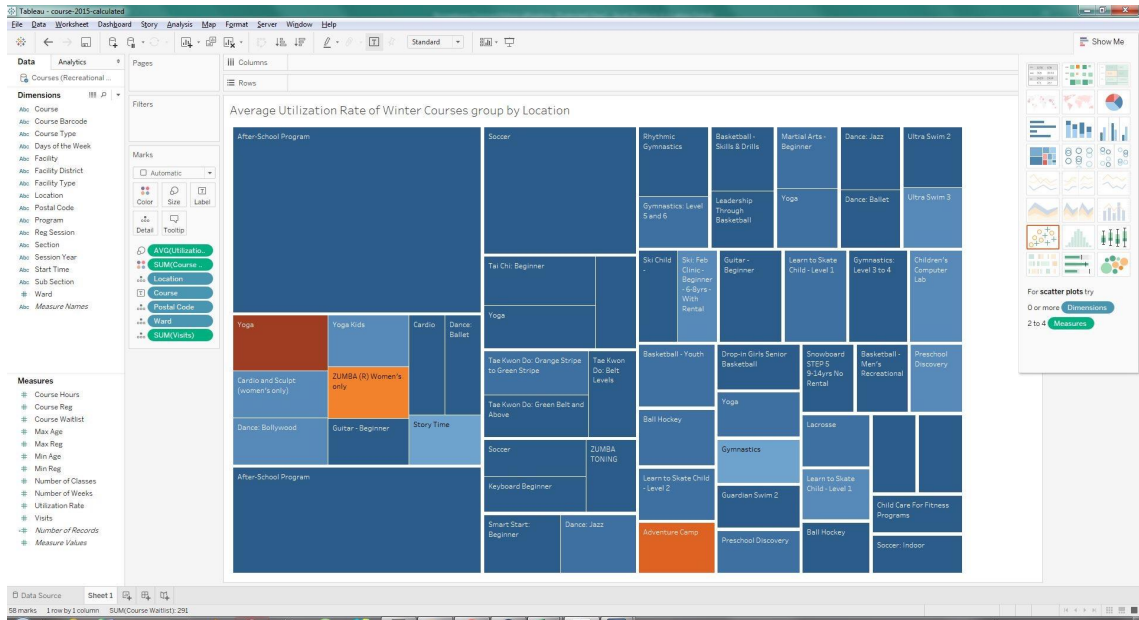
Figure 3.1: Filter and aggregate data using Tableau

3.6 Iteration 1.0 Tech Mashup

The first iteration was to experiment with different combinations of current open-source and commercial technologies and determine what software tools and libraries best serve the prototyping. I made the following decisions based on my previous experience in developing web applications and video games,

- Use Unity over Unreal Engine as the development and distribution platform.

- Modify external open-source libraries or projects that contain functionalities that help build the VR application.

In the first iteration (see Figure 3.2), I built a scene with 3D visualizations in Unity with the following feature:

- Visualizing data into 3D cubes.

- Real walking with room-scale tracking.

- Grabbing and releasing a cube.

It was my first attempt in integrating VR camera and controls in Unity. With SteamVR SDK[22], I was able to easily program key mappings of the controllers. If room-scale tracking mode is selected, walking is enabled by default once a user wears the headset. To add more interactivity, I implemented simple grabbing and releasing virtual objects.

In terms of data visualization, it took surprising more efforts to build 2D visualizations in Unity as it is a 3D game engine. I simply created primitive shapes in Unity such as 3D cubes. For loading the data, I used a csv parser to convert spreadsheet data into manipulable objects in Unity. Since during this iteration I had not decided what data set to visualize, I used the City of Toronto's Ward Profiles from National Household Survey 2011 (City of Toronto, 2017).
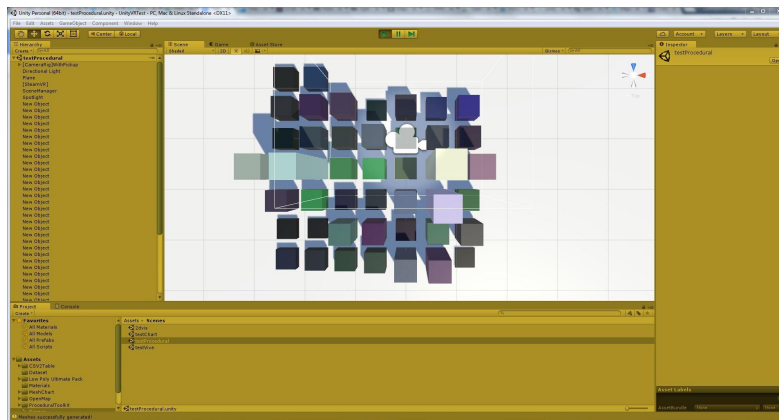
Figure 3.2: 3D visualization in Unity. A 3D visualization of sample census data. The cubes represent household data in 44 wards by encoding household size as height and total population aged 15 years and over with University's certificate as color.

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[22] https://developer.valvesoftware.com/wiki/SteamVR

3.6.1 Iteration 1.1 Map Construction

As I am tackling geographically distributed data, it is necessary to map them out

for pattern recognition. For map construction, I referenced Kahyaoğlu's (2016)

MapzenGo and Mapbox Unity SDK[23]. MapzenGo is a Unity application that

procedurally generates a map with multiple 2D and 3D layers given a location or geo-

coordinates. Rendering 3D map in Unity is non-trivial. There are two approaches, 3D

models and procedural generation. The former approach is easier for non-

programmers to create mockups. The downside of using 3D models is that it is difficult

to customize the map and to integrate data visualization programmatically. Although

procedural generation takes tremendous time to implement and may introduce

performance issues to the application, it is ideal for building visualization environment

because I can programmatically add layers of information onto the base map.

MapzenGo serves this purpose exactly. With the author's permission, I extended

MapzenGo from a 3D map to a map-based data visualization environment. As shown

in Figure 3.3, I tested a variety of possible configurations in MapzenGo to gain

understanding on the technical limitation and the aesthetics.

MapzenGo basically constructs a NxN grid of map tiles and renders 3D

buildings and roads on top of it. The map style can be changed by selecting from a few

different vector tile services. More advanced features include dynamically loaded map,

and cached map. The former one is useful when rendering a larger size of maps

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[23] https://www.mapbox.com/blog/mapbox-unity-sdk/

because it only renders adjacent tiles to the user, but it requires internet connection. The latter one is to cache tile data beforehand and has performance bottleneck.

The next step is to build a map-based data visualization environment that a user can navigate around and interact with.
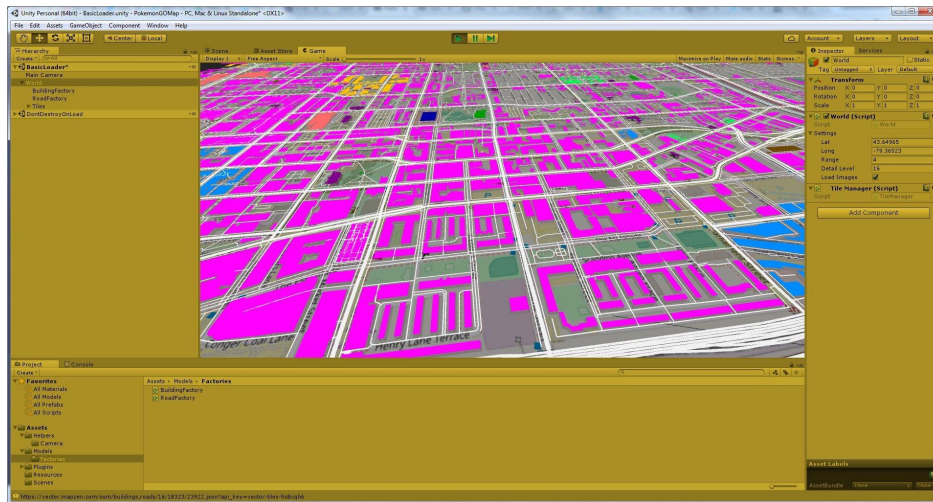
Figure 3.3: MapzenGo 3D map. The rendering of a 3D map of Toronto in Unity, with a customization of latitude and longitude values, map size, zoom level, and colors on the land use.

3.7 Iteration 2.0 Data Visualization Environment

The goal of the second iteration is to create an immersive data visualization environment that affords data exploration. It also facilitates different views and travel strategies. Unlike desktop-based applications, users see the data representation from a real world perspective instead of through a flat screen. Users can navigate the virtual environment using natural methods such as walking.

The following features are supported:

- Dynamically loaded map of Toronto

- Data visualization of recreational courses historical data

- Data Tooltip

- Teleportation

In this iteration, users can travel within a 3D visualization environment. The map is partially rendered for better application performance. As a user is about to travel out of map boundaries, new areas are loaded with slight delay. In terms of navigation, real walking with room-scale tracking is naturally supported by the HTC Vive VR headset. As the virtual space is much larger than the physical play area, teleportation is added to support long distance travel (see Figure 3.4). More navigation methods are planned to be implemented in the next few iterations. Three visualization types are supported: 3D spheres, 3D particles, and 3D cubes. 2D data tooltip (see Figure 3.4) is implemented to provide detailed information of each data point. By adjusting the camera position, the data visualization can be investigated from different perspectives: first-person (see Figure 3.5) or bird's eye view (see Figure 3.6). Users can change perspective through different navigation methods, but some may be more efficient than the others. For example, flying through allows users quickly obtain bird's eye view by flying to a higher point in space.
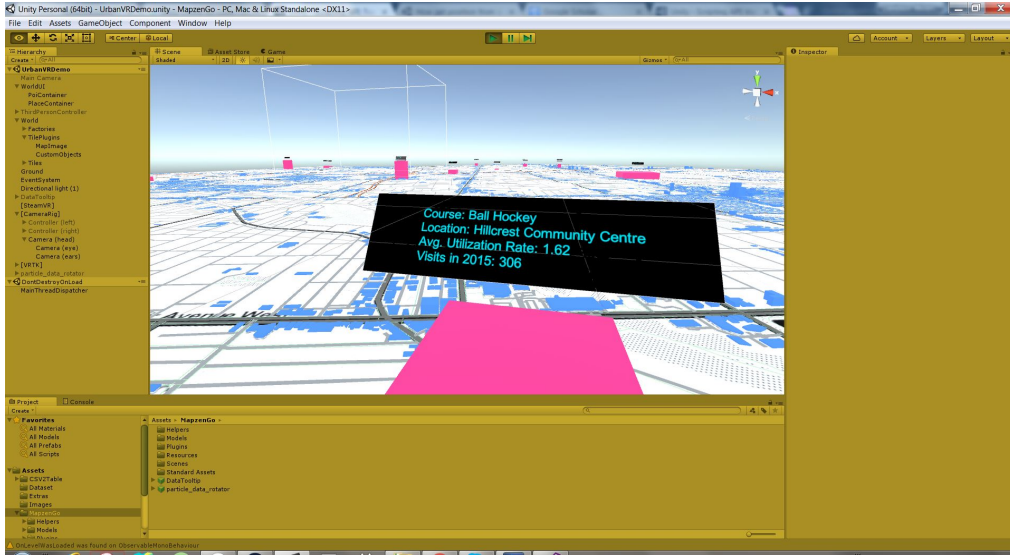
Figure 3.4: Data Tooltip. The 2D text panel hovers on a cube or data point shows more detailed

information about the community centre.

Figure 3.5: First-person perspective of the 3D map of Toronto. A user is trying to travel to a distant

location through teleportation.

Figure 3.6: Bird eye's view of the 3D map of Toronto. Each cube represents the average utilization rate of all the courses at a community centre in Toronto.

3.8 Iteration 3.0 Improvement for User Test

Built on top of the data visualization environment in iteration 2.0, this iteration finalizes the functions for supporting navigational and analytical tasks during user testing. The application is broken down into three components or scenes in Unity. Only one of them is active at a time. Each scene is tested with the same set of tasks but with different configurations in terms of navigation capability, perspective mode, and data set.

The major improvements in version 3.0 are:

- **Use real data**. Initially, I loaded a subset of the data set with over 14000 rows and visualized the utilization rate of each course as a cube across different locations (see Figure 3.7). It was impossible to compare courses but it showed the sample size. In a different configuration, I loaded aggregate data with over

220 rows (see Figure 3.8). It then became possible to spot outliers and distribution patterns on the map.

- **Use cached map data**. There are two kinds of data for rendering the map: tile data and tile images. Tile data are GEOJSON files returned by the map server. They are used for procedurally generating 3D buildings and roads and other types of visualizations. Tile images are the building blocks of the base map. Since the user tasks can be performed on a 2D map, tile data is not needed. Every time the application is restarted, it loads cached tile images from local storage. It is faster than downloading the image data from the internet.

- **Add zooming out for bird's eye view transition**. When a user is in a room-scale map, she is not able to get an overall view of the data space. A custom zoom function was implemented to achieve bird's eye view. It allows users to view the map from a distance above, like in Figure 3.8. However, in the current implementation, instead of altering the camera frustum, the map is shifted away from the user for a fixed distance so she is relatively zoomed out. Users have no control on the extent of zoom. They can only toggle the bird's eye view. This feature is to be improved in future iterations.

- **Create a tabletop scene**. This scene is created to give users a real world perspective and a more natural overall view of the map. It simply places the map on a table that is approximately 80 to 100 cm in height in real world. Users are allowed to walk, crouch, or teleport but no long distance travelling is needed.

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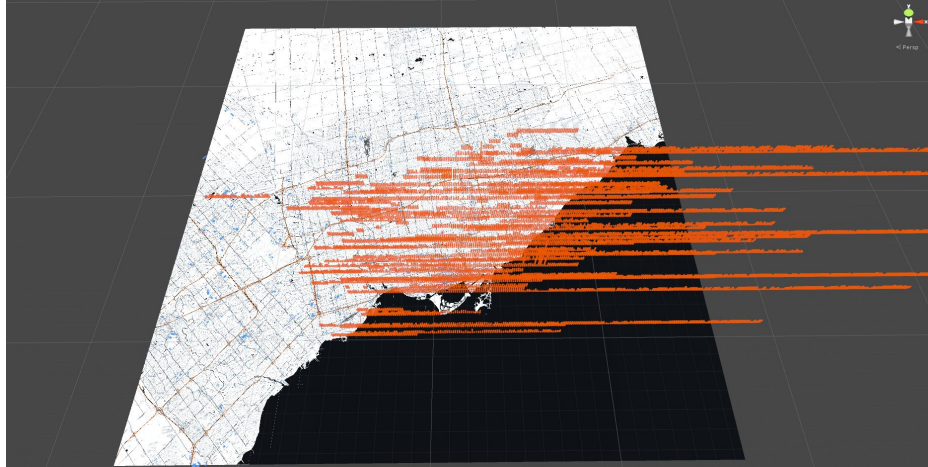
Figure 3.7 Visualize by single course
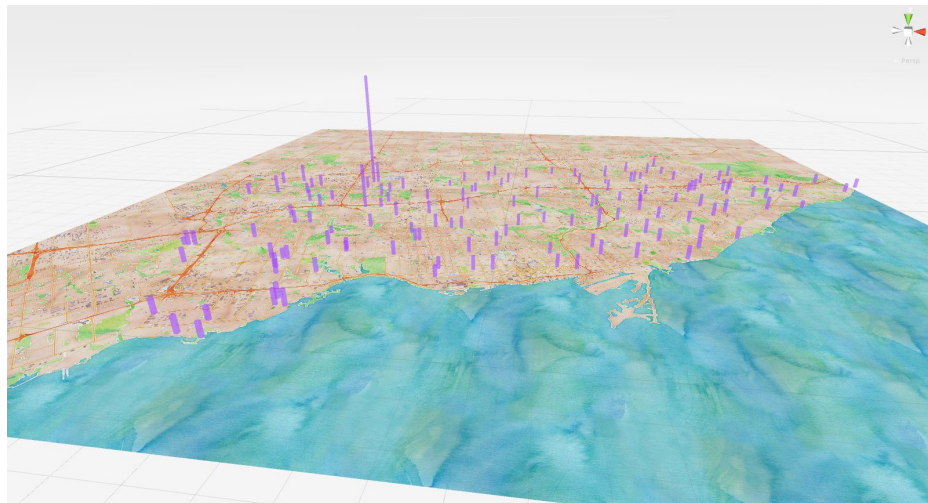
Figure 3.8 Visualize by community centre

Iteration 3.0 is the master version for the subsequent iterations. It is already a fully functional prototype. For user testing, specific configurations are applied to three different scenes for each set of the tasks. The detailed configurations can be found in Table A.4 Prototype Specifications in Appendix A. Next, I discuss each of the key configurations in detail.

3.8.1 Data Specification

Each scene in the VR application uses different data. Version 3.1 and 3.2 are configured with identical data specification. However, user test results showed the data in Scene 2 are not effective for completing certain tasks such as finding outliers. For example, version 3.1 uses all the regular swimming courses offered in the Summer in the Child / Youth sub sections. But the differences in the average utilization rate are much smaller compared to the data used in Scene 1 and 2. Identifying the data point with the highest value becomes visually challenging. To cope with this problem, I used all the regular courses offered in the Fall in Scene 2 and all the regular courses offered in the Winter in Scene 3 in version 3.3, which contain more outliers. A detailed description of the data being used can be found in Table A.5 Data Specification for User Test in Appendix A.

3.8.2 Map Configuration

For zoom level, I use zoom level 14 throughout all versions and all scenes because it shows the entire GTA with rich terrain features. According to Openstreetmap[24] standard, map at zoom level 14 has 9.547 meters per pixel and has a scale of 1:35000.

For map style, since there was no zone or street labels on the map in version 3.1 (see Figure 3.9 (a)), I decided to try Mapbox's satellite image in version 3.2 (see Figure 3.9 (b)). Later, I realized the labels are too small when in bird's eye view and did not

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[24] https://wiki.openstreetmap.org/

help much with some of the tasks. So I added my own ward boundary image and ward

labels in version 3.3 (see Figure 3.9 (c)).

(a)   (b)

(c)
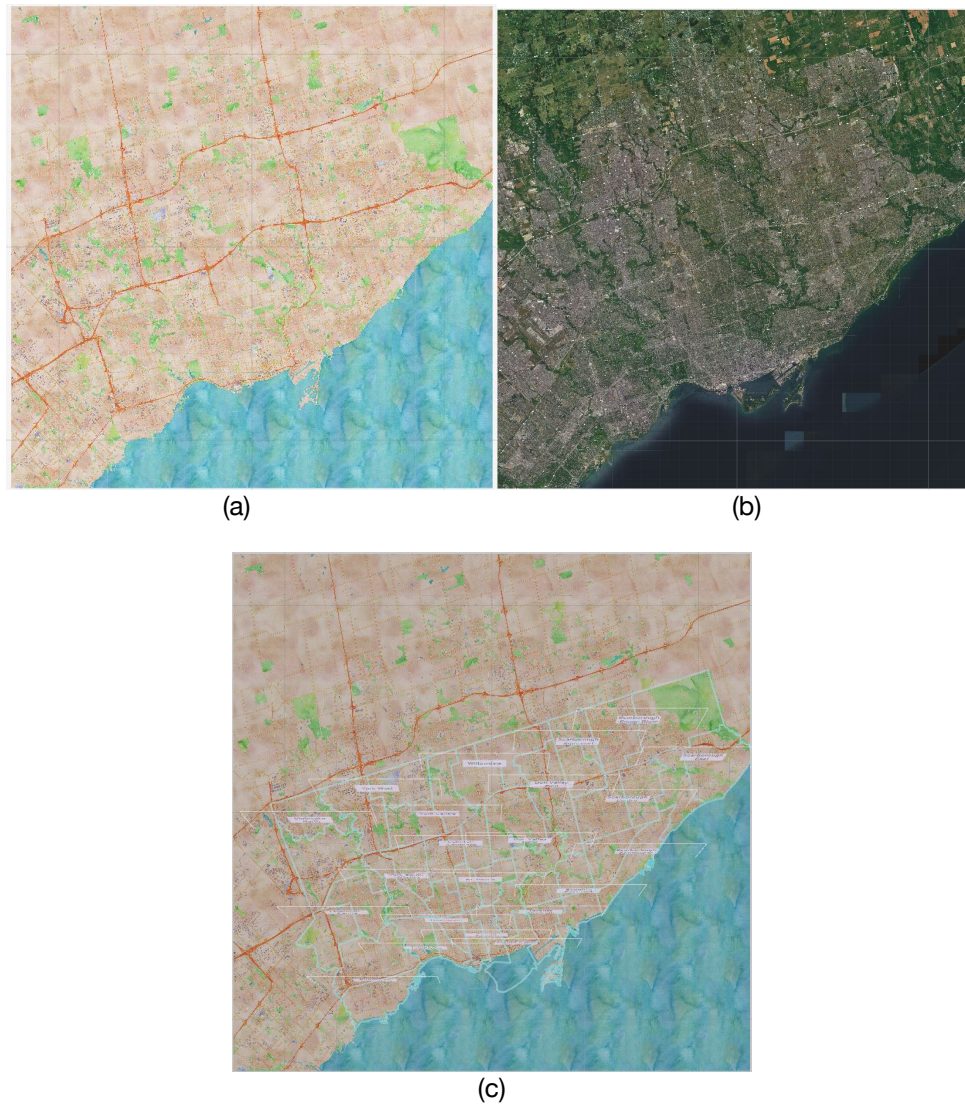
Figure 3.9: (a) Stamen Maps watercolor. (b) Mapbox Satellite Streets. (c) Ward boundary overlay.

3.8.3 Data Visualization and Data Tooltip

For visualization types, I chose 3D bar or cube because it is the simplest to

understand and to implement. Despite it may not be an effective visualization for

showing smaller differences in size, it is a very common type. For each cube, I append

a data tooltip to it, which is a 2D panel with texts. Users can acquire both qualitative

and quantitative information by reading the tooltips. However, in both version 3.1 and

3.2, they are not positioned properly. Because the position of the tooltip is fixed with

the cube, tooltips that belong to cubes that are close to each other overlap. This

causes legibility issues. In version 3.2 and 3.3, I hide all tooltips by default. I added

object highlighting using the laser beam to toggle tooltips. Since one tooltip is

supposed to be visible at a time, it eliminates the overlapping issue. However, this

prevents comparison between multiple tooltips.

(a)   (b)
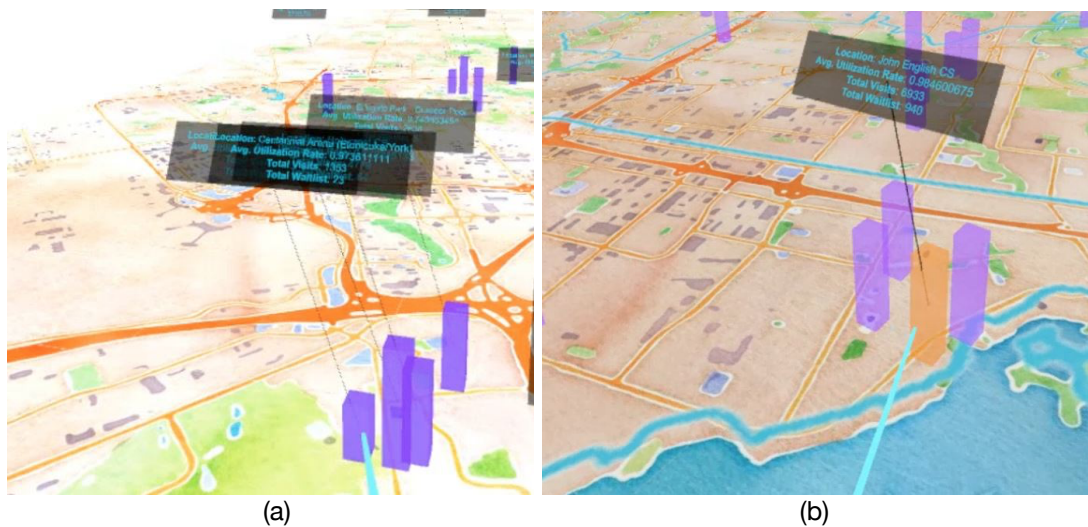
Figure 3.10: (a) Overlapping tooltips. (b) On-demand tooltips.

3.8.4 Navigation and Controls

For version 3.1 and 3.2, the main navigation methods include physical walking,

teleportation, and zoom. For teleportation, I employ the dash teleportation from VRTK.

According to the original author of the library, the dash teleportation allows to have the

user's position dashing to a new teleport location. To avoid simulation sickness, the

duration of dashing is set to 100 milliseconds by default. Teleportation is good for instant long distance travelling on the map.

The primary purpose of zoom function is to switch to bird's eye view or overall view when the scale of the map is much larger than the user. I am not able to find a way to modify the VR camera frustum. Instead, I shift the map away from the user following a predefined path to achieve the same effect (see Figure 3.11). I map the trigger key of the controller to move the map forward and the side grip button to move it to the right side. When the trigger is pressed and held, the map is shifted away. When the trigger is released, the map shifts back to its original position. But if the user teleports during the process, the map will return to its absolute world position instead of its relative position to the user.
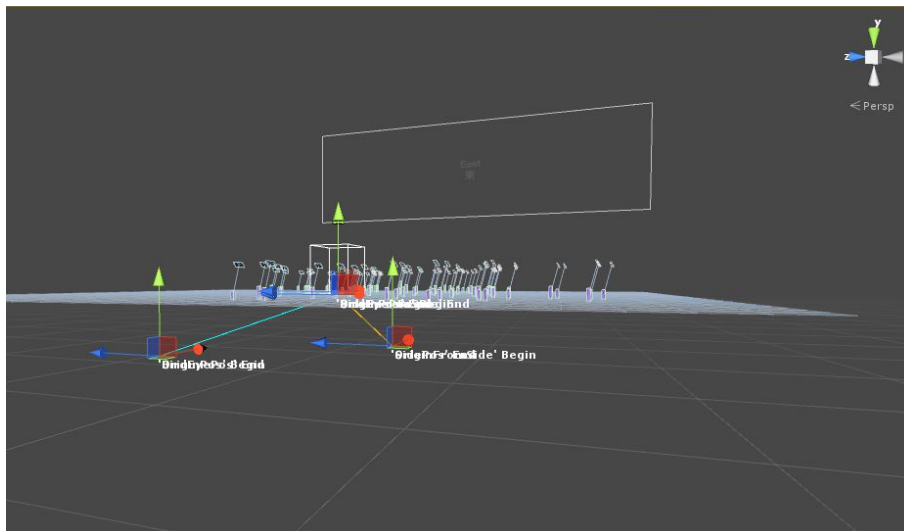
Figure 3.11: Movement paths of the map triggered by zoom. The blue path represents forward and the orange path represents side movement.

For version 3.3, zoom is removed due to the negative feedback from users. Instead, I add 3D mountains and platforms around the map in Scene 2. Users can

navigate to higher ground and observe in bird's eye view (see Figure 3.12). For navigation on a more complex terrain, straight line beam is not effective because the pointer can get occluded. So I change the teleportation beam to Bezier curve, which allows users aim at occluded targets (see Figure 3.13).
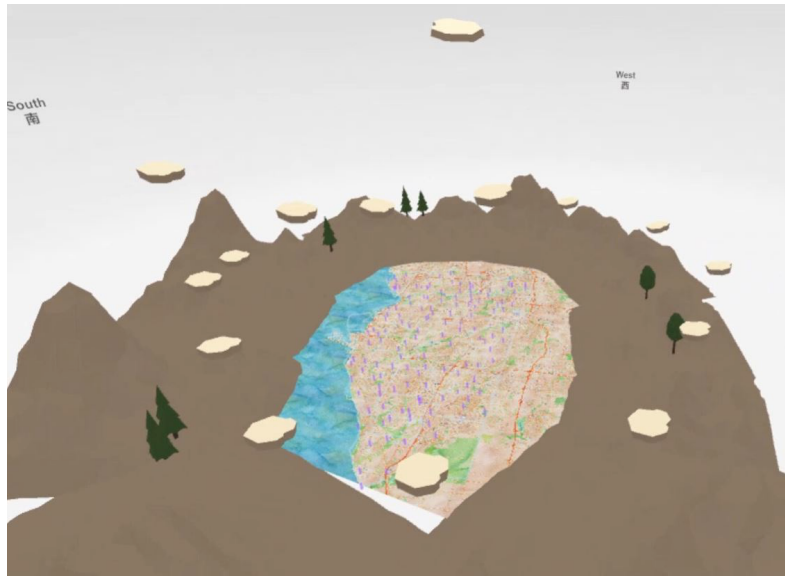
Figure 3.12: Bird's eye view on top of one of the platforms.
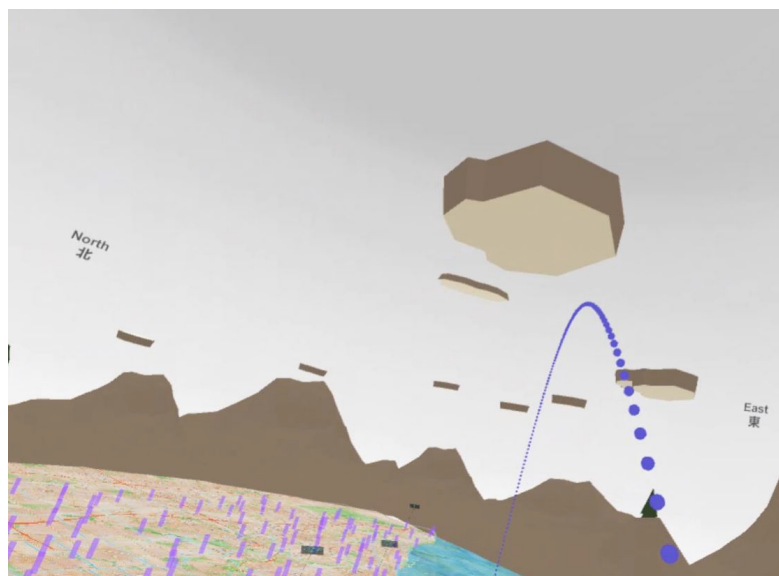
Figure 3.13: Teleport using Bezier curve beam.

A final improvement in version 3.3 is toggling ward labels using the trigger of the left controller, which is also for highlighting cubes. I bind all the UI-related controls to the left controller and navigation to the right controller. It potentially adds more cognitive load but it is presumably less confusing than coupling different kinds of controls in one input device.

3.9 Next Steps

By the end of version 3.3, the prototype has undergone significant changes. Although the functionality is not comparable to a desktop-based visualization tool, it provides the basic infrastructure for integrating more data sets and navigation methods. There are a few main areas that it can be improved to better serve different tasks.

First, the data loading can be extended from static CSV file loading to live connection to an external database or an API. They are usually supported by standard query language such as SQL and standard data format such as JSON. This gives two advantages: one is performance boost in loading and parsing larger data sets and the other is enabling more common tasks such as sorting and filtering.

Second, the map is currently built out of an external open-source project, which has limited functions and is not maintained over time. Recently, Mapbox has released the Mapbox Unity SDK. By migrating to this new plugin, I can generate stylized maps and have more optimized 3D buildings rendering. It is also possible to create visualizations with their map editing tools and import it into Unity. The entire workflow can be optimized.

Finally, existing implementation of navigation controls needs to be improved and methods are to be added. Zoom currently does not work reliably. More robust implementation is needed for changing perspective using zoom. Although fly-through in VR tends to cause nausea, there are exceptions that if instant acceleration is applied it may alleviate the effect. A good testing ground is Google Earth VR, where it employs a variety of navigation techniques such as map tilting, map rotating, and fly-through.

4. User Testing

4.1 Overview

This chapter illustrates the process of data collection and data analysis. The data collected includes the transcribed answers from the audio recordings of all the interviews and the coded data from all the recorded sessions of user interacting with the prototype. For data collection, I first talk about the rationale of interviews questions and tasks. I then summarize the process and the challenges. For data analysis, I explain the evaluation criteria and variables that are being examined. At the end of this chapter, I summarize the findings and future improvements. The findings are further condensed into a set of design recommendations and are integrated into the next chapter, Design Guidelines.

4.2 Data Collection

4.2.1 Interviews

For qualitative data collection, I conduct three types of semiformal interviews, expert interview, pre-test interview, and post-test interview. Expert interview is one-hour interview with city analysts. The primary purpose of this is to learn about the business values of the data set being used in my prototype. Thus real world problems are taken into consideration when designing the tasks. I conducted two interviews with domain experts who work at the Parks, Forestry & Recreation Division at City of Toronto. One is the IT Lead and the other is the supervisor in the Business Intelligence

(BI) team. They are managing the production and the maintenance of the Recreational Courses Historical Data as well as conducting analysis using the data set. In particular, the BI supervisor explained the real world cases associated with the data set as well as their analytical approaches. The key insights drawn from the interviews are concluded in Data Analysis. One challenge was that, when interviewing the IT Lead, there were some questions, such as the process city analysts are following and the challenges they are facing cannot be answered as his responsibilities are more on the management and the operation end.

Pre- and post-test interviews are part of the user tests. Pre-test interview includes questions on demographics, visual perception, technological experience, and so forth. They are crucial in terms of discovering certain correlations between user characteristics and behaviours. I collected user profiles from all eight participants and none of them felt discomfort in answering any of the questions. Please refer to B.4.1 Interview Template 3 in Appendix B for the detailed format.

Post-test interview serves as a retrospective session for both me (as a researcher) and a participant to learn about her perspectives and decision making process during a task. The comments also help address general design issues. All eight participants responded to all the post-test interview questions. Please refer to B.4.1 Interview Template 3 in Appendix B for the detailed format.

4.2.2 User Test

4.2.2.1 Overview

Each test session took from 20 to 40 minutes, plus variable length of breaks for each participant. Three different iterations of the prototype were tested, namely version 3.1, 3.2, and 3.3. I tested with six participants on prototype version 3.1, one on version 3.2, and one on version 3.3 respectively. I compiled a specification that summarizes all the features (as shown in Table B.1.2 Prototype Specifications for User Test in Appendix B), which is also introduced in detail in Prototype. I originally planned to have three rounds of tests with a larger sample size with a mix of new and experienced users in each round. Having experienced users progress through each round is effective in isolating external factors, such as ambiguity in instructions and software bugs, that might affect the performance outcomes. However, after I tested with six participants I had found implementation issues that prevent users from performing tasks effectively. I decided to redesign and re-implement some functions of the prototype and to test with a new participant to see if the changes lead to less confusion during the test. But existing problems did not get fully resolved and new usability issues emerged. So I repeated the process in order to come up with a more robust prototype before I could continue to test with a larger sample size.

Out of eight participants, only one person felt dizzy in the first set of tasks because she did not wear the VR headset properly. She fully answered the interview questions but only completed 20/30 tasks in total. Therefore, I only excluded her from

the quantitative data analysis.

4.2.2.2 Test Template

Three different test templates were used. The template for version 3.1 contains

30 tasks in total and they are grouped into three sets, where each set contains 10

identical tasks. Both of the templates for version 3.2 and version 3.3 contain 24 tasks

and are grouped into three sets, where each set contains 8 identical tasks.

After conducting tests on prototype version 3.1, several participants reported

ambiguity in the task instructions and difficulties in carrying out some of the tasks. So I

decided to improve the template in which the instructions are more objective and

specific and see if participants have less confusion in the next iterations. The majority

of the tasks remain consistent in terms of content across all three templates. For

example, outlier search tasks are present in all three versions of the templates. The test

template for version 3.3 can be found in B.5.1 Test Template 3 in Appendix B.

4.2.2.3 Task Design

The tasks designed for all three groups include height judgment and pattern

recognition on a 2D map. Because of perspective cues, it is nearly impossible to judge

the actual size of objects at a distance in real world (Ware, 2013). Similar in VR,

participants need to navigate around the environment to make more accurate

judgment.

Under this assumption, participants are asked to identify one or more data

cubes on a 2D map of Toronto with certain characteristics. Each cube represents a

unique community centre. The average utilization rate of selected recreational courses in that community centre is encoded into the height of a cube. For example, one is asked to locate a community centre with the highest average utilization rate across the entire map. Different metrics are collected to evaluate whether or not a navigation method is effective in completing the search task, such as accuracy, completion time, frequency of use, ease of learning, and ease of use.

The functions of the prototype limit the complexity of the tasks to some extent. Each set of tasks is associated with a unique environment in the VR application, which is run at the beginning of one set of tasks. For simplicity, each of the environment is called a "scene." Each scene is also loaded with a subset of the recreational program data, which is derived by applying different data filters. Since the set of tasks are identical in each scene, I use different data so that participants' memories of the spatial mapping of the data is reset.

Furthermore, each scene has slightly different functional design or they afford different interactions. All scenes afford travel on a horizontal plane using teleportation or physical walking. Scene 2 affords bird's eye view using a custom zoom control (available in version 3.1 and 3.2) or teleporting to higher positions (only in version 3.3). Scene 3 is known as the tabletop scene or world-in-miniature as the map is placed on a square table with real-world scale. Although scene 3 offers exactly the same controls in scene 1, the map is much smaller and is placed at a different height.

There is a significant difference between version 3.1 and the other two versions, which is the spatial organization of the data tooltips. Data tooltips are 2D text panels

that hover over a data cube and show detailed information of a community centre, such as location name, average utilization rate, number of visits, and waiting list. They are generated as static objects in version 3.1. To cope with occlusion, I set all the tooltip objects to invisible and let users toggle one of them at a time in version 3.2 and 3.3. Finally, ward boundaries and ward labels are added to the map in version 3.3 to give participants more map knowledge and reference when doing comparison tasks. The differences in these versions are discussed in depth in Prototype.

To conclude this section, the tasks are designed under the assumption that with the same set of tasks and different configurations of the environment, the effectiveness of a navigation technique varies. The interview scripts and the user tasks I design help me collect data that can be coded in a structural way. In the next section, I explain the data analysis process in detail.

4.3 Data Analysis

4.3.1 Evaluation Criteria

I report the results from expert interviews, pre- and post-test interviews, and the user tests. The evaluation of navigational tasks is based on combination of quantitative and qualitative data from the user test. Quantitative data is primarily compiled from my observations of participants and their own reflections. Qualitative data is summarized based on participant's self reflections during and after the test. As shown in Table B.1.1 Evaluation Criteria in Appendix B, the evaluation criteria attempt to link objective measures with subjective experience when evaluating the effectiveness of use of navigation techniques for completing analytical tasks in VR. They are established based on the current complexity of the functionalities of the prototype and the tasks. Although not listed, more granular performance metrics are possible to be collected, such as numbers of comparisons made, numbers of turns made, average distance between each teleportation per task, duration of zoom, numbers of objects compared, and so on. I intend to develop a more extensive understanding of the perceivable factors with the recent iterations of the prototype, including the ease of use, ease of learning, user comfort, information gathering, and decision making.

4.3.2 Qualitative Data Analysis

4.3.2.1 Key Insights Related to the Data Set

Insights gathered from the expert interviews reveal how the data set is being used by the City of Toronto in their planning process. They can be found in B.2. Research Notes in Appendix B. To mimic the analysis in real-world scenarios, I use different data for each set of the tasks during a user test, where the data specification can be found in Table A.5 Data Specification for User Test in Appendix A. For instance, I filter all the registered courses in the Child / Youth sub sections because the insights indicate that:

- It would be nice to classify the visualization into registered programs and drop-in programs.
- One of the biggest mission in Parks, Forestry, and Recreation is to serve children and youth.

I then design tasks surrounding the data because users are more likely to find information that potentially have business values. More importantly, the insights suggest future improvements to the prototype such as using dynamical visualizations to show the changes of course utilization over a certain time frame.

4.3.2.2 User Characteristics

User characteristics are identified from the pre-test interview. Understanding the differences in users is important when evaluating their performance and experience in VR environment (Bowman et al., 1998). By referencing Bowman et al.'s (1998)

framework of evaluation of travel techniques, I select a few metrics that are most relevant to the scope of the user test. Demographics identifies whether a participant is in the group of expert users or not. Biological characteristics provides information on individual's visual and perceptual abilities in VR environment. Technological background affects how comfortable users are with virtual environment and how fast they learn and adapt to virtual travel techniques and controls. Map knowledge has influence on the accuracy of a task. For a full description of user characteristics, please refer to B.3.1 Data - User Characteristics in Appendix B.

4.3.2.3 Test Results

The test results combine user reflections during the test and the post-test interview as well as my observations from the video footage. Because three iterations were tested and slightly different tasks were assigned, it is more rational to compare results of a group of participants who perform the same tasks given the same prototype specification, as shown in Table B.1.2 Prototype Specifications for User Test in Appendix B. Thus, I summarize the results of user reflections into three groups in Table B.1.3 Aggregated Results of User Reflections in Appendix B.

The following findings provide the most relevant insights in answering my research questions:

1. Teleportation is mostly used and preferred by all groups of participants because it is fast and easy to learn. But teleporting onto cubes and on more complex terrain are not intuitive enough.

2. Walking is preferred by only one participant in Group 1, but it is often used in combination with teleportation for micro-adjustment. It also works well with the tabletop perspective.

3. Switching to bird's eye view is considered to be useful to find generalization and outliers, but the zoom control is not intuitive and there is no way to control the amount of zoom.

4. In the room perspective (Scene 1 and 2), standing on top of a map is disorienting.

5. Because the data tooltips always face one direction, users need to re-orient themselves around them through teleportation or walking.

6. Coupling two functions in one control is confusing. In contrast, it takes time to adapt to two identical interfaces (controllers) with different functions.

7. Participants' energy levels tend to decrease after the test.

8. Immersion is broken by the hardware and the level of the details of the environment. Participants also feel disconnected without seeing their physical bodies.

The findings above show what users think how effective each navigation technique is in helping them complete the tasks and how effective the interface and the controls are in facilitating the interactions. Most participants think teleportation is a more effective technique for travelling in the provided environment, but its interface and controls can be enhanced to reduce extra cognitive efforts and to alleviate disorientation. Bird's eye view is seen as useful but it is less intuitive to use. Tabletop

perspective requires less travelling. For more details on user behaviours, please refer to B.3.2 Data – User Behaviours in Appendix B.

Apart from the navigation techniques, participants also report problems associated with the environment that they are navigating. They have mixed feedback on the data cubes, the tooltips, the mountains and floating islands, and the map. Some of the common problems the participants experience, such as 6, 7, and 8 can be turned into design recommendations because they are also common to other applications. For navigation-related designs, such as from 1 to 5, I merge both the qualitative and quantitative data and create guidelines from generalization.

4.3.3 Quantitative Data Analysis

I divide the data into three groups. The sample size is 5 in Group 1, 1 in Group 2, and 1 in Group 3. Because the sample size is not appropriate for statistical analysis, I merely present general insights at this point. Since there are three scenes, I first analyze the performance of participants in each scene individually. I examine the average task completion time, the number of teleportations made in each task, the frequency of walking in a scene, the frequency of zoom in a scene, the success rate of outlier search tasks, and so forth. Then I compare the behaviours between each scene. Finally, I compare the performance of outlier search task between three groups.

The key findings from all three groups are:

- Zoom is less used than teleportation and walking.

- Bird's eye view is primarily used to find the highest cube.

- Participants teleport more than they walk initially.

- Participants teleport more frequently in Scene 2 than in Scene 1.

- Participants walk less frequently in Scene 3 and least in Scene 2.

- Participants spend less time in Scene 2 or 3 than in Scene 1.

- Participants spend less time on finding the highest cube, but more time on comparing similar heights.

- Participants' accuracy of in outlier search tasks improves over time.

The quantitative data shows objectively how each navigation technique is being utilized in each scene. In general, teleportation is utilized more than zooming and walking and gets used more frequently over time. Zooming, being introduced in Scene 2, is not so effective as it is less used. Walking is often used but not as much as teleportation. Participants also tend to spend less time on tasks in subsequent scenes, which may imply they are more accustomed to the interface and controls. On the other hand, the findings also validate some of the comments regarding the ease of use of the navigation controls. For the full analysis by user groups, please refer to B.3.3 Quantitative Data Analysis in Appendix B.

4.3.4 Initial Findings and Potential Improvements on Methodology

A group of expert users with different levels of experience and preference in 2D and 3D software and immersive environments were asked to carry out a series of navigational and analytical tasks in an immersive data visualization environment. Three navigation methods were evaluated based on user reflections and observations. Preliminary analysis shows varied performance and behaviours across participants who are divided into three groups.

According to my findings, given the current prototype specifications, the effective use of different navigation methods is affected by the affordances of the environment, the ease of control, the hardware configuration, the task requirement, as well as users' knowledge and experience. The findings from the qualitative data suggest that teleportation is easier to learn and use than physical walking and zoom. They also suggest that bird's eye perspective (through zoom) and tabletop perspective are more effective than room perspective (without zoom) in completing tasks of identifying outliers and finding patterns of distribution. The findings from the quantitative data partially support the user preference on teleportation, bird's eye perspective, and tabletop perspective. The longer time spent on outlier tasks and the lower accuracy of completing them also indicate that users have difficulties interpreting the data visualization and using the provided controls. Furthermore, the findings from the qualitative data address numerous critical design issues in the current application that hinder users from navigating effectively. Although the latest iteration has resolved some common problems such as overlapping tooltips, more efforts are to be put into improving the user interface. For example, visual cues for actions should be made clearer in the user interface.

Aside from the application-side, task design, data collection, and data analysis methods can be improved. Currently, some tasks are too subjective to be used for evaluating performance. The types of tasks are also limited to outlier search. If the map includes more information such as public transit route or visualizations of neighbourhood characteristics, the tasks can include exploring correlations between

an attribute of the community centre and an attribute of the surrounding area. This provides more valuable insights into the accessibility and the user characteristics than just identifying the outliers in the average utilization rate of a community centre. Other alternatives may depend on the available data manipulation methods.

The quantitative data collection process is not entirely strict as there may be errors and bias in my observations from the video footage. For more objective data, log functions can be implemented such that every button push is automatically logged and timed. But this may increase overhead in parsing and exporting those data into a spreadsheet.

Speaking of data analysis methods, the sample size should be substantially increased and statistical methods can be used to find correlations between variables. The correlations in the findings are mostly reflections from the participants and may be biased. In particular, it is difficult to objectively draw a link between user characteristics and their performance by only looking at how users complete a task using a navigation method. The way that how the quantitative and qualitative data are merged to form initial findings are established are mostly based on my subjective judgment. Therefore, a more rigid analysis procedure may be applied.

In the next chapter I will discuss design guidelines that will incorporate some of the findings.

5. Design Guidelines

In this chapter, I extend selected existing design guidelines and create my own ones. I incorporate part of the recent findings through user testing and attempt to provide fresh perspectives with those findings.

1. Increase the naturalness of the interface.

2. Group similar functions on one controller.

3. Provide different perspectives.

4. Orient the user in the virtual world.

5. Design artifacts that are appropriate for the task, enhancing the ability to make judgments.

6. Make things visible.

7. Have at least one reliable navigation control in the virtual environment.

8. Design the virtual environment that contains information relevant to the tasks.

9. Know the limitation of the hardware.

10. Arrange breaks.

1. Increase the naturalness of the interface. Regarding to this rule, McLellan (1998) explains that "increase the naturalness of the interface to reduce the cognitive effort required in navigation and interpretation, while creating dynamic interaction and novel perspectives" (p. 196). McLellan also suggests that

Follow natural mappings between intentions and the required actions; between

actions and resulting effect; and between the information that is visible and the

interpretation of the system state (p. 197).

My findings show that the interface of navigation methods such as teleportation

in the prototype incur evident mental efforts. Users actually ended up spending more

time orienting themselves and understanding the system state than gathering

information relevant to the tasks (see B.3.2.1 Teleportation Behaviours in Appendix B

for full description). I suggest that the naturalness of interface is not to be neglected.

2. Group similar functions on one controller. Users tend to get confused

when one interface is coupled with different types of functions. However, for systems

with multiple controllers, it may pose extra cognitive efforts in memorizing the key

mappings. One design I suggest is to group data manipulation controls on one

controller and navigation controls on the other. However, it takes time for users to get

accustomed to it.

3. Provide different perspectives. In my application, I tested different

perspectives and each has its pros and cons. Bird's eye perspective in Scene 2 and

the tabletop in Scene 3 are useful for finding generalization but difficult to navigate. In

contrast, the room perspective in Scene 1 provides more freedom in navigation.

Therefore, in an immersive environment, users should be able to choose one that best

helps with their tasks.

4. Orient the user in the virtual world. McLellan (1998) suggests that "orient

the user in the virtual world: highlight anchors for understanding direction and

navigation" (p. 196). As addressed in the previous guideline, users tend to get disoriented after using teleportation and zoom in the room perspective in Scene 1 and 2 specifically. This implies two potential problems, either the navigation cues are not clear enough or the interface design is not natural enough. Regardless, it is recommended to provide visible cues on the user's current orientation in the virtual world.

5. Design artifacts that are appropriate for the task, enhancing the ability to make judgments. McLellan (1998) promotes that "design artifacts that are appropriate for the task, enhancing the ability to make judgments, to discover relevant regularities and structures" (p. 196).

My prototype (version 3.3, Scene 2) follows this guideline clearly. By adding 3D mountains and platforms to the environment, users are given the ability to inspect the map and the data points with bird's eye view, which is considered a useful perspective for the tasks by the participants. However, the table in Scene 3 fails to provide eye level comparison if users do not crouch or bend down, which is difficult for judging similar heights. Participants suggest that the table height should be adjustable. Therefore, the artifacts should be carefully designed to support interactions related to the tasks.

6. Make things visible. McLellan (1998) suggests that

Make things visible, including the conceptual model of the system, the alternative actions, and the results of actions. Use technology to make visible

what would otherwise be invisible, thus improving feedback and the ability to keep control (p. 196).

One insight related to this guideline is that the participants try to interact with objects in VR environment even though there are no indicators of possible actions. I also think that there should be visual cues on the affordances of an object and the environment that follow users' viewpoint.

7. Have at least one reliable navigation control in the virtual environment. This recommendation is more confined to the current data visualization environment in the prototype. Participants tend to prefer more on navigation controls that are fast, reliable, and easy to learn, such as teleportation (see Experience with Navigation Methods in Table B.1.3 Aggregated Results of User Reflections in Appendix B). Although other methods are helpful, participants can almost use teleportation to complete all the tasks after they get accustomed to it. Similarly, walking is almost the most reliable travel method for the average population in real world.

8. Design the virtual environment that contains information relevant to the tasks. This guideline is closely related to the types of tasks. For identifying an area on the map, for example, there should be boundaries and labels to define zones (see Experience with Tasks in Table B.1.3 Aggregated Results of User Reflections in Appendix B).

9. Know the limitation of the hardware. Many participants report issues related to the hardware. The immersion is broken by the cord, the size of the tracking area, as well as the comfort of the headset (see Immersion in Table B.1.3 Aggregated

Results of User Reflections in Appendix B). The limitation also poses challenges on

task completion. It should be noted that the VR experience can be affected in a variety

of ways.

      10. Arrange breaks. Most participants' feel exhausted after the test (see Energy

Level in Table B.1.3 Aggregated Results of User Reflections in Appendix B), given that

they have spent 20 to 40 minutes in average on analytical tasks in VR. Although the

fatigueness are subjective, it is possible that users are more visually engaging when

they are in immersive environments than in real world. I recommend that with the

current hardware specification, users should not spend an extended period of time in

VR working on too intensive analytical tasks.

6. Conclusions and Future Work

The goals of this project are to develop a set of design guidelines for VR navigation that support data analysis, which contributes to the standardization of interaction and user interface design in immersive analytics applications. Another outcome is a process documentation of building immersive data visualization environment using the latest consumer-grade VR hardware and primarily open-source software toolkits. The results aim to inspire hobbyists and benefit the VR communities to some extent.

Through an extensive literature review, I establish the design and requirement of the prototype and a process of prototyping, user testing, and data analysis. The initial findings show the effectiveness of navigation methods in the current prototype is dependent on a wide range of factors, including the affordances of the environment, the ease of control, the hardware configurations, the task requirement, as well as user characteristics.

The results of qualitative data analysis suggest that teleportation is easier to learn and use than physical walking and zoom. They also suggest that bird's eye perspective (through zoom) and tabletop perspective are more effective than room perspective (without zoom) in completing tasks of identifying outliers and identifying patterns of distribution. The insights from quantitative data partially support the user preference on teleportation, bird's eye perspective, and tabletop perspective. The longer time spent on outlier tasks and the lower accuracy of completing them also

indicate that users have difficulties interpreting the data visualization and using the provided controls.

For drawing more rigorous conclusions, major improvement ought to be made to the prototype, the tasks, and the evaluation methodology. The findings are partially integrated into Design Guidelines. I comment on existing guidelines made by McLellan (1998) with more recent evidence and make several recommendations based on my own interpretations on the results of data analysis.

6.1 Future Work

As stated in conclusions, there are major improvement to be done in order to compile a more rigorous study on the effectiveness of navigation techniques for analytical tasks in an immersive data visualization environment. For the prototype, a list of design issues should be resolved. Existing issues are related to the user interface, the mechanics of each navigation method, and the virtual environment. Common data manipulation methods can be integrated, such as sorting, grouping, marking, comparing geographically distant objects, and so forth. For the architecture of the application, data loading and storage mechanisms can be changed from static file-based to live connections to database and API servers.

In terms of future directions, other research questions that support the current line of research may be focused more on various design issues associated with novel interfaces. For instance, what aspects of experiencing conventional interfaces can affect the experience of gestural interfaces? Besides, an important perspective that is

missing in this paper is collaboration, such as distant collaboration in immersive

environment. Collaborative visual analytics is undergoing a great amount of

development these days. There is great potential in using VR as a collaboration

platform because it eliminates geographical boundaries and augments the perceptual

ability of a single person through the parallel processing of multiple participants. The

collaboration perspective in VR is better supported by the Media Naturalness Theory

because VR facilitates more natural communication between humans.

Immersive analytics is a promising research direction as it makes use of humans'

cognitive powers, through multiple sensory systems. In my point of view, developing

applications with immersive technologies and haptic input devices for different

purposes are still facing many design challenges. More design research should be

done in this field. The standardization of design strategies is necessary before we

integrate them into more mission critical scenarios.

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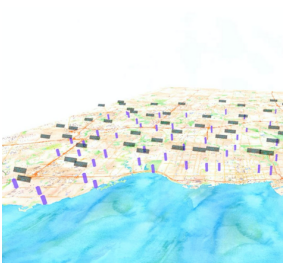Wickens, C. D., & Baker, P. (1995). Cognitive issues in virtual reality.
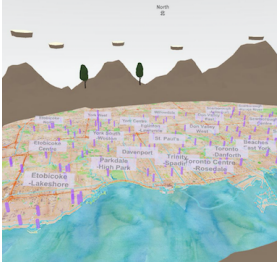
Appendix A: Prototype Components

Table A.1 Tethered VR Headset Comparison 2017			
	HTC Vive	**Oculus Rift**	**PlayStation VR**
Price (CAD)	1149	849	550
Platform	PC	PC	PlayStation 4
Controller	Hand controllers / PC compatible gamepad	Hand controllers / Xbox One gamePad	Six-axis motion sensing system (three-axis gyroscope, three-axis accelerometer)
Tracking Area	15 x 15 feet	5 x 11 feet	N/A
Display Method	OLED	OLED	RGB OLED
Resolution	2160 x 1200	2160 × 1200 (1080 × 1200 per eye)	1920×RGB×1080 (960×RGB×1080 per eye)
Field of View	110 degrees	110 degrees	~ 100 degrees
Recommended Graphics Card	NVIDIA GeForce GTX 970 /AMD Radeon RX 480	NVIDIA GeForce GTX 960	N/A

Table A.2 Hardware Specification	
Operating System	Windows 7 64-bit
Graphic Cards	Nvidia GeForce GTX 1080
CPU	Intel i5-6400
Memory	16GB

Table A.3 Development Software Specification		
Category	**Name**	**Description**
Development	Unity 5.4.2f2	Game Engine
	Visual Studio 2015	Code Editor
	Github	Open-source repository, source code available at https://github.com/Minsheng/MapzenGo/tree/prototype_mar_2017
	MapzenGo	2D/3D map in Unity
Plugins/Libraries	SteamVR SDK	Development toolkit for VR
	VRTK	Locomotion toolkit
	iTween	Animation system for Unity
	CSV2Table	CSV parser generator
Data Processing	Excel 2016	Data processing
	Tableau 10.1	Data processing and visualization

Map Services	Mapzen	Vector Tile Service
	Mapbox	Vector Tile Service
	Openstreetmap	Tile server
	Stamen Maps	Tile server

Table A.4: Prototype Specifications			
Prototype Version	3.1	3.2	3.3
Data Set Specifications	Scene 1: all Summer courses in Child/Youth sections Scene 2: all Summer swimming courses in Child/Youth sections Scene 3: all Fall courses in Child/Youth sections	Same as in 3.1	Scene 1: all Summer courses in Child/Youth sections Scene 2: all Fall courses in Child/Youth sections Scene 3: all Winter courses in Child/Youth sections
Map Zoom Level	14	14	14
Map Style	Stamen Watercolor	Mapbox Satellite Streets (with labels)	Same as in 3.1
Map Features	2D tile images	Same as in 3.1	2D tile images + ward boundaries image overlay + 3D mountains and platforms
Map Sample Image			
Scale	Scene 1: human scale Scene 2: human scale Scene 3: tabletop	Same as in 3.1	Same as in 3.1
Perspectives Supported	Scene 1: immersive first person (room) Scene 2: immersive first person + bird's eye (room)	Same as in 3.1	Scene 1: immersive first person (room) Scene 2: immersive first person (room)

	Scene 3: immersive first person (tabletop)		Scene 3: immersive first person (tabletop)
Navigation Methods	Scene 1: Physical Walking + Teleportation Scene 2: Physical Walking + Teleportation + Zoom Scene 3: Physical Walking + Teleportation	Same as in 3.1	Scene 1: Physical Walking + Teleportation Scene 2: Physical Walking + Teleportation Scene 3: Physical Walking + Teleportation
User Interface (Right Controller)	Beam color: blue (active) red (passive) Beam shape: straight line	Beam color: green (active) grey (passive) Beam shape: straight line	Beam color: blue (active) red (passive) Beam shape: dashed bezier curve
User Interface (Left Controller)	N/A	Beam color: blue Beam shape: straight line	Beam color: green Beam shape: straight line
Key Mapping (Right Controller)	Trigger: shift map to front/down Side grip: shift map to right/down Trackpad: teleportation	Same as in 3.1	Trackpad: teleportation
Key Mapping (Left Controller)	N/A	Trackpad: highlight cube	Trackpad: highlight cube Trigger: toggle ward labels
Data Tooltips	Always on	On when colliding with left controller beam in Scene 1 and 2. Not available in Scene 3.	Same as in 3.2

Table A.5 Data Specification for User Test		
File Name	**Definition**	**Number of Rows**
summer.csv	all the regular courses offered in the Summer in the Child / Youth sub sections	254
summer-swim.csv	all the regular swimming courses offered in the Summer in the Child / Youth sub sections	83
winter.csv	all the regular courses offered in the Winter in the Child / Youth sub sections	240
fall.csv	all the regular courses offered in the Fall in the Child / Youth sub sections	233

Appendix B: User Testing Components

B.1. Tables

Table B.1.1 Evaluation Criteria	
Quantitative	**Definition**
Task Completion Time	The duration between when a user starts to carry out a task after any clarification on the task instruction and identifies the target by navigating to it on the map. It does not necessarily represent the search performance. Some participants need more time to understand the question before starting to search. It is judged subjectively by the researcher from the video footage.
Numbers of Teleportations Per Task	The number of times a participant teleports both intentionally and unintentionally in a given task. A teleportation is made to travel to a distant location on the map or to make micro-adjustment of the position to examine objects close by.
Utilization of Distinctive Perspectives	The utilization rate of bird's eye view to solve a task in the second set. In prototype version 3.1 and 3.2, bird's eye view or zooming out is triggered by pressing a button on the controller. In prototype version 3.3, participants have to travel to a higher position through teleportation.
Utilization of Physical Actions	The utilization rate of either physical walking or crouching. It equals Number of tasks that physical actions are observed / Total number of completed tasks.
Accuracy	This only applies to certain tasks such as identifying outliers. It is the rate of a participant for identifying the correct outliers in all outlier tasks, where there are six such tasks in a test session. Accuracy = Number of success / Number of completed outlier tasks.
Qualitative	**Definition**
Energy Level	The energy level at the beginning of post-test interview after a participant finishes all tasks. In Group 1, I did not explicitly use a scale and did not ask this question before the test started. For Group 2 and 3, it is evaluated on a scale of 1 to 5, 1 being very low and 5 being very high. This was also gathered prior to the test.
Immersion	The level of immersion of the prototype judged by a participant after she finishes all the tasks. It is given a score from a scale of 1 to 5, 1 being very low and 5 being very high, as well as a short explanation.
Experience with Tasks	Subjective comments on the clarity and the difficulty of tasks.
Experience with Navigation Methods	Subjective comments on the effectiveness of all navigation methods used in the test.
Experience with Perspectives	Subjective comments on the effectiveness of all available perspectives in the test.

Experience with Visualization	Subjective comments on the effectiveness of data visualization present in the test.
Experience with User Interface	Subjective comments on the usability of the VR interface.
Experience with Input	Subjective comments on the effectiveness of controllers.
Experience with Map	Subjective comments on the test environment.
Experience with Hardware	Subjective comments on the experience with HTC Vive VR headset.

Table B.1.2 Prototype Specifications for User Test			
	Group 1	**Group 2**	**Group 3**
Prototype Version	3.1	3.2	3.3
Test Template Version	1	2	3
Number of Participants	6	1	1
Data Set Specifications	Scene 1: all Summer courses in Child/Youth sections Scene 2: all Summer swimming courses in Child/Youth sections Scene 3: all Fall courses in Child/Youth sections	Same as in Group 1	Scene 1: all Summer courses in Child/Youth sections Scene 2: all Fall courses in Child/Youth sections Scene 3: all Winter courses in Child/Youth sections
Map Features	2D tile images	Same as in Group 1	2D tile images + ward boundaries image overlay + 3D mountains and platforms
Perspectives Supported	Scene 1: immersive first person (room) Scene 2: immersive first person + bird's eye (room) Scene 3: immersive first person (tabletop)	Same as in Group 1	Scene 1: immersive first person (room) Scene 2: immersive first person (room) Scene 3: immersive first person (tabletop)
Navigation Methods	Scene 1: Physical Walking + Teleportation Scene 2: Physical Walking + Teleportation + Zoom Scene 3: Physical Walking + Teleportation	Same as in Group 1	Scene 1: Physical Walking + Teleportation Scene 2: Physical Walking + Teleportation Scene 3: Physical Walking + Teleportation

	Table B.1.3 Aggregated Results of User Reflections		
	Group 1	**Group 2**	**Group 3**
Energy Level	• I felt the same as it was when I got started. • I felt noticeably tired compared to before the test.	• Same as before.	N/A
Immersion	• It is almost as though I am interacting with a carpet. And outside the carpet it's clearly not reality. It was just visual immersion but no tactile. • The black edges around my eyes and the goggle that's pressing against my nose break the immersion. From a design view, the content is good. I never felt I was actually in it. • It was very immersive. But part of it was disorienting because it was visually immersive and I felt disconnected without being able to see my arms. Sometimes it appears blurry to me, that breaks the immersion • In the final one with the table, it seems it was glitching out. My immersion decreased there. • The rendering is pretty basic.	• There is no illusion in the sense of feeling myself to be inside of a thing more like standing on a map, which is not immersion per se.	• I like how I can move around the map and point at things and see popup. Would've been nice if I can do more.
Experience with Tasks	• It was taxing to use it for a long period of time. I was using more cognitive load to orient myself and less to analyze data. • I was conscious about the physical furnitures around. • Without zones or boundaries on the map, it was difficult to define downtown area or pin down a dense or sparse area. • There was no way to highlight one data cube for comparison with another geographically different one. • Without the zoom and the table it was hard to tell the outliers.	• The hardest thing was evaluating the relative sizes of elements that are widely distant without reading the tooltips.	• It was difficult sometimes to travel to where I wanted to.
Experience with Navigation Methods	• I like how I can move around the map, point at things, and see pop-ups. • Teleportation can solve most of the tasks. • Sometimes the teleportation beam does not work or trigger. • Zoom helps find information quicker but the control was problematic and difficult. It did not do what I wanted. • Walking was intuitive and helps with the immersion. It was nice with the tabletop scene. • I would like to do virtual walking slowly.	• Teleportation was instant and reliable. • Zoom did not change the distance so it did not do what the participant wanted.	• Teleporting is more natural than flying (prior experience). • Teleportation was buggy and it was hard to maintain my flow of control. • It was hard to get onto the platforms in Scene 2 (using teleportation).
Experience with Perspectives	• The tabletop perspective was useful. • The room perspective, standing on top of a map, was disorienting. • I felt natural to kneel down to examine data in the tabletop perspective. • Tabletop perspective was the most efficient one to complete all the tasks	• The scale of the data cubes relative to the level of fine motor control was better in the room perspective (Scene 1 and 2). • The individual elements in	• Room perspective (Scene 1) was more natural.

	because I can see everything all at once. • It was hard to situate myself around the table. There was not enough physical space to walk around the table. • Table should be higher to get eye level comparison. • It was impossible to find detailed information in the tabletop perspective. • It was difficult to compare similar heights in bird's eye view. • Bird's eye view was good for spotting taller objects and identifying density.	the tabletop perspective was too small to click on reliably.	
Experience with Visualizati on	• It was quicker to get generalization than in 2D but it was difficult to drill down. • Instead of looking at the text labels to get the values, if there was some scale reference, I can use it to quickly check the heights of cubes. • There was a lot of data points that look similar. • The text labels were overlapping with each other. It was difficult to tell which label was associated with which cube.	• The representation was abstract. • The color was clear. • I like being able to read the data tooltips.It would be nice if they could face towards me in any direction, but it worked well.	• In bird's eye view, dynamically scaling up the data tooltips would be useful. • It would help to keep the data tooltips on for comparison.
Experience with User Interface	• Selection and teleportation should be decoupled to prevent unintentional movement. • I feel disconnected without being able to see my physical body.	• I would put a bunch more stuff in to navigate. It got a lot of head room in terms of the complexity it would support.	N/A
Experience with Input	• Using different parts of the controller was problematic. • If you make the zoom toggle instead of press and hold, that would be much better. • I do not necessarily want to zoom back in after I zoom out.	• It took me a minute to get used to two identical interfaces with different functions.	N/A
Experience with Map	• The map image has low resolution. • A more dynamic map could give more immersion. • Map should have scale label. • The less of aesthetics on the map makes it easier to highlight important information.	• The imagery was clear. • Street labels that scale dynamically would be useful.	• The boundaries of the city could be highlighted better.
Experience with Hardware	• The cord limited my behaviour.	• The cord and the virtual boundaries break immersion. • Walking between the play area and the cord was a disaster.	N/A

B.2. Research Notes

The following insights were transcribed from the interviews with the managers in Park, Forestry, and Recreation Division at the City of Toronto.

a. There is an overall concern about supply and demand of programs. For instance, swimming pool is usually at high demand. Utilization rate is important because we want to maximize facility use. It means the number of program spaces that were used.

b. There is a large interest in special type of programs such as summer camp.

c. At a local level, senior manager at a community centre want to know about the trends of their programs and whether they are offering the right balance of courses or not.

d. Locations that have big waitlists in a specific age group or type of programs is one of the indicators that there is no capacity for additional programs or course offerings.

e. It would be nice to classify the visualization into registered programs and drop-in programs.

f. We are analyzing our courses by types of programs. For instance, we take a block of courses and look at the availability and the utilization rate for a specific age group within that range.

g. It would be great to have a dynamic visualization showing the changes of utilization of courses by different time units, such as days, hours, or weeks. But time-lapsed analysis can only be good if you have 10 years of data.

h. Free community centres are located across the city in circles of 1.5km that cover up the low income neighbourhoods.

i. One of the biggest mission in Parks, Forestry, and Recreation is to serve children and youth. We would find out where are all the youths living in the City of Toronto by looking at demographic distribution.

j. Business Intelligence team maps out particular demographic characteristics and see how it matches with how program are being offered.

k. It would be interesting to find out how many residents are using the programs as a form of child care because child care is expensive in the City of Toronto.

l. It would be helpful to combine multiple data set such as combining subway routes to see how accessible those community centres are.

m. The average distance people go to our community centres across the city is around 3.2km. It would be interesting to look at the drive cultures.

B.3.1 Data - User Characteristics

The characteristics is summarized as follows:

- Based on the area of studies or occupation, all participants are considered expert users. Five participants have project experience in urban planning and development.

- No participants have difficulties identifying colours.

- One participant does not have a good stereo vision.

- All participants have experience in immersive environment and video games.

- All participants have experience with data analysis software, but mostly with 2D desktop applications such as Excel and Tableau.

- All participants are mobile phone users and use map-based navigation services such as Google Maps.

- All participants have experience with urban simulation software such as Esri CityEngine[25] or Esri ArcGIS[26] or video games such as SimCity[27].

- All participants are most familiar with third-person perspectives such that the virtual camera either follows an avatar from a distance behind or above it. Three participants are familiar with bird's eye view, where the virtual camera is further away from above from an object.

- The majority of participants prefer handheld controllers with joystick and buttons, such as XBOX controller and/or PlayStation controllers.

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[25] http://www.esri.com/software/cityengine
[26] http://www.esri.com/arcgis/about-arcgis
[27] http://www.simcity.com/

- All participants are accustomed to keyboard plus mouse and touch-based devices.

- Five participants claim to be very familiar with Toronto's geographical environment.

B.3.1.1 Demographics

A list of attributes is selected:

- Age group

- Gender

- Education background

- Occupation

The results show that all participants are considered expert users based on their education background or occupation. Out of all participants, there are 5 males and 3 females. Four people are in the age group of 25 to 35, two are in 45 to 55, one is in 35 to 45, and one is under 25. The minimum education level is bachelor degree and recent areas of study cover Knowledge Sharing, Computer Science, Informatics, Data Visualization, Urban Planning, Psychology, and Interdisciplinary. Half of them are students and the other half are taking one or more positions including software developer, consultant, artist, part-time lecturer, or post doctoral research fellow. Moreover, five participants have been involved or are currently involved in research projects that fall into the scope of urban planning and development. Others are experts in data visualization design and development.

B.3.1.2 Biological Characteristics

The following biological characteristics are collected:

- Height**, height of users in VR environment affects their eye level.**

- Visual acuity**, users need to take off their glasses when wearing the VR headset.**

- Color vision**, users with color blindness will have difficulty in identifying different types of lands on the map in the prototype.**

- 3D vision**, users may feel discomfort or have troubles fusing the 3D images in VR if they have problems related to 3D vision. This will affect the task performance.**

All the males are around 180cm in height and the height of females range from 160 to 172cm. None of the participants have difficulty identifying colours. Half of them need to wear glasses or contacts in order to perform computer works. In terms of viewing 3D graphics, one participant is not comfortable seeing 3D stereogram and another participant does not have good stereo vision. However, the two participants have no problems using head-mounted displays.

B.3.1.3 Technological Background

These aspects are considered as technological background:

- Experience with immersive environment including VR

- Experience with data analysis software tools

- Experience with urban simulation software

- Experience with navigation mobile applications

- Experience with video games

- Experience and preference with input devices

All participants had previous experience with immersive environment, not limited to head-mounted displays. When they were asked to briefly talk about their experience with immersive environment, most of them said it was pleasant in general but five of them reported that they experienced nausea in VR. According to an experienced VR user, "I sometimes have troubles registering everything from 3D cinema but don't suffer from headache." Another more novice user described an unpleasant experience with a VR app in Google Cardboard, "the movement wasn't calibrated properly with my moment, so it was very nauseating and I cannot do it longer than 3 minutes."

In terms of familiarity with data analysis software, Excel is the most common one, followed by Tableau, R, SPSS, ArcGIS, and many other commercial software and academic prototypes. All participants are mobile phone users and use map-based navigation services such as Google Maps smartphone app. Only two participants use Google Maps on a daily basis and the other use it less regularly. Other common services include TTC transit app, Yelp[28], Uber[29], Waze[30], and so forth. All participants have experience with urban simulation software such as Betaville[31], Esri CityEngine[32], or Esri ArcGIS[33] or video games such as SimCity[34].

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[28] https://www.yelp.ca
[29] https://www.uber.com
[30] https://www.waze.com/
[31] http://betaville.net/
[32] http://www.esri.com/software/cityengine
[33] http://www.esri.com/arcgis/about-arcgis

Video game experience is also considered as a factor in learning and adapting to navigation and controls in virtual reality applications. All participants have played video games. Five of them have played first-person shooter, while the next popular genres being RPG and 2D platform games. All participants are most familiar with third-person perspectives such that the virtual camera either follows an avatar from a distance behind or above it. Three people are familiar with God's eye or bird's eye view, where the virtual camera is further away from above from an object. For game input devices, seven participants prefer handheld controllers with joystick and buttons, such as XBOX controller and/or PlayStation controllers. For daily input devices, all of them are accustomed to keyboard and mouse and touch-based devices.

B.3.1.4 Map knowledge

The attributes collected are:

- Length of residency in Toronto

- Regions lived

- Familiarity with Toronto

Five participants have lived over 20 years in Toronto. They are very familiar with Toronto's geographical environment in general. The other three participants who have lived in Toronto for 10 years or less are unclear about certain regions such as the north or the east.

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[34] http://www.simcity.com/

B.3.2 Data – User Behaviours

B.3.2.1 Teleportation Behaviours

Participants in Group 1 tend to prefer teleportation as the primary method in room perspective (Scene 1 and 2), even though they reported assorted functional challenges and difficulties in completing several tasks using this method. Teleportation was actually the first interaction introduced to all three groups of participants at the beginning of the first set of tasks. One simply presses and holds the trackpad, points the teleportation beam to a location, and releases it. Participants usually get very familiar with it within a few minutes.

In terms of task completion, participants from Group 1 had mixed comments on teleportation. The participant in Group 2 thought it was "instant and reliable" as he used an improved version of the feature. Due to the changes in the environment, the participant in Group 3 complained about the teleportation interrupted her "flow of control." Although it was preferred over walking and zoom, it does not always work well given a different environment setup. In particular, there were a few interface design problems associated with teleportation.

1. Straight line-style teleportation beam did not provide visual cue on the exact target position. Group 1 participants tend to start by pointing the beam directly to an object, expecting that they will be teleported right in front of it (see Figure B.3.1 (a)). That often causes over-teleportation. Later they learned to point to the ground near a target because that will reduce the chances of overshooting (see

Figure B.3.1 (b)). With Bezier curve-style beam, the participant in Group 3 did not have problem teleporting on the 2D map but found it difficult to aim at platforms in 3D space as the endpoint was occluded.

2. Participants tend to teleport unintentionally when they use it as a selection tool. Teleportation beam naturally affords pointing at objects. As a result, participants in Group 1 often ended up teleporting when they tried to point at an object. For participants in Group 2 and 3, this was solved by using another controller for dedicated selection.

3. Bezier curve-style teleportation beam was not reliable for aiming at occluded planes in 3D. This was a specific issue reported by the participant in Group 3 when she was trying to teleport to a higher point on a mountain or a floating platform.
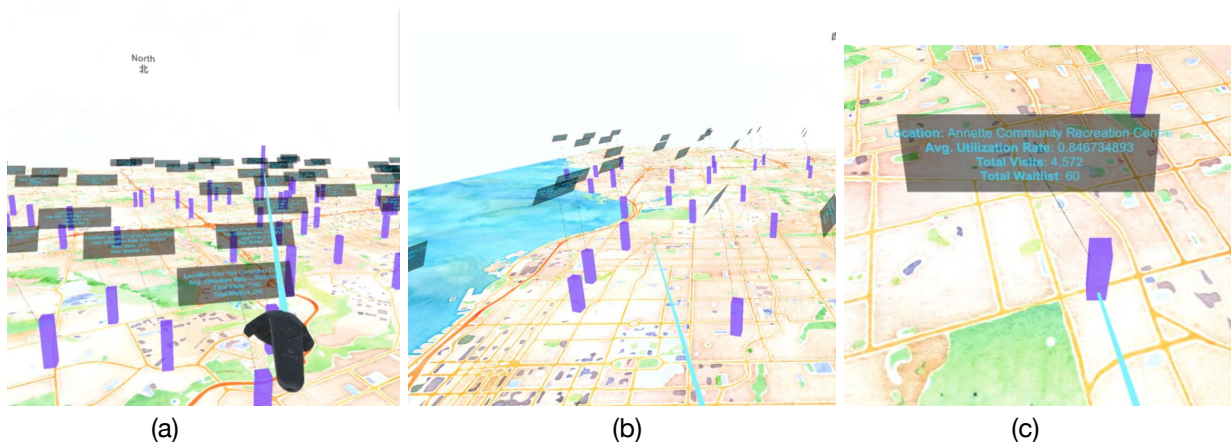

| (a) | (b) | (c) |

Figure B.3.1 A participant in Group 1 navigation around the map using the teleportation beam. (a) He wanted to teleport to in front of the cube by pointing at it, but he ended up being out of the map. (b) In a later task, he learned to point at the ground. (c) He used the same beam for selecting a cube.

In terms of movement patterns, teleportation accompanies with head movement as if one is physically walking. The majority of participants triggered teleportation to a different direction after rotating their heads. One participant often teleports backwards without seeing the teleportation beam because he felt the cord behind him limited his movement. "I don't feel like my head is as free as I would like it to be. I was clicking behind myself when I am trying to back up. If my head is free, I would just turn around and click. It limited my behaviour." Another behaviour was that a portion of the participants aimed slowly and teleported at least as possible, and several participants sometimes teleport small distances frequently.

B.3.2.2 Walking Behaviours

Participants became more passive in walking and more aggressive in teleporting in the subsequent sets of tasks. However, they occasionally walk backwards when they over-teleport by a few steps. In the first set of tasks, several participants started by walking a lot and ended up being close to the physical boundary even knowing they can teleport. In Group 1, two participants felt there was not enough room for walking around the table in Scene 3, but it would be natural to do so.

B.3.2.3 Zoom Behaviours

All participants in Group 1 had problems with the zoom control. One participant thought bird's eye view helps tell the difference in heights, but the control to achieve that was difficult. However, two participants in Group 1 used zoom or started with zoom in most of the tasks in Scene 2. The participant in Group 2 did not use it at all

because he thought "it did not actually change the distance."

B.3.3 Quantitative Data Analysis

B.3.3.1 Group 1 Results

One of the participants in Group 1 did not complete all the tasks in each set, so she is excluded from the quantitative data analysis. The general insights from the observation are:

1. Participants tend to spend less time in Scene 3 with tabletop perspective than in Scene 1 and 2 with room perspective.

2. When only walking and teleportation are made available in Scene 1, teleportation is utilized more than physical walking.

3. When zoom is enabled in Scene 2, it is used in combination with teleportation to complete the tasks and it is utilized the second most.

4. Zoom is used the most in finding the community centre with the highest utilization rate on the map and it is least used in comparing two individual data points.

5. Walking is most utilized in Scene 1 and least utilized in Scene 2. In Scene 1, walking is used the most in the task of finding the lowest utilization rate in the entire map.

6. For outlier search task, participants spend significantly more time in finding the lowest utilization rate in Scene 1 than in Scene 2 and Scene 3.

7. All participants find the correct community centre with the highest utilization

rate in all three scenes. In contrast, some participants have difficulties to locate the correct community centre with the lowest utilization rate.

8. Participants tend to teleport more frequently in Scene 2 than in Scene 1.

For 1., I compare the average task completion time in each scene for each participant (see Figure B.3.2). All participants spent less than 30 seconds in a task in Scene 3 with the tabletop perspective. It may be because that the data tooltips are disabled in Scene 3, participants spend less time reading and comparing the exact values.
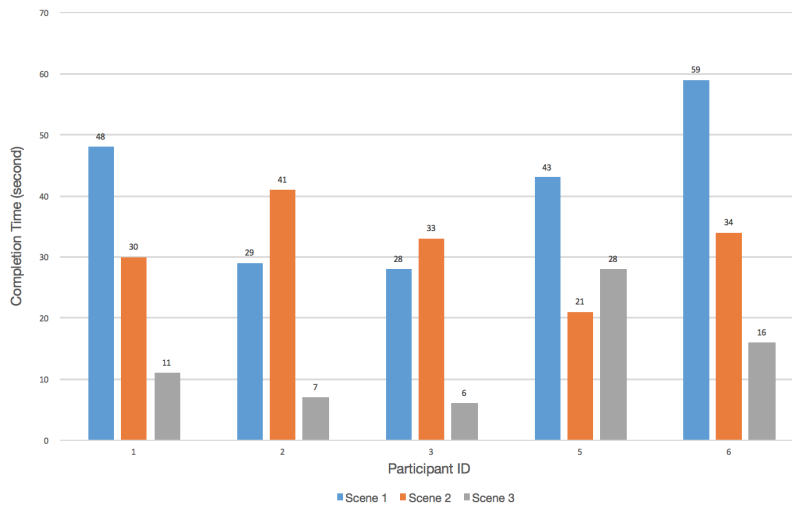

Figure B.3.2: Average Task Completion Time

For 2., I compare the number of tasks in which a navigation method is used in Scene 1 (see Figure B.3.3). Most participants used teleportation in all 10 tasks.
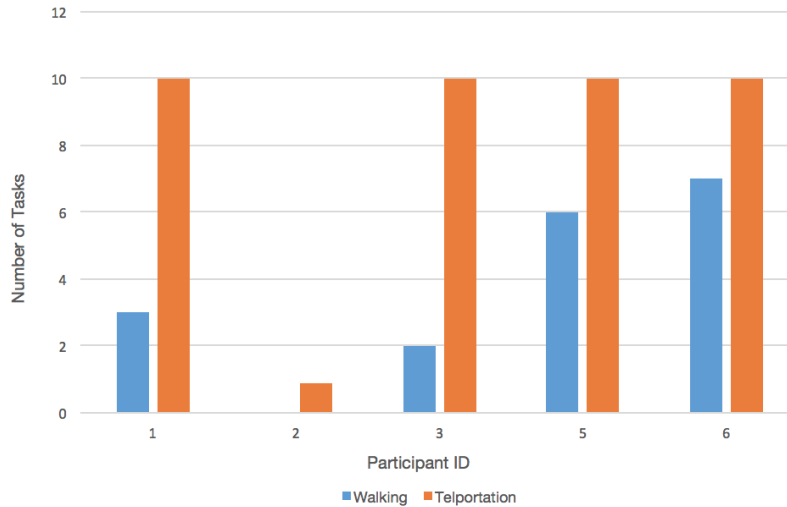

Figure B.3.3: Use of navigation methods in Scene 1

For 3., I compare the number of tasks in which a navigation method is used in Scene 2 (see Figure B.3.4). Teleportation is almost always used. Participants make use of the new feature more than physical walking.
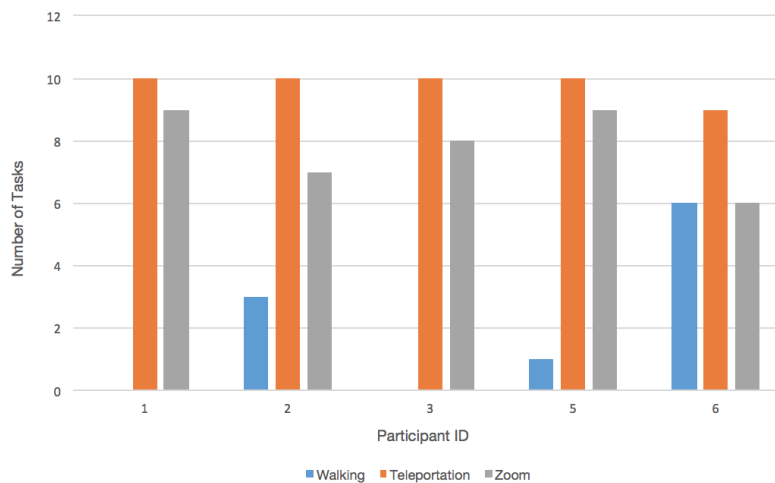

Figure B.3.4: Use of navigation methods in Scene 2

For 4., I compare the the percentage of participants who use zoom in each task

in Scene 2 (see Figure B.3.5). All participants have used zoom in task 2-2, 2-3, 2-7, and 2-8. The tasks are all about finding the community centre within an area with the highest utilization rate. In contrast, less participants use zoom in comparing two similar or identical values. For full description of the tasks, please refer to B.5.1 Test Template 3 in Appendix B.
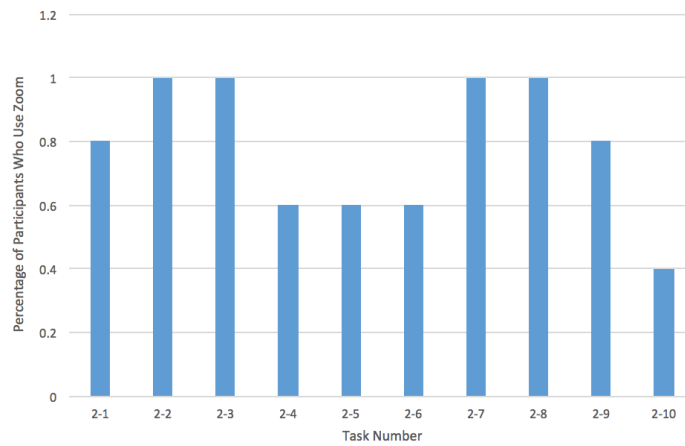
Figure B.3.5: Use of zoom in Scene 2

For 5., I compare the number of tasks where physical walking is used across all scenes (see Figure B.3.6). Walking is less frequently used other than in the first scene.
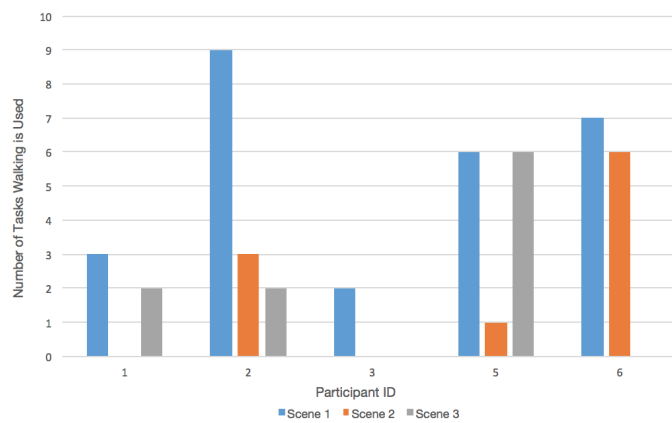
Figure B.3.6: Use of physical Walking in all scenes

For 6., time spent on the outlier tasks in all three scenes are compared (see Figure B.3.7). The third task in each scene (e.g. 1-3) is to locate the community centre with the highest utilization rate and the fourth one (e.g. 1-4) is to locate the lowest. In Scene 1, participants spend at least 50 seconds on finding the lowest rate. The completion decreases dramatically at the third scene.
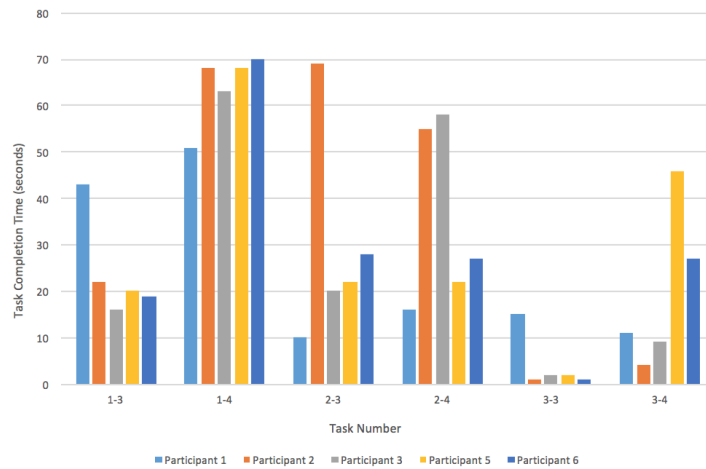

Figure B.3.7: Completion Time by Task Number group by participant

For 7., I simply compare the percentage of all the outlier tasks in three scenes that a participant finds the correct answer (see Figure B.3.8). There are six outlier tasks in total. Three participants' success rate decreases in finding the lowest utilization rate.
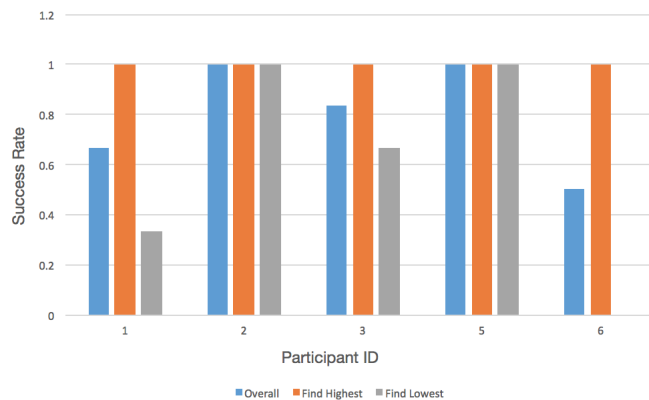

Figure B.3.8: Success Rate by Participant ID

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Finally, I compare the average number of teleportation made in Scene 1 and Scene 2. The number of teleportation have increased evidently as participants become more familiar with the control (see Figure B.3.9).
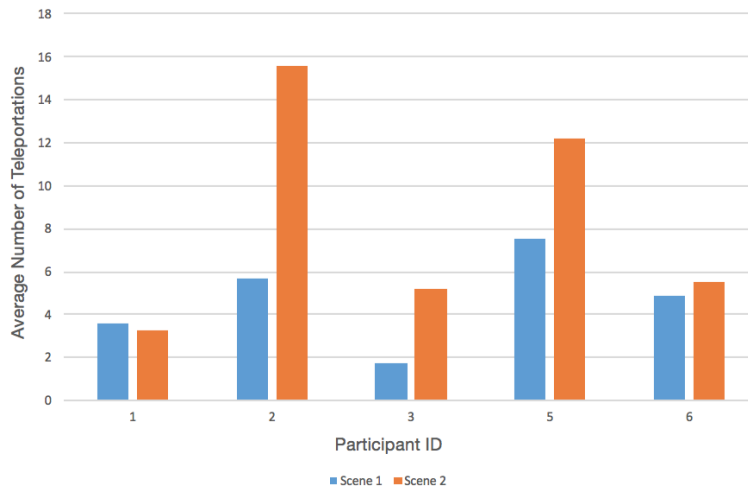
Figure B.3.9: Average Number of Teleportation by Participant ID

B.3.3.2 Group 2 Results

Group 2 uses a different test template. There are 8 tasks for each scene. It has the same outlier tasks (i.e. every third and fourth task in each scene) as for Group 1. One exploration task in each scene is excluded in the analysis of completion time because it is determined by the participant. The insights are:

1. Zoom is not used at all in Scene 2.

2. The participant has 100% correctness on all 6 outlier tasks in three scenes.

3. The participant walks less in Scene 2 and 3 compared to in Scene 1.

4. The participant spends less time in Scene 3.

B.3.3.3 Group 3 Results

For Group 3, a slightly different test template is used. Bird's eye view is obtained through teleporting instead of zoom control. The insights are:

1. The participant utilizes bird's eye view in 2/8 tasks in Scene 2.

2. The participant has 100% correctness on all 6 outlier tasks in three scenes.

3. The participant walks less in Scene 3 than in Scene 1 and 2.

4. The participant spends less time in Scene 2.

B.3.3.4 Cross Group Comparison

Since the sample sizes are different in each group and the test templates used are different, it is difficult to draw logical conclusions from directly comparing the overall results of each group. However, it is possible to gain insights in performance in similar tasks that use similar configurations.

In terms of success rate of outlier search tasks, there are no significant differences (see Figure B.3.10). Participant 7 from Group 2 has the same success rate in identifying the outliers in the entire map as participant 2 and 5 in Group 1. Participant 8 from Group 3 has the same success rate as participant 3 from Group 1.

For completion time, there are slight differences (see Figure B.3.11). participant 7 from Group 2 spent more time on task 2-4 in Scene 2 than participants from other groups. Participant 8 from Group 3 spent less time on task 2-3 and 2-4 in Scene 2 than others.
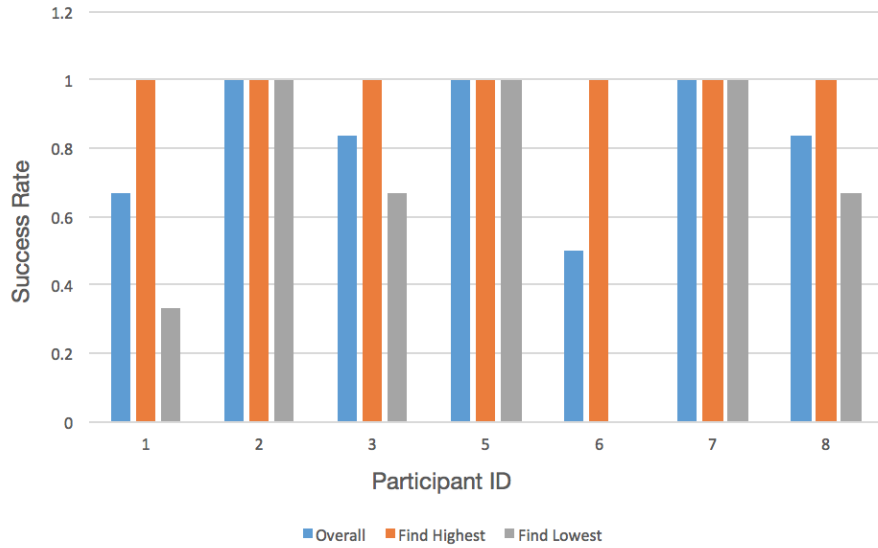
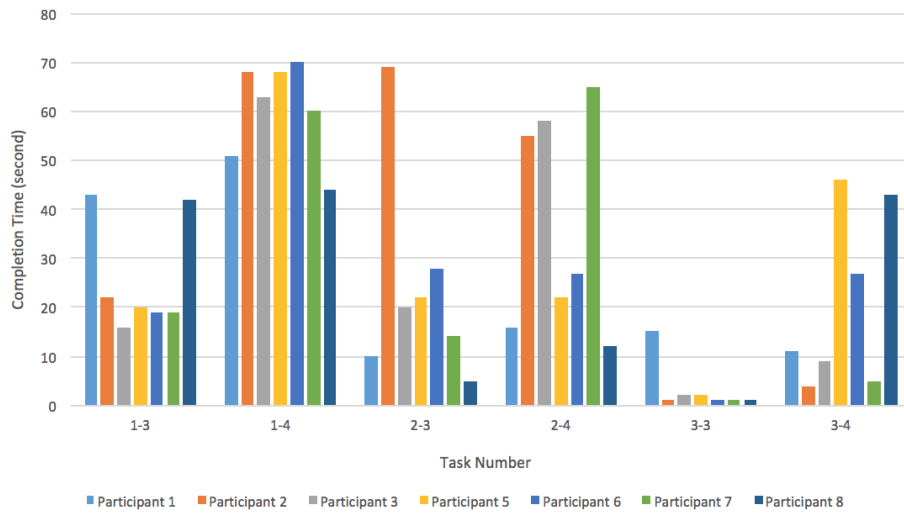Figure B.3.10: Success Rate by Participant ID (all groups)

Figure B.3.11: Outlier Tasks Completion Time by Task Number (all groups)

B.4. Interview Template

B.4.1 Interview Template 3

<div align="center">

Interview Guide

</div>

<u>Project Title</u>:   Navigation in VR for visual analytics using the latest consumer-grade hardware

The interviews are semi-structured and include closed and open ended questions in order to provide some easily comparable responses from participants but also allow for more in-depth discussions regarding VR experience.

<u>Pre-interview Script</u>

1. Greet participant.
2. Read, explain, and have participant sign the consent form. In particular, any risks, confidentiality, or privacy issues will be clarified at this stage.
3. The VR experience will take place in between the two interviews. Based on your level of experience with VR technologies and data analysis, it may take 20 to 40 minutes.
4. Again, you may experience eye fatigue, neck fatigue, or nausea during the process.
5. I would also like to conduct two short interviews with you, one before the experience and the other after it.
6. The pre-test interview questions are mostly related to demographics, general background and experience, and some general perspectives. It will take 5 to 10 minutes.
7. The post-test interview questions will be a review and reflection based on the experience you have in the test. It will take 10 to 15 minutes.
8. You may decline to answer any questions and you are welcome to let me know any concerns at any moment of the interview.
9. Do you have any questions regarding the interviews and the VR experience before we start?
10. Start interview.

<u>Pre-User Test Interview Guide</u>
Duration: 5 ~ 10 minutes
Questions:

Personal
1. What is your age group? (Choose from, 20~25; 25 ~ 35; 35 ~ 45; 45 ~ 55; 55 ~ 65)
2. What is your height?
3. What is your latest education background and area of study?
4. What is your occupation?
5. Do you have any project experience on urban planning?
    a. If yes, please briefly describe.
    b. If yes, what data set have you dealt with?

Visual Perception
6. Do you have any difficulty identifying colours? (Yes / No)
    a. If yes, which colours?
7. What is your visual acuity / clarity of vision? Or do you need to wear glasses/contacts in order to read or watch digital contents?
8. Do you have any difficult viewing 3D graphics? (Yes / No)
    a. If yes, what in particular?

Technological background

9. Do you have any experience with VR or immersive environment as a user? (Yes / No) yes; not a lot
    a. If yes, was it a pleasant one or not? (Yes / No)
    b. If yes, can you briefly describe your experience?
    c. If no, what are your expectations of using VR equipment?
    d. If no, why was that?
10. Which tools have you used that are related to data analysis/manipulation?
    For instance, Excel/Tableau/Google Analytics/Database Tool/Others (please specify)
11. Do you use any map-based web apps or mobile apps? (Yes / No)
    a. If yes, can you give one or two examples?
    b. If yes, how often?
12. Do you have any experience with video games? (Yes / No)
    a. If yes, what types of games? (FPS, strategy, platform, space shooter, and etc.)
    b. If yes, what types of perspectives or view angles are you most familiar with in all games? (1st-person; 3rd-person)
    c. If yes, what types of game controllers or input devices do you prefer?
13. Do you have any experience with city simulation software? (Yes / No)
14. What types of input devices do you use the most on a daily basis?

Map
15. How long have you lived in Toronto?
16. Which region(s) of Toronto have you lived at?
17. How well do you know Toronto in terms of geographical environment?

18. What is your current energy level, on a scale of 1 to 5, 5 being very high?
19. Do you have any questions about the VR experience that you are about to have?

Post-User Test Interview Guide
Duration: 10 ~ 15 minutes
Questions:
General
    1. How would you describe your current energy level, on a scale of 1 to 5, 5 being very high?
    2. How immersive do you think the experience was, on a scale of 1 to 5, 5 being extremely immersive? Why?
    3. Is there anything in the virtual environment that you feel that breaks the immersion?
    4. Which part of the experience did you like the most? Please elaborate.
    5. Which part of the experience did you dislike the most? Please elaborate.

Navigation/View Control
    6. Which one of the navigation techniques did you prefer the most (teleportation; physical walking)? Why?
    7. Which perspective, out of room-scale, bird's eye, and tabletop, do you like the most and why?
    8. Did you have any difficulties navigating around the map? Please elaborate.
    9. Did you have any difficulties with the hand controllers? Please elaborate.

Visualization
    10. Did you find something interesting or insightful from the dataset?
    11. What else do you think that can be useful to have in the data visualization environment?

    12. What other challenges did you have related to task completion and the experience?
    13. What improvement do you think can be made to the map? For example, size, orientation, lighting, level of details, sounds, and etc.
    14. What improvement do you think can be made to the user interface? For example, colour, layout, legibility, and etc.
    15. Do you have any other questions or suggestions about the VR experience that you just had?

B.5. Test Template

B.5.1 Test Template 3

User Test Manual

Goal
Evaluate the performance of navigational tasks and subjective experience in an immersive data visualization environment.

Dataset
You are exploring the City of Toronto's recreational courses historical data in 2015. Each row in the data represent a recreational course, that falls under a registered program or a drop-in program. Each season every community centre will have different programs and courses. For example, Summer Camps for Child/Youth is a special program only available during summer (See Figure 1).
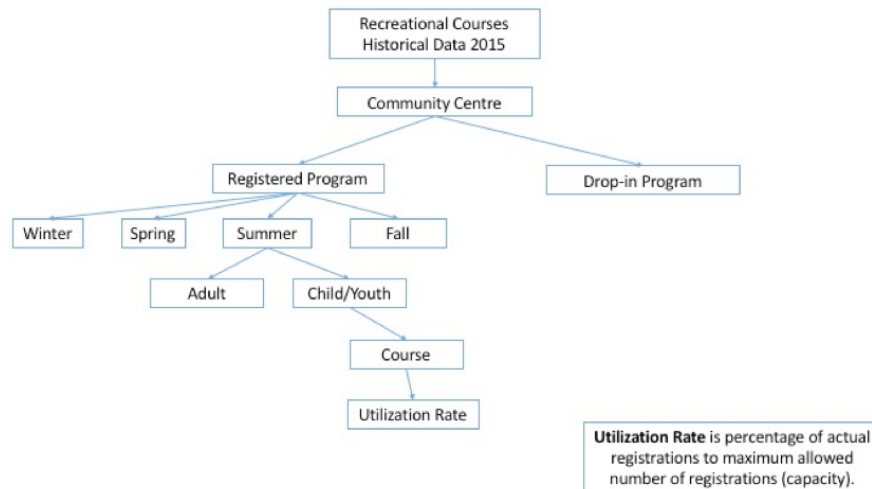

Figure 1 Recreational Courses Historical Data Hierarchy Diagram

You filtered all the summer courses of all child and youth sections of registered programs. You are particularly looking into the average utilization rate of all the courses in registered programs in community centres across Toronto.

You are now immersed into a data visualization environment where the data is represented as 3D bars. The heights of those bars represent the average course utilization rate at each location.

In this environment, two virtual controls are available to help navigation, teleportation and zoom. You can also walk within a physical play area where your head and body movement will be tracked. Please take a few seconds to adapt.

In the following tasks, you are asked to locate a target on a 2D map. When you identify the target, please point it out using the controller and say "Done." You should think aloud while carrying out the tasks. You can ask questions at any stage. You can choose to skip any questions.

1st Round
Search tasks using teleportation and physical movement.
In the first round, you are looking at Summer courses of child and youth sections.
1. Find a community centre near the neighbourhood you currently live or have lived recently and tell me the utilization rate.
2. Find the location in Trinity-Spadina and Toronto Centre-Rosedale wards with the highest utilization rate.
3. Find the location with the highest utilization rate from the entire map.
4. Find the location with the lowest utilization rate from the entire map.
5. Find the location near the waterfront of the city or along the shoreline with the highest rate.
6. Find the location along the Highway 401 Express (second horizontal one from the top) with the lowest rate.
7. Find two locations that are next to each other and they have an evident difference in the utilization rate.
8. Please explore the map for 2~3 minutes and tell me what distribution patterns you have found. You are free to talk about the patterns of distribution of community centres, proximity to certain types of lands, and so forth.

2nd Round
Search tasks using teleportation, zoom, and physical movement.
In the second round, you are looking at Summer swimming courses of child and youth sections.
1. Find a community centre near the neighbourhood you currently live or have lived recently and tell me the utilization rate.
2. Find the location in within Trinity-Spadina and Toronto Centre-Rosedale wards with the highest utilization rate.
3. Find the location with the highest utilization rate from the entire map.
4. Find the location with the lowest utilization rate from the entire map.
5. Find the location near the waterfront of the city or along the shoreline with the highest rate.
6. Find the location along the Highway 401 Express (second horizontal one from the top) with the lowest rate.
7. Find two locations that are next to each other and they have an evident difference in the utilization rate.
8. Please explore the map for 2~3 minutes and tell me what distribution patterns you have found. You are free to talk about the patterns of distribution of community centres, proximity to certain types of lands, and so forth.

3rd Round
Search tasks using teleportation, zoom, and physical movement.
In the third round, you are looking at all Fall courses of child and youth sections.
1. Find a community centre near the neighbourhood you currently live or have lived recently and tell me the utilization rate.
2. Find the location in within Trinity-Spadina and Toronto Centre-Rosedale wards with the highest utilization rate.
3. Find the location with the highest utilization rate from the entire map.
4. Find the location with the lowest utilization rate from the entire map.
5. Find the location near the waterfront of the city or along the shoreline with the highest rate.
6. Find the location along the Highway 401 Express (second horizontal one from the top) with the lowest rate.
7. Find two locations that are next to each other and they have an evident difference in the utilization rate.
8. Please explore the map for 2~3 minutes and tell me what distribution patterns you have found. You are free to talk about the patterns of distribution of community centres, proximity to certain types of lands, and so forth.

B.6. Consent Form

Invitation / Consent Form

Date: September 1st, 2016
Project Title: Design challenges in data exploration in VR environments using the latest consumer-grade hardware

Co-Investigator / Student Researcher: Principal Investigator / Faculty Supervisor:
Minsheng Zheng   Patricio Dávila, Associate Professor
OCAD University   OCAD University

INVITATION
You are invited to participate in a study that involves research. The purpose of this study is to learn about the efficacy of user navigation and user interface in virtual reality based visualization.

WHAT'S INVOLVED
As a participant, you will be asked to wear a HTC Vive VR headset, immerse into a virtual world, and perform a series of navigation and data exploration tasks. Participation will take approximately 40 to 60 minutes of your time. During the VR experience, your physical movement, facial expression, and spoken words may be videotaped for data collection purposes. You will be asked to talk about your thought process during the experience. There will also be two short interviews on site, one before and the other after the experience.

POTENTIAL BENEFITS AND RISKS
Participants will gain experience with VR hardware and applications as well as domain knowledge in the context of urban planning. There may be risks associated with participation related to the use of VR headsets including eye fatigue, neck fatigue, or nausea. If you experience any of these sensations you can stop at any time. We will make our best effort to minimize the risks by carefully monitoring the entire user testing session and giving adequate verbal instructions.

CONFIDENTIALITY
All information you provide is considered confidential; your name will not be included or, in any other way, associated with the data collected in the study. Furthermore, because our interest is in the average responses of the entire group of participants, you will not be identified individually in any way in written reports of this research.

Data collected during this study will be stored in the co-investigator's personal hard drive and will be kept secure. Data will be kept for 6 months after which time they will be digitally removed from the storage. Access to this data will be restricted to Principal Investigator, Patricio Dávila, Co-Investigator, Minsheng Zheng, and thesis committee member, Adam Tindale.

VOLUNTARY PARTICIPATION
Participation in this study is voluntary. If you wish, you may decline to answer any questions or decline to participate in any component of the study. You may decline to be audio or video recorded. Further, you may decide to withdraw from this study at any time, or to request withdrawal of your data (prior to data analysis between January and February 2017), and you may do so without any penalty or loss of benefits to which you are entitled.

PUBLICATION OF RESULTS
Results of this study may be published in student's theses. In any publication, data will be presented in aggregate forms. Quotations from interviews will not be attributed to you without your permission.

CONTACT INFORMATION AND ETHICS CLEARANCE
If you have any questions about this study or require further information, please contact the Co-Investigator Minsheng Zheng or Principal Investigator, Patricio Dávila, using the contact information provided above. This study has been reviewed and received ethics clearance through the Research Ethics Board at OCAD University [100857]. If you have any comments or concerns, please contact the Research Ethics Office.

CONSENT FORM
I agree to participate in this study described above. I have made this decision based on the information I have read in the Information-Consent Letter. I have had the opportunity to receive any additional details I wanted about the study and understand that I may ask questions in the future. I understand that I may withdraw this consent at any time.

Name: _____

Signature: _____   Date: _____

Thank you for your assistance in this project. Please keep a copy of this form for your records.