



DEGREE PROJECT IN MEDIA TECHNOLOGY,
SECOND CYCLE, 30 CREDITS
STOCKHOLM, SWEDEN 2017

Interacting with information visualizations in virtual reality

Motion tracked hand controller interaction for common filtering operations in a VR information visualization application.

ERIK FORSBERG

Interacting with information visualizations in virtual reality

Motion tracked hand controller interaction for common filtering operations
in a VR information visualization application.

Interaktion med informationsvisualiseringar i virtual reality

Interaktion för rörelsespårade handkontrollers för vanliga filtreringsoperationer
i en VR-informationsvisualiseringsapplikation.

ERIK FORSBERG

eforsbe@kth.se

Master's Thesis in Media Technology
Master of Science in Engineering – Media Technology
Royal Institute of Technology

Supervisor: Björn Thuresson

Examiner: Tino Weinkauff

Date: 2017-05-18

Abstract

As we are heading into immersive virtual reality environments for different purposes - entertainment being the most prominent lately - we should consider how we design interactive information visualizations for VR. Is it wise to hold onto the same elements of interaction with which we are familiar from contemporary web-based interfaces? The study explores this question along with others, to explore ways to conduct familiar filtering operations known from web environments, in VR.

An interactive information visualization application in VR was created to evaluate two web-inspired interaction methods used for filtering data. Thirteen users participated in the tests, in which each participant worked through eight predetermined tasks as well as one open-ended task. Qualitative feedback was gathered both through think-alouds during the tasks and in semi-structured interviews when the test had been concluded. Quantitative data was gathered in the application, containing logs of usage statistics.

Results show that using web-inspired interaction methods to carry out filtering operations in VR helped the participants to understand the functionality of the interactions. By implementing haptic and visual feedback, natural interactions can be imitated which according to the results of the study generally is perceived as helpful while making the interactions feel more natural. Designing the interaction methods to function like previously known interactions (such as ones found in web interfaces) helped the participants to understand the functionality of the filters.

Sammanfattning

I och med framfarten av VR och dess olika användningsområden – där underhållning gått i bräschen på senare tid – borde vi fundera på hur vi designar interaktiva informationsvisualiseringar för VR. Är det klokt att hålla fast vid samma interaktionselement som vi känner igen från webbaserade gränssnitt? Studien utforskar denna fråga tillsammans med andra, för att utforska sätt att genomföra bekanta filtreringsoperationer som känns igen från webbmiljöer, i VR.

En interaktiv informationsvisualiseringsapplikation i VR skapades för att utvärdera två webbinspirerade interaktionsmetoder som användes för att filtrera data. Tretton användare deltog i studien, där varje deltagare tog sig igenom åtta förbestämda uppgifter samt en öppen uppgift. Kvalitativ återkoppling samlades in både via think-alouds under uppgifterna samt i semistrukturerade intervjuer när testet hade avslutats. Kvantitativa data samlades in i applikationen och innehöll användningsstatistik.

Resultaten visar att användandet av webbinspirerade interaktionsmetoder för att genomföra filtreringsoperationer i VR hjälpte deltagarna att förstå interaktionens funktionalitet. Genom att implementera haptisk och visuell feedback kan naturliga interaktioner efterliknas, vilket enligt studiens resultat uppfattas som hjälpsamt samtidigt som interaktionerna kändes mer naturliga. Att utforma interaktionsmetoderna för att efterlikna de som återfinns i webbgränssnitt hjälpte deltagarna att förstå filtrens funktionalitet.

Table of contents

1 Introduction	1
1.1 Definitions	2
1.1.1 Immersion	2
1.1.2 Head-mounted display (HMD)	2
1.1.3 NPS	3
1.2 Case	3
1.3 Research question	3
1.4 Problem definition	4
1.5 Objective	4
1.6 Delimitation	4
2 Concepts from related work	6
2.1 Immersive Virtual Environments (IVE)	6
2.2 Natural VR interaction	6
2.2.1 Two-handed interaction	7
2.3 Spatial and non-spatial interfaces	7
3 Method	8
3.1 Data	8
3.2 Interaction methods	8
3.2.1 Binary filtering	8
3.2.2 Defining intervals in continuous data ranges	9
3.3 Used software	9
3.3.1 Unity3D	9
3.3.2 SteamVR	9
3.3.3 VRTK	9
3.3.4 Lumen	10
3.4 Implementation	10
3.4.1 Graph container	10

3.4.2 Product buttons	11
3.4.3 Sliders	12
3.4.4 Off-hand display	14
3.4.5 Environment	15
3.5 Process	15
3.5.1 User tests	15
3.5.2 Pilot study	16
3.5.3 Demo scene	16
4 Test plan	17
4.1 Overall objectives for the study	17
4.2 Relevant questions	17
4.3 Location and setup	18
4.4 Recruiting participants	18
4.5 Methodology	19
4.5.1 Usage of between-subjects design	20
4.5.2 Session outline and timing	20
4.5.3 Moderator role	23
4.6 Tasks	24
5 Design iteration	25
6 Results	28
6.1 Participants	28
6.2 Presence Questionnaire	28
6.3 Predetermined tasks	30
6.3.1 Task paths	31
6.3.2 Data logs	31
6.4 Semi-structured interview	33
6.4.1 Button interaction	33
6.4.2 Slider interaction	34
6.4.3 Room scale immersion influence	35

7 Discussion	37
7.1 Buttons and sliders in VR	37
7.1.1 Button issues	37
7.1.2 Slider issues	38
7.2 Confusing data dimension	38
7.3 Haptic feedback	38
7.4 Real-time interactions	39
7.5 Comparison between data subsets	39
7.6 Error rates and design iterations	39
7.7 Controller buttons	39
7.8 Translating web-like interactions	40
7.9 Method critique	40
7.9.1 Think-alouds	40
7.9.2 Task paths	41
8 Conclusions	42
9 Future work	43
10 Bibliography	44
11 Appendix	46
Appendix A. Presence Questionnaire	46
Appendix B. Regarding development and testing	51

1 Introduction

In this study, I will explore how we can interact within an information visualization scenario, in a virtual reality environment.

Visualization in VR is nothing new (Koutek, 2003; Bayyari & Tudoreanu, 2006; Wang, Paljic & Fuchs, 2012; Garcia-Hernandez et al., 2016), however research examining methods for information visualization using VR is sparse and interaction methods for the purpose likewise. This despite research showing that virtual reality can improve our understanding of data visualization drastically (Bayyari & Tudoreanu, 2006).

Much has been published examining VR interaction methods and how the psychology behind information visualization work separately, but seldom have we tried to connect these fields.

Today, we are familiar to what could now be considered traditional input methods in a web environment. The input methods could for instance be checkboxes, text fields, drop-down menus or range sliders. These could all be used for filtering and navigating through data. Experienced Internet users have likely used all the above-mentioned input methods and are familiar with how they work. However, what we have learned on the web is usually bound to a specific set of tools to be used with the input methods. We see these methods on 2D computer screens, and we interact with them by typing on keyboards and clicking with computer mice or trackpads. The input methods mentioned are common when it comes to filtering and interacting with data on the web.

With the introduction of touch-screen enabled smartphones, these methods were introduced to a new environment with new ways of interacting with the content. The new devices introduced new challenges that forced web developers to consider new input methods. For instance, most modern smartphones do not have a physical keyboard, nor does it include a pointing device in the form of a visual marker overlay on the screen, controlled by your hand. The most prominent input method used with these devices are your fingers, touching the screen on the places you want to “click”.

Looking back at how web development has been adapted to the new ways of interacting with mobile devices, somewhat clumsy input methods have become the standard, likely because of the way we are used to interacting with computers. On-screen touch keyboards have become the standard for text input, even though we cannot feel the edges of the virtual keyboard like we do using a physical keyboard. This makes the input method prone to errors, as the touch buttons usually are too small for us to accurately hit because of the limited screen size. The advantage of a virtual keyboard is that we have the same layout on the keyboards we use for our computers, making the shift between devices somewhat painless - if we can live with the occasional spelling mistake or “auto-correct error” created by spell-check software common in smartphones.

If we look at other forms of mobile interaction, we usually tap the screen with our fingers when we want to select or click something. The action itself is quite like what you would do using a computer mouse or trackpad. The difference is, by using a mobile touch screen, you do not have to move a pointer around the screen using a separate pointing device - you can simply tap on the elements you want to click. The drawback of not having a pointer is that you lose some visual cues that would otherwise indicate interactivity. Common visual cues could be changing the pointer icon while hovering the pointer over

interactive elements, or in different ways change the look of the element being hovered over. Currently, these forms of visual cues are usually partly or completely lost when using a smartphone to browse the same content as we would on a desktop computer.

Modern smartphone devices contain a plethora of sensors and other forms of possible input methods which most web content choose to ignore as the content to be viewed is shared across platforms. Modern smartphones usually have gyroscopes, barometers, proximity sensors, cameras, accelerometers, compasses, microphones and other sensors with the potential of being the source for input. An example of a well-functioning input method made for the camera-enabled smartphone is the rise of image-recognition software, for instance giving the user the opportunity to use the camera to snap a photo of an invoice, enabling the application to automatically fill in the correct amount and reference numbers instead of having to type it in manually using a virtual keyboard.

As we are heading into immersive virtual reality environments for different purposes - entertainment being the most prominent lately - we should consider how these interaction methods translate to VR environments, using the motion tracked hand controllers available with this generation's high-end VR sets. Is it wise to hold onto the same elements of interaction with which we are familiar from contemporary web-based interfaces? The study explores this question along with others, to explore ways to conduct familiar filtering operations known from web environments, in VR.

1.1 Definitions

A few definitions of central concepts and words used within this report will be explained here.

1.1.1 Immersion

Immersion, as defined by Slater & Wilbur (1997) is a description of a technology, and describes the extent to which computer screens can deliver an illusion of reality to the senses of the user. To further describe in which ways the technology can deliver said illusion, the authors list five aspects: *inclusive*, *extensive*, *surrounding*, *vivid* and *matching*.

Inclusive describes the extent to which the outside world is shut out. Extensive describes the range of sensory modalities used within the application. Surrounding describes the field-of-view within the application, meaning how narrow or wide the field is. Vivid describes the information content, how it is displayed and visualized, as well as more hardware focused aspects such as the resolution and quality of the displays used.

1.1.2 Head-mounted display (HMD)

A HMD is a stereoscopic display, placed on the head of the user. The field of view for the display mimics the field of view of the eye, effectively replacing what the user sees with the content shown on the display. The HMD used in this study also uses motion tracking technology, which enables the user to experience full 360-degree immersion in the virtual environment.

1.1.3 NPS

NPS is an abbreviation of the measurement Net Promoter Score. NPS is a way to measure customer loyalty and satisfaction. It is based on customers' rating to the question "How likely is it that you would recommend our company/product/service to a friend or colleague?". Customers rate this question on a scale from 0 to 10 where 10 is most likely and 0 is least likely. Customers who rate 9 to 10 are viewed as promoters of the company/product/service, whereas scores from 0 to 6 are viewed as detractors. Scores 7 to 8 are viewed as passives.

A final score is then calculated using the following formula: $((\text{Promoters}/\text{SUM}(\text{Promoters}, \text{Passives}, \text{Detractors})) - (\text{Detractors}/\text{SUM}(\text{Promoters}, \text{Passives}, \text{Detractors})))$. The result is a number from -100 to 100, where a positive number is viewed as good and +50 is excellent.

1.2 Case

The study will be conducted in tandem with Adaptive Media AB as the housing company during the study, but more importantly a client of Adaptive Media AB - Ownit Broadband, henceforth referred to as "the principal". The principal is a Swedish Internet service provider which mainly delivers services such as high-speed Internet connections, television packages and telephony to personal customers, housing cooperatives and companies.

The principal currently collects data regarding their customers, to gain better understanding of their customers. Any form of insight that may assist the principal in tailoring their services, more accurately targeting their sales campaigns or proactively reducing the workload of their customer support has been mentioned as exceedingly interesting to their business. As the principal has shown significant interest in innovative technology, an opportunity to explore emerging technology such as virtual reality has been proposed to improve their understanding of the data they collect.

The initial idea of the study came after a meeting with the principal, in which we discussed information visualizations and how it could benefit their business. The purpose of creating an interactive information visualization for the principal is founded in the idea that it could increase their possibilities to explore their customer data. The hypotheses and information gathered using the application could then be applied to analyze ended sales campaigns so that more efficient sales campaigns can be created in the future.

The principal has shared a data set to be used for the visualization. The data set contains extensive information about customers, products, campaigns and other parameters. Customer data will be the focus of the information visualization created for this study.

1.3 Research question

The main research question to be examined during the study is:

How can we translate common data filtering operations such as binary selections and defining intervals in continuous data ranges in VR for use with motion tracked hand controllers?

1.4 Problem definition

There are several aspects to consider when designing interactions for the purpose described above. For instance, we need to take into consideration the area in which the user comfortably can reach and see in an immersive virtual environment. Depending on their working position, some movements are easier to carry out than others. For instance, a user sitting down is constrained in vertical head rotations, making interactions and interfaces above eye-level more difficult to use compared to when standing up (Alger, 2015).

We also need to consider the interfaces' distance from the user. Having a large interface, far away from the user in world space may disturb the depth perception of the user should other objects overlap with the interface. At the same time, we do not want to put the interface too close to the user as it can be straining on the eyes, while making it hard to comfortably interact with the interface using hand controllers.

A significant difference when it comes to comparing desktop computer and smartphone interaction to VR interaction is how the content is presented and viewed. Both desktop and smartphone web content look quite alike, and is in most cases the same content on both devices although sometimes rearranged for readability on a smaller device screen. We are used to scrolling a canvas filled with text and images as we consume information on the web using these platforms. However, since there is no one way to display content in a virtual reality environment, or even a standardized framework to display the same form of content, a great deal of experimental usage scenarios will be conducted to better understand what works and what does not.

1.5 Objective

From the perspective of the degree project, the desired outcome is to reduce the gap in the research field of interactive information visualizations in immersive virtual environments by contributing an explorative study. Exploring ways to interact with visualized data in VR is the focus of the study. In particular, interactions to be explored are common filtering operations inside of an immersive virtual environment as a user wears an HMD and motion tracked hand controllers. These operations consist of binary filtering and defining intervals in continuous data ranges. Furthermore, possibilities and difficulties with such interaction in VR will be discussed.

In addition to the academic objective of contributing to state-of-the-art research within the field of interaction design in virtual reality information visualizations, the ambition is to at the end of the study be able to deliver a functional prototype of an information visualization tool for a virtual environment, ready for the first stages of experimental usage by the principal. The focus of the prototype is for the principal to be able to perform postmortem analysis of campaign results to evaluate and form new hypotheses for new sales campaigns.

1.6 Delimitation

To try and keep the opinions on the interactions focused, the operations will be limited. As mentioned above, there will be two main operations available in the application. The method of carrying out these

operations will be with the motion tracked hand controllers available with the HTC VIVE, a current generation high-end VR platform. All interaction will be focused around the hand controllers.

The VR application used for the experiments will be shown through the HMD of the HTC VIVE, a motion tracked headset with six degrees of freedom.

The visualized data will be limited both for time constraining reasons during the development process as well as to not overwhelm a test subject since the interaction methods is the focus of the study. During the testing, some data will be fabricated for consistency and confidentiality reasons although with the same structure as the original data provided by the principal.

2 Concepts from related work

In this chapter, several concepts used within in this study will be explained. The theory is supported by both peer-reviewed papers and non-peer-reviewed content such as developer blogs, conference talks and development and design guides from VR technology companies such as Google, Oculus and Leap Motion. Most of the time, the non-peer-reviewed sources are solely qualitative and anecdotal, making the credibility questionable from an academic perspective, however not irrelevant when making design decisions in the development process. Current VR technology is still in its infancy, making peer reviewed sources discussing this generation of VR technology sparse and hard to find.

2.1 Immersive Virtual Environments (IVE)

When a user puts on a head-mounted display (HMD), they enter what is referred to as an immersive virtual environment, also referred to simply as “VR” in this context. Immersion in VR could be described as the perception of being physically present in a non-physical world (Steuer et al., 1992). In other words, the virtual environment is convincing enough to make the user suspend disbelief and fully engage with the IVE. This immersion is commonly made possible by visual stimuli, for instance that of which a user receives when wearing a HMD. Loomis et al. (1999) write that the ultimate representational system would allow the observer to interact "naturally" with objects and other individuals within a simulated environment or "world", an experience indistinguishable from "normal reality".

Naturally, the quality of the experience varies, based on how the VR application is designed as well as the display quality and overall responsiveness of the hardware. An extension which may strengthen the immersion is, for instance, the use of 3D sound. Current generation of high-end VR sets enables the user to physically move around in a room-scale VR application, which along with motion tracked hand controllers makes for an exceedingly convincing IVE as users can see their own “hands”. Even though the 3D models portraying the hands may not look like the user’s real hands, the user can experience the feeling of virtual body ownership, an illusion which makes the virtual “hand” feel like their own (Kiltner, Bergstrom and Slater, 2013).

2.2 Natural VR interaction

Interestingly enough, with the rise of this generation’s VR technology, interaction design can take a step away from current digital interaction design trends. Norman (1988) writes about how we interact with everyday things, such as door handles and coffee makers. Adapting interaction methods in the 2D-space of a computer screen according to Norman may seem like a stretch, as we cannot reach out and grab objects with our hands using a computer screen. However, this changes with current VR technology. Now, we can actually reach out and grab a door handle using motion tracked hand controllers. The objects we see and interact with in VR are perceived almost as actual physical objects, even though they are virtual. According to Cairo (2013), instead of describing the functionality of an interface, we should highlight it in such a way that users can sense its relevance and how it operates. For instance, we should make virtual buttons look and appear as if they were physical buttons. The more a user can understand the functionality of the interface just by observing it, the easier it will be for them to understand and remember how it works (Norman, 1988).

2.2.1 Two-handed interaction

Two-handed interaction is normally how we interact with physical objects in the real world. Thus, using two motion tracked hand controllers to translate hand movements could be a natural way of interacting in VR. Current generation of high-end VR-technology allow real-time translation of hand movements into the virtual world along with real-time rendering of 3D models portraying the controllers, making the movements feel and look natural.

Whether a VR interface built upon two-handed interaction gets perceived as natural varies depending on the implementation. A two-handed interface can perform worse than one handed interaction, should the two-handed interaction be poorly designed (Kabbash et al., 1994). In the same study by Kabbash et al. (1994), another two-handed interaction technique was in fact the one with the best overall performance. More relatable for virtual environments is a study by Schultheis et al., (2012) in which a two-handed interface significantly outperformed a traditional computer mouse based interface for basic 3D tasks.

2.3 Spatial and non-spatial interfaces

Commonly in non-VR applications, we use what is known as non-diegetic interfaces, meaning an interface that is displayed as an overlay on a computer screen. These interfaces are also referred to as an HUD (Heads Up Display). This interface could for instance show health bars, high-score counters etc. Usually, the interface displays information that makes sense within the context of the application, but does not exist by itself within the world (Unity, 2017). This type of interface is a non-spatial interface, meaning it does not take into consideration the world space - making it suboptimal for a VR application.

Designing user interfaces in VR gives us the opportunity to make full use of the spatial environment in which our applications function. For instance, we could create a wall on which we display instructions, forcing a user to turn their head towards the wall to read the instructions. While a spatial interface such as the one described may confuse the user should the implementation of the interface not be made in a logical way, opportunities to connect information to interactions arise. We could for instance let a user freely walk around in a virtual environment with several interactable objects, having information about the interactions appear next to the object as the user approaches it, creating spatially adaptive interfaces.

3 Method

The study conducted exploratory research to gather first impressions when it comes to interacting with visualized data in VR upon which further research could be based. Looking at the individual research fields of information visualization, virtual reality and human-computer interaction, there is a significant amount of research to draw upon for inspiration and methodologies. The ambition was to use and combine current standards within those areas in order to make a contribution to the academic world of interactive information visualization in VR. For instance, parts of the “Presence Questionnaire” by Witmer & Singer (1998) was used as a method of evaluating the immersiveness of the virtual environment, along with a test plan created along the guidelines of Rubin & Chisnell (2008).

By creating a virtual reality application, impressions were gathered by letting test subjects explore the interactions and the interface, carrying out pre-determined tasks as well as an open explorative task in VR. The experiments focused on the two main interaction methods. All interaction methods were used to filter or display details about the visualized data.

After testing the VR application, semi-structured interviews with the test subjects were conducted to gain qualitative data regarding the functionality of the interactions. By conducting semi-structured interviews, there was room for the test subjects to expand on areas they found interesting, giving further detailed opinions on the functionality. The tests also had a focus on the intuitiveness and familiarity of the interactions within the virtual environment. No benchmarks were made to compare participants directly, however tasks were timed to collect quantitative data as well. Further quantitative data was collected automatically in the application and later exported to a tabulated format.

3.1 Data

The data set used for the visualization contained extensive information about customers, products, campaigns and other parameters, however the visualized data was limited both for time constraining reasons during the development process as well as to not overwhelm a test subject since the interaction methods is the focus of the study. During the testing, some data was fabricated for consistency and confidentiality reasons although with the same structure as the original data. The ambition was to retain the same structure to allow the principal to use their own, real-world data for their own explorations when the academic purpose of the study was concluded.

3.2 Interaction methods

Although the final version of the application did include other forms of interaction (see chapter 5), the following two were the main methods evaluated throughout the study.

3.2.1 Binary filtering

Binary data filtering was carried out by selecting or deselecting a data dimension or a data set. For instance, the test subject was asked to only show data that includes a certain dimension. In the application created for the study, this dimension was defined by customers who own a particular product. The

filtering was done by pressing a button with your hand, making use of the hand controller. No buttons on the hand controller had to be pressed to interact with the button as you simply placed your hand on it and physically pushed down the button - just as you would in real life. The button then showed its current state - meaning if the filter was active or not - by emitting light to indicate an active state. When the filter was inactive, the button had a darker shade of its color as well as having a non-emissive material.

3.2.2 Defining intervals in continuous data ranges

This operation was similar to using a range slider in a web environment. In a web environment, a user can interact with a slider by clicking and dragging on the handle (the stop at the number 3 in figure 1). By doing so, the user can define a value with the slider. The range slider in the VR application had two stops, allowing the user to define a minimum and a maximum value, effectively defining an interval within the data range. The application for the test included range sliders as such, with the difference of it being made with 3D objects and the value handles were controlled by grabbing each handle with the controllers and then moving your hand. The grabbing mechanic was done by placing the hand controller over the handle and then pressing a button on the controller, imitating a grabbing interaction.

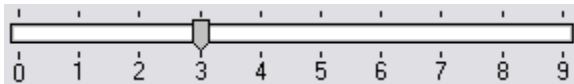


Figure 1. Range slider in a web environment.

3.3 Used software

To be able to create the application, several software solutions were used. The application consisted of two parts: a web-based backend to deliver the data in the needed format, and the VR application working as the frontend. Below are descriptions of the software solutions used for the experiments.

3.3.1 Unity3D

The VR application was created with Unity3D, a free-to-use game development platform supporting 2D and 3D as well as VR. Unity can deploy a project to a wide range of platforms such as PC, OSX, Android phones, WebGL and others. The VR application was written using C#, in Unity. Unity also allows for automatic logging of events within the application, enabling the collection of quantitative data as well as exporting the data in a tabulated format for further analysis.

3.3.2 SteamVR

SteamVR is a plugin for Unity used to give full VR functionality for the several types of VR headsets, for instance the HTC VIVE, within Unity.

3.3.3 VRTK

VRTK (Virtual Reality Toolkit) is an open-source plugin for Unity, which contains a collection of scripts and concepts to aid rapid production of VR applications. VRTK gives support for usable features and

interaction methods for the HTC VIVE within Unity, for instance several ways to pick up and interact with items as well as locomotion methods - ways to move around in VR.

3.3.4 Lumen

To make the data available to the VR application, an API connected to the data was created. The API was web-based, written in PHP and was created using Lumen, an open-source micro-framework made for building micro-services and API's. The API was connected to the database running PostgreSQL.

3.4 Implementation

Using the software solutions listed in 3.3, a VR application was built to conduct the usability tests regarding the chosen interaction methods. The application is best described as a three-dimensional interactive information visualization in VR. As this may be a complex concept to grasp, the functionality is broken down into modules as follows.

Since an iterative process was used during this study, there are two versions of the application - one used for the first test round, and one which contains changes to functionality implemented according to the feedback gathered from the first test round. Any functionality that was changed or implemented for the next iteration is therefore presented separately in chapter 5.

3.4.1 Graph container

The graph container, as seen in figure 2, was the main part of the visualization. The container itself was a virtual cube with a side length of approximately 65 centimeters. All edges except for the top four were rendered as lines in a gray color, to aid the user in seeing the bounds of the container. The reason why the top four edges were omitted was to minimize clutter.

Inside the container were all the data points. The number of data points was set to 675, a subjectively suitable value chosen during the development process with the motivation of it being not too many and not too few considering the size of the container and the size of the data points. Also taken into consideration was the rendering capabilities of the software, as a frame rate above 90 frames per second was desired in order to avoid motion sickness using the HMD. Too many data points reduced the frame rate significantly during the development process, which was a limiting factor for the number of data points.

Each data point represented one customer subscribing to one out of three broadband connections: 100 mbps, 250 mbps and 1000 mbps. Each data point was represented by a small cube, color coded according to the broadband connection the customer was subscribing to. The cube shape was chosen as it is cheaper to render compared to a sphere, enabling the application to render more data points. The color cyan represented the 100 mbps connection, magenta represented 250 mbps and yellow represented 1000 mbps. The material of the customer cubes was made semi-transparent to not completely occlude customers situated behind another customer from the user's perspective.

The data points were spatially positioned along the three axes of the container, depending on three data dimensions: age of customer, time as customer, and NPS. Age of customer meant simply how old the

customer was. Time as customer was a measurement describing how long the customer has been a customer of the company from which the data was borrowed. NPS is defined in 1.1.3. The dimensions' minimum and maximum values depended on the data set, although NPS always has a minimum value of 0 and a maximum value of 10. The data set was spread out on the entire length of the container axes, meaning that, for instance, the youngest customer was placed at one end of the container, and the oldest customer was placed on the opposite end of the axis.

The height of the graph container was chosen so that an adult of average height in Sweden comfortably could see the entire graph and its content. The average height was estimated to be approximately 175 centimeters, which resulted in an implementation which functioned without drawbacks for users between 165 and 190 centimeters.

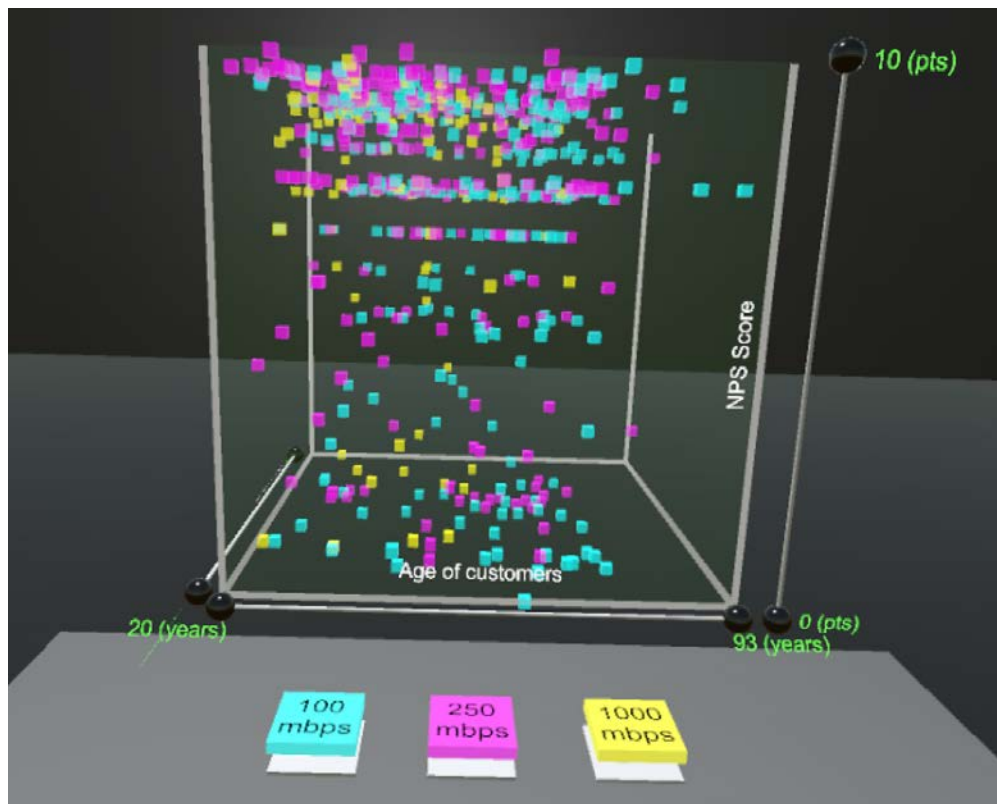


Figure 2. The graph container, product buttons and sliders of the first application version.

3.4.2 Product buttons

Functioning as a binary filter to the data set, the three product buttons were one of the main interaction methods evaluated. Each of the three products (broadband connections) visualized had one button used to display or hide the customers with that specific product. The buttons were colored according to the broadband type to give a visual indication of which button relates to which data. In addition to the color, the button had a label on top of the button with the broadband name, for instance “100 mbps”. The buttons were used by physically pushing a hand controller down on the button. The button followed the hand controller down for a little bit, until it stopped and “activated”. This means a user had to push the button all the way down for it to activate. When the button was activated, it either lit up or dimmed its

color depending on the current state of the button. If a button was “lit”, the color is emissive and strong which indicates an “on” state, meaning that the data points related to that product were currently shown in the graph container. When the button was in an “off” state, all data points related to that button were dimmed in a similar fashion as the button. When a button was touched by a controller, the interacting controller emitted haptic feedback in the form of vibrations. This enabled users to “feel” and use the buttons, even if they were not directly looking at the buttons.

The three buttons were placed in a horizontal row at the bottom of the graph container, parallel to the side, as seen in figure 2. The buttons faced upwards, to minimize the risk of accidentally pressing the controllers against the buttons, had they been rotated towards the user. Since the container had four sides where the user could possibly stand, a design decision was made to have the button row follow the user wherever he or she stood. This means that at any given time, there was only one row of product buttons visible to the user to avoid potential clutter that could be experienced if there were four sets of product buttons. Whenever a user walked to another side of the container, the product buttons appeared on the user’s side of the container.

Product button height was chosen to be at comfortable distance from the user’s head, viewable at an angle that was not straining on the neck in a standing position, as well as being easy to reach with their hands. Label size was made appropriate at a normal viewing angle, with button spacing small enough to easily keep the three buttons in the viewport at once. The buttons were placed to be reached from a resting arm position, with about a 90-degree elbow bend.

3.4.3 Sliders

Each axis of the graph container had a continuous data range which defined it. NPS was placed on the vertical Y-axis, and the two horizontal axes were “Age of customers” and “Time as customer”. The three axes each had a slider connected to it for the user to define intervals in the data range. The sliders were, in contrast to the product buttons, fixed spatially at the edges of the graph container.

There was one slider for each dimension. Each slider had two handles, effectively defining the minimum and maximum value of the interval in the data range. The handles could be moved by placing the hand controller onto the handle, holding down a button on the controller and then dragging the handle horizontally or vertically depending on the slider. To aid the user in selecting the wanted handle, an orange outline was triggered as the user placed the controller onto the handle. This behavior is demonstrated in figure 3. The handle followed the hand movement in real time along the slider axis (all movement in other axes was disabled), stopping where the user released the button on the controller. When a handle was moved, thus changing the interval, any data points outside of the data range were dimmed down to a less opaque, dark grey shade.

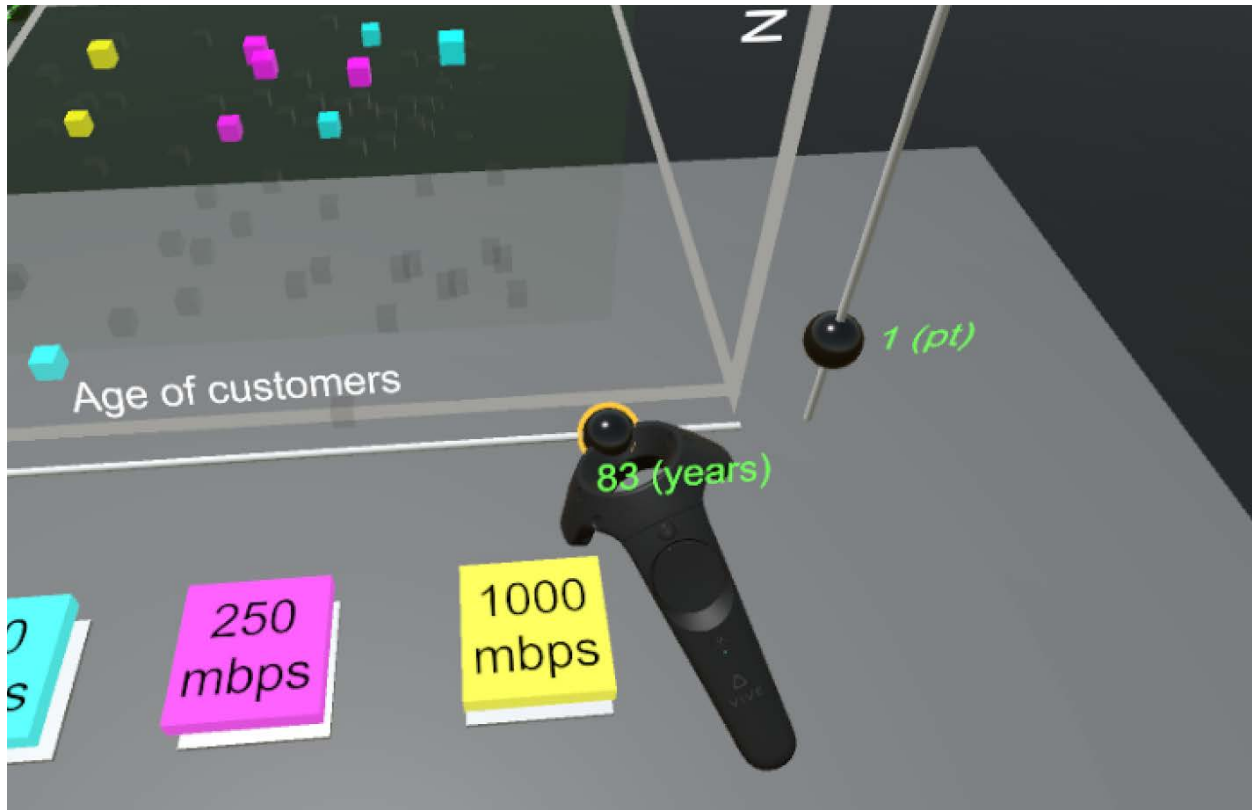


Figure 3. Orange outline highlight effect when touching controller on slider handle.

As seen in figure 2, the three sliders were spread out around the container. This decision was grounded in two arguments. First, having all three sliders in close proximity to one edge (if the vertical slider in figure 2 would instead have been placed on the left side of the container), legibility of the labels would have been compromised as well as selection of the wanted slider handle would have been made more difficult. Second, by placing the three sliders on separate edges, a user is “forced” to move around the container, prompting more depth cues by physically moving around, which enables users to gain perception regarding the geometric structure of the data points visualized.

Slider length was made equal to graph container side length, meaning that the filtering interaction was scaled 1:1 to the movement of the slider handles. To ease the task of spatially filtering out a subset of data points, the decision to have the sliders’ range be the full length of the container was made during internal testing of the application, as the interaction was subjectively perceived as more intuitive using the full length of the container sides.

Each slider handle had a text label fixed to it, as seen in figure 3. If the handle was moved, the label moved with it to easily keep track of changes in value. As the handle was moved, the value in the label updated in real-time. The labels of each slider were placed as to not intersect with each other even if the handles were moved right next to each other. A collision of the text labels would otherwise decrease legibility.

To aid the user in setting the interval ranges correctly, a faint green, semitransparent three-dimensional box was implemented to show the currently defined area within the graph container. This box is referred to as the highlight area and contained all data points currently highlighted, demonstrated in figure 4. The

sides of the highlight area followed the handles of each slider in real time as they were moved, giving visual feedback to the user. The highlight area was implemented during internal testing as a visual aid when defining intervals using the sliders.

3.4.4 Off-hand display

To aid the user in counting the amount of data points currently selected, a display panel was implemented, showing the number of currently visible customers. This panel was placed on one of the controllers, in what could be described as a wristwatch position as seen in figure 4. Since the controllers of the HTC VIVE can be held in either hand without any difference in functionality, participants were asked to hold the controller with the display in their off-hand to minimize interference with their interactions, which are likely to be conducted mostly with their dominant hand - something that was discovered during internal testing of the application as well as during the pilot study.

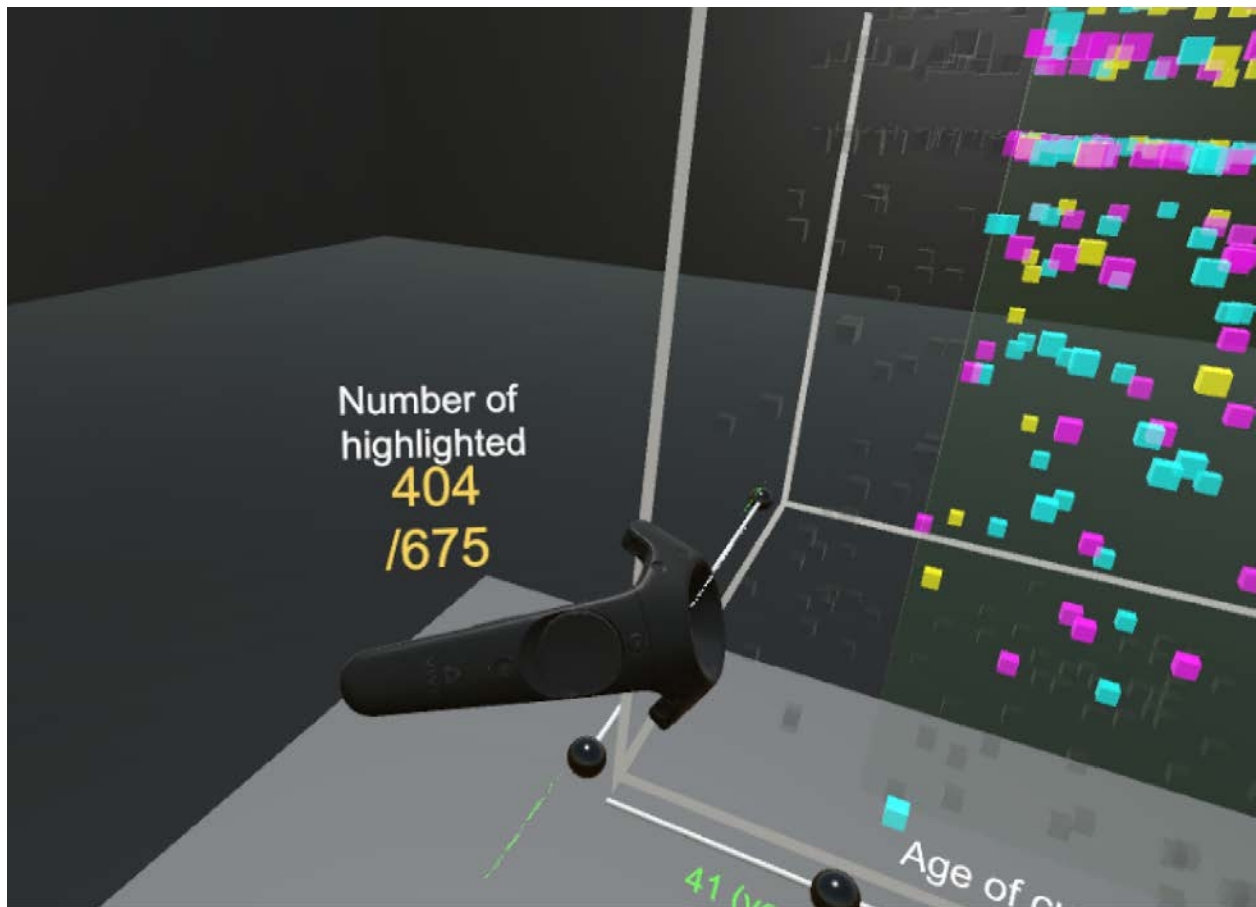


Figure 4. Off-hand display and highlight area demonstrated.

The display contained the number of currently displayed customers as well as the total number of customers. To increase readability, the display was always rotated perpendicular towards the eyes.

3.4.5 Environment

The environment was kept minimal with the purpose of not being intrusive to the experience as well as to give focus to the visualization itself. The environment consisted of four dark gray walls and floor with a slightly brighter shade of gray, so users would not feel uncomfortable standing in complete darkness. A dark gray shade was chosen to contrast the rather bright colors of the data points. The floor in the so called “play area”, the physical region of movement in which the user freely can walk around without bumping into things in the room, was made brighter to strengthen the feeling of importance around the visualization as well as to guide users not to go beyond that area. Neither the walls nor the floor were textured, to keep focus on the visualization.

No custom 3D models were used for the controllers, the ones used are the standard models used in the SteamVR plugin for Unity.

3.5 Process

After creating the VR application, impressions were gathered by letting test subjects explore the interactions and the interface to carry out pre-determined tasks in VR. After testing the VR application, parts of the Presence Questionnaire (Witmer & Singer, 1998) was filled out by the participant. Following that, semi-structured interviews with the test subjects were conducted to gain qualitative data regarding the functionality of the interactions. By conducting semi-structured interviews, there was room for the test subjects to expand on areas they found interesting, which gave further detailed opinions on the functionality. The tests focused on the intuitiveness and familiarity of the interactions within the virtual environment. No benchmarks were made with the purpose of comparing test subjects, however usage data was collected to gain quantitative data.

Browsing the data with the help of common visualization operations such as filtering on different dimensions are the basis of the interaction. Having two motion tracked hand controllers enables the user to freely explore and interact with virtual objects and thus the visualization itself, potentially spawning new ways to carry out the operations in more perceptually intuitive ways.

3.5.1 User tests

To evaluate the interaction methods created for the study, two rounds of user tests were conducted, as well as a pilot study to eliminate early usability problems and identify problems with the test plan. In between the user tests, a design iteration was done in which fixes for the problems found during the first test round were attempted. An iterative process was chosen in order to effectively pinpoint and fix potential issues with the interaction methods and the application usability in general, as suggested by Nielsen & Landauer (1993).

The tests were created along the guidelines of Rubin & Chisnell (2008) on how to plan, design and conduct user tests. This included the work of creating a test plan which served as a blueprint for the tests. The reason of creating a test plan is to have a solid foundation on aspects such as how, why and what to test.

3.5.2 Pilot study

During the pilot study, the test plan was tried out for the first time in order to rule out any obvious problems with the method. It also served the purpose of preparing both moderator and observer for the testing process, to get used to the setting and situations that may arise during the evaluations. The pilot study included two participants with minimal VR experience, expert/intermediate experience of data filtering as well as expert experience with information visualizations (minimal, intermediate and expert experience as defined in table 1 in section 4.4).

The pilot study showed that some phrasings for the tasks had to be revised for clarity. In addition, the pilot study showed the need for some fixes regarding the quantitative data logging of user behavior done automatically by the application during the tests.

3.5.3 Demo scene

Separate from the application created for the study, a demonstration scene was used by test participants with non-expert experience with VR. The scene is a pre-created scene, found in the VRTK plugin for Unity.

The demo scene is run for two main reasons. First, an inexperienced user must get comfortable in the virtual environment as well as learn the controls, mainly the button placement and understand what button does what on the controllers. The second reason is to decrease the novelty effect that inexperienced users commonly experience when they enter a virtual environment for the first couple of times. The usual reactions that a new participant who never used a HMD along with motion tracked hand controllers includes those regarding the accuracy of the motion tracking, and expressions about how “real” the virtual environment seems. This novelty effect could affect the participant’s feedback regarding the application, which is why an accustomization period in a demo scene is important for the feedback.

The demo scene contained several interactive elements such as buttons, sliders, knobs, balls and other basic interactable objects. The buttons and the sliders functioned the same way as the ones used in the application created for the study, however the hand controller button used for interacting with the sliders was not the same. The scene was run for about five minutes, or whenever the participant felt comfortable with the environment, the hardware and the interaction methods.

4 Test plan

We are familiar with data filtering interactions in a web based environment. This could for instance be how we search and filter for products in a web shop, or using an interactive graph. However, we do not currently have a standard on how the same operations should be done in an immersive virtual environment. This leads to an uncertainty when creating interfaces, which can be helped by exploratively testing the usability of the design proposals to create a usability baseline.

A test plan was created to have a clear structure of the evaluation process and make sure the tests were performed the same way every time.

Here follows the test plan created and used for all user tests.

4.1 Overall objectives for the study

The study aims to gather baseline data about the overall usability of the filtering interactions. The goals of this study are to:

- Assess the overall perceived naturalness of the filtering interactions in VR, for different types of users performing basic, common tasks.
- Identify obstacles regarding filtering interactions in VR.

4.2 Relevant questions

In addition, this study will try to answer these questions:

- How can we translate common data filtering operations such as binary selections and defining intervals in continuous data ranges in VR for use with motion tracked hand controllers?
- How natural does interacting with buttons and sliders in VR feel?
- How easy is it to define intervals using sliders? Is it possible to define the numbers wanted precisely?
- How well does the visualization follow/respond to the filtering operations?
- Do the interaction methods work as expected?
- Do the interaction methods give the participant enough feedback?
- How does room scale immersion affect the user when trying to carry out the given tasks?

At the end of the sessions, quantitative data is gathered:

- Number of interactions – how many times buttons/sliders were used.
- Number of rotations - how many times the user has changed his/her physical position around the visualization (a 90-degree shift, with the pivot point in the middle of the visualization, counts as one “move”).
- Time using sliders – how long the user has held the sliders grabbed.
- Time to completion – per task and all tasks.

Qualitative data is also gathered:

- The verbal protocol – the running commentary that participants make as they think aloud – will give us indicators about what participants were confused by and why.
- Semi-structured interviews after the test sessions will tell what stands out about the experience of using the interaction methods, which should help to set priorities on potential changes to the interactions.

4.3 Location and setup

A controlled setting will be used to conduct the test sessions. The study will take place in the Visualization Studio (VIC) at KTH. The room will be closed off for other people so that we do not get disturbed during the sessions. Participants will use a Windows PC with Unity running the VR application, as well as a virtual machine running on the same PC to provide access to data via the API. The PC the participant uses will have a HTC VIVE HMD and hand controllers connected. During the tasks in the VR application, the PC monitor will mirror what the participant sees and does, to control and monitor the tasks. I will use a smartphone during the semi-structured interviews to record the participant's answers, in addition to the notes that will be written down during the interview.

4.4 Recruiting participants

Participants who have a wide variety of experience using VR applications will be chosen. They will be people who have used data filters in a web environment before, however they do not need to be experts within the subject. The participants do not need any previous experience with VR, however it is interesting to see how previous VR experience affects the participant's performance which is why this factor will be varied.

Excluded from the study are people who are unaware of or extremely inexperienced regarding data filtering operations. This is done to test the recognition factor of the interaction methods.

For the test sessions, approximately 12 participants will be recruited, with the desired characteristics outlined in table 1. According to Nielsen & Landauer (1993), a study based on iterative design with fewer test participants per test session is more effective than one large user test when it comes to finding usability problems, which is why this study is designed to test two versions with one design iteration between the sessions. The authors argue more iterations are better, increasing measured usability by 38% per iteration. The reason why this study will only iterate its design once, conducting two user test rounds, is simply time constraints.

Characteristic	Desired number of participants
Participant type	
pilot	2
session #1	6
session #2	6
Total number of participants	12 (+2 in pilot)
VR experience	
<i>none</i> : never used VR	2
<i>minimal</i> : 1-3 times used VR	3
<i>intermediate</i> : 4-9 times used VR	3
<i>expert</i> : 10 or more times used VR	4
VR experience with motion tracked hand controllers	
<i>none</i> : never used VR with motion tracked hand controllers	2
<i>minimal</i> : 1-3 times used VR with motion tracked hand controllers	3
<i>intermediate</i> : 4-9 times used VR with motion tracked hand controllers	3
<i>expert</i> : 10 or more times used VR with motion tracked hand controllers	4
Data filtering experience	
<i>minimal</i> : use filtering operations once of a few times per month	2
<i>intermediate</i> : use filtering operations once or a few times per week	6
<i>expert</i> : use filtering operations daily	4

Table 1. Desired test participant characteristics.

4.5 Methodology

This usability study will be exploratory. Assessment data will be gathered about the usage of the proposed interaction methods. Participants will first fill out a pre-study questionnaire to indicate their previous experience with VR and data filtering operations. The pre-study questionnaire will quickly be looked through when the participant completes it, to get an overview of the previous experiences the participant has with VR and data filtering operations. Unless the participant is very used to using VR with motion tracked hand controllers (has checked VR experience with motion tracked hand controllers as “expert” according to table 1), the participant will put on the HMD and the controllers and play around a couple of minutes within the demo scene described in section 3.5.3 to get comfortable with the hardware setup.

Following some initial time getting used to VR in the demo scene, participants will be put within the test application in which the actual testing will be carried out. They will be given several tasks regarding the information visualization and the filters. The first number of tasks will be predefined, and the last one will be a larger open-ended task in which the participant will be asked to find correlations in the data, or simply aspects of the data they find interesting. During all tasks excluding the larger open-ended task, participants will be asked to think aloud, meaning they will be asked to describe their actions and thoughts as they complete the tasks. This is done in order to more easily pinpoint issues with the usability

of the application. Participants will not have to think aloud during the final task, however they will be asked to describe and talk about their findings.

Following the tasks in VR, the participant is asked to fill out relevant parts of the Presence Questionnaire, designed by Witmer & Singer (1998). Following that, a semi-structured interview will take place in which the participant is able to talk freely about their impressions during the test session.

Communication with the participants will be done by voice while they are using the HMD and participants will be asked to reply by voice as well. Log data will be automatically collected in Unity regarding the filter usage as well as qualitative data in semi-structured interviews about the participants' experiences using the application.

4.5.1 Usage of between-subjects design

In this between-subjects study, each participant will work through one task path. I will conduct approximately 14 individual 60-minute usability study sessions. Each participant will perform one of three task "paths" using the VR application.

4.5.2 Session outline and timing

The test sessions will be around 60 minutes long. I will use 20 minutes of each session to explain the session to the participant, review basic background information with the participant and then introduce the participant to VR and the interaction methods to be used in the study. Following the introduction is the testing which will go on for about 20 minutes to carry out several tasks using the interaction methods within the VR application. During the last 20 minutes of the session, the participant will fill out the presence questionnaire and I will conduct a post-test semi-structured interview with the participant. The sessions will take place at the Visualization Studio at KTH.

Pre-test arrangements

Have the participant:

- Fill out the pre-study questionnaire.

Introduction to the session (10 minutes)

- Review and sign recording permissions.

Discuss:

- Description of the study.
- Participant's experience with usability studies and focus groups.
- Importance of their involvement in the study.
- Moderator's role.
- Room configuration, recording systems, observer, etc.
- The protocol for the rest of the session.
- Thinking aloud.

Fill out pre-study questionnaire (5 minutes)

In which the participants describe their:

- Experiences with VR (with and without motion tracked hand controllers).
- Experiences with data filtering operations.

Trying out a demo scene in VR (5 minutes)

If needed, the test participant will spend a few minutes within the demo scene for the purpose described in section 3.5.3, otherwise this step is skipped.

Tasks (20 minutes)

Participants will carry out a series of predetermined tasks using the filters for the information visualization. The final task is an open-ended task in which the participant will be asked to find correlations in the data, or simply describe aspects of the data they find interesting.

Fill out Presence Questionnaire (5 minutes)

Directly after the participant finishes the tasks, the participant will be asked to fill out the Presence Questionnaire, in which he or she evaluates the sense of presence in the VR application. The reason why they fill it out immediately after finishing the tasks is to have the experience fresh in their minds.

Here follow the questions and the scales to define the answers chosen from the Presence Questionnaire. Questions regarding sound has been omitted, as there was no sound implemented in the application.

The scale of the answer alternatives goes from 1 to 7 and is written as a nested list item to the question, separated with a dash. The leftmost text description describes the value 1, the middle text description describes the value 4 and the rightmost text description describes value 7.

- How much were you able to control events?
 - NOT AT ALL - SOMEWHAT - COMPLETELY
- How responsive was the environment to actions that you initiated (or performed)?
 - NOT RESPONSIVE - MODERATELY RESPONSIVE - COMPLETELY RESPONSIVE
- How natural did your interactions with the environment seem?
 - EXTREMELY ARTIFICIAL - BORDERLINE - COMPLETELY NATURAL
- How much did the visual aspects of the environment involve you?
 - NOT AT ALL - SOMEWHAT - COMPLETELY
- How natural was the mechanism which controlled movement through the environment?
 - EXTREMELY ARTIFICIAL - BORDERLINE ARTIFICIAL - COMPLETELY NATURAL
- How compelling was your sense of objects moving through space?
 - NOT AT ALL - MODERATELY COMPELLING - VERY COMPELLING
- How much did your experiences in the virtual environment seem consistent with your real world experiences?
 - NOT CONSISTENT - MODERATELY CONSISTENT - VERY CONSISTENT
- Were you able to anticipate what would happen next in response to the actions that you performed?
 - NOT AT ALL - SOMEWHAT - COMPLETELY
- How completely were you able to actively survey or search the environment using vision?
 - NOT AT ALL - SOMEWHAT - COMPLETELY

- How compelling was your sense of moving around inside the virtual environment?
 - NOT COMPELLING - MODERATELY COMPELLING - VERY COMPELLING
- How closely were you able to examine objects?
 - NOT AT ALL - PRETTY CLOSELY - VERY CLOSELY
- How well could you examine objects from multiple viewpoints?
 - NOT AT ALL - SOMEWHAT - EXTENSIVELY
- How involved were you in the virtual environment experience?
 - NOT INVOLVED - MILDLY INVOLVED - COMPLETELY ENGROSSED
- How much delay did you experience between your actions and expected outcomes?
 - NO DELAYS - MODERATE DELAYS - LONG DELAYS
- How quickly did you adjust to the virtual environment experience?
 - NOT AT ALL - SLOWLY - LESS THAN ONE MINUTE
- How proficient in moving and interacting with the virtual environment did you feel at the end of the experience?
 - NOT PROFICIENT - REASONABLY PROFICIENT - VERY PROFICIENT
- How much did the visual display quality interfere or distract you from performing assigned tasks or required activities?
 - NOT AT ALL - INTERFERED SOMEWHAT - PREVENTED TASK PERFORMANCE
- How much did the control devices interfere with the performance of assigned tasks or with other activities?
 - NOT AT ALL - INTERFERED SOMEWHAT - INTERFERED GREATLY
- How well could you actively survey or search the virtual environment using touch?
 - NOT AT ALL - SOMEWHAT - COMPLETELY
- How well could you move or manipulate objects in the virtual environment?
 - NOT AT ALL - SOMEWHAT - EXTENSIVELY

Post-test interview (15 minutes)

The purpose of the interview is to ask broad questions to collect preference and other qualitative data.

The following questions will be used as a basis for the interview, with the follow up questions (nested list items) used for clarification and further explanations regarding the main question:

- How did it feel to use the product highlight buttons?
 - Did they seem as if they were real to you?
 - Did they react as you thought they would when you used them?
- How did using the different sliders feel?
 - Was there any difference between the sliders?
 - Did they seem as if they were real to you?
 - Did they react as you thought they would when you used them?
- How did you use the interaction methods?
 - Did they help you understand the data?
 - What was the most useful/useless filter?
- Did the interaction methods fit the data set?
 - What could have been other appropriate/inappropriate interaction methods?
- Did you get any sort of feedback when using the product highlight buttons?

- Visual?
- Haptic?
- Audible?
- Did you get any sort of feedback when using the sliders?
 - Visual?
 - Haptic?
 - Audible?
- Did you think the tasks were difficult to carry out?
 - Why/why not?
- Did you feel like you had control over the filters?
 - Did you have to do something specific to use certain filters?
- Did you feel like there was something missing, or something that could be changed regarding the interaction/filters?
- Other questions?

The following questions were added after the first test round had been concluded and the design iteration had been implemented.

- How did it feel to use the “reset filters” button?
 - Did the functionality seem necessary to you?
- How did it feel to get details on demand by clicking an individual customer?
 - Did you use the feature a lot?
 - Did the feature help you? If so, how?
- Did you find any use of the panel on your off-hand?
 - Why did you use it?
 - Did the feature help you? If so, how?

Depending on opinions and issues which may arise during the tasks:

- Follow up on any particular problems or insights that came up for the participant.

4.5.3 Moderator role

I will sit in the room with the participant while conducting the session. I will introduce the session, let the participant fill out a short background form, and then introduce tasks as appropriate. Because this study is exploratory, I may ask unscripted follow-up questions to clarify participants’ behavior and expectations. I will also take detailed notes and record the participant’s behavior and comments.

After each session, I will debrief with one other observer. I will ask the other observer to contribute their observations about surprises and issues and we will continue to identify and tally those throughout the sessions. This way, the observer has an active part in the sessions and we may reach consensus about key issues before analyzing the test results in order to iterate the design.

Using my notes, the recordings and the quantitative data gathered from automatic logging, I will tabulate and analyze the data to answer the research questions (listed in the Research questions section of this document) with findings and recommendations.

4.6 Tasks

In order to counterbalance learning transfers that may appear when doing tasks in a specific order, I will use three different task “paths” for the participants to use. I will spread out the tests on the different paths as well as possible to not get skewed results, affected by learning transfers. All the task paths contain all tasks, with the only difference being them being carried out in a different order.

Here follows a list of all the tasks:

1. What are the minimum respectively maximum values of the “Age of customer” slider?
2. Filter out customers who are 50 years old and older, with an NPS score from 6 to 10
3. What is the total number of customers within category 1 (100 mbps)?
4. How many customers are there for each product category, in total?
5. How old is the oldest customer within category 3 (1000 mbps)?
6. Are there more customers with an NPS score of 8 and above, compared to 7 and below, for customers within product category 2 (250 mbps)?
7. Which product has the most customers in the age interval 20-40 years old?
8. Have more customers registered in the last 10 months, or before?

The three paths are defined as follows:

- Path #1, tasks in the following order: 1, 2, 3, 4, 5, 6, 7, 8
- Path #2 (reversed), tasks in the following order: 8, 7, 6, 5, 4, 3, 2, 1
- Path #3 (semi-random), tasks in the following order: 5, 7, 4, 8, 2, 6, 1, 3

5 Design iteration

During the first test round, some usability problems and desired features were identified. Here follows a list of changes to the functionality, look and feel that were identified during the first test round and applied to the second design iteration of the application.

- **Problem:** Direction for “Time as customer” axis is wrong.
 - **Explanation:** Common feedback identified the desire of having the low value to the left in the axis direction. Having low values to the left made it feel more like a general 2D graph, which was the desire of some participants as they were used to that form of visualization.
 - **Solution:** The solution was to invert the axis direction, putting new customers to the far left on the axis.
- **Problem:** The sliders do not have any haptic feedback.
 - **Explanation:** Some participants noticed that the sliders did not have any haptic feedback like the buttons, and therefore mentioned that haptic feedback for the sliders would both increase consistency in the application as well as increase the usability of the sliders. Haptic feedback was considered a positive effect which increased the physical illusion of the interface.
 - **Solution:** Haptic feedback was implemented in two ways on the sliders. Feedback was received when first touching the slider handles, as well as each time the sliders were moved to toggle the visibility of a customer. The haptic feedback was thus more prominent when moving the slider handle through an area with a dense population of customers as compared to when moving the handle past an area where the customer population was sparse.
- **Problem:** It is hard to identify the precise values of one specific customer.
 - **Explanation:** Participants tried to “click” a customer by hovering their controller over a customer and then clicking a button on the controller with the thought that it would bring up details on demand for that specific customer. When asked why they wanted to carry out that interaction, the explanation was an experienced difficulty of pinpointing exact values of a customer’s data dimensions.
 - **Solution:** A “details on demand”-system was implemented with the exact functionality described in the problem explanation. When clicking a customer, a display panel similar to the off-hand display appeared next to the dominant hand controller with the values of all dimensions for the selected customer. The display was hidden by clicking the same button on the controller while not hovering over a customer, imitating a “deselection” operation found in many desktop visualization systems. A semitransparent background was used to not occlude the data points. Furthermore, when hovering the controller over a customer, a short haptic pulse similar such as the one experienced when hovering over a slider handle was sent through the controller to trigger a cue of interactivity for the user. The same kind of highlight effect was also implemented on the customer cubes when hovered upon, as seen in figure 5. The visual and haptic feedback was implemented to strengthen the feeling of interactivity as well as to retain continuity regarding interactive elements.



Figure 5. Details on demand display shown on the dominant hand when selecting a customer.

- **Problem:** Axes description labels and slider value labels can be seen from behind, cluttering the view from other sides.
 - **Explanation:** Participants in the first test round noted that the labels describing the different axes, as well as the labels showing the values for the sliders' handles, were visible while viewing them from behind. This was experienced as disruptive as the text when read from the backside was mirrored, making it hard to read. In addition, the “time as customer” max value handle label and the “age of customer” min value handle label intersected as the filters were reset, interfering with the readability as seen in figure 6.
 - **Solution:** All text labels were hidden when viewed from behind.

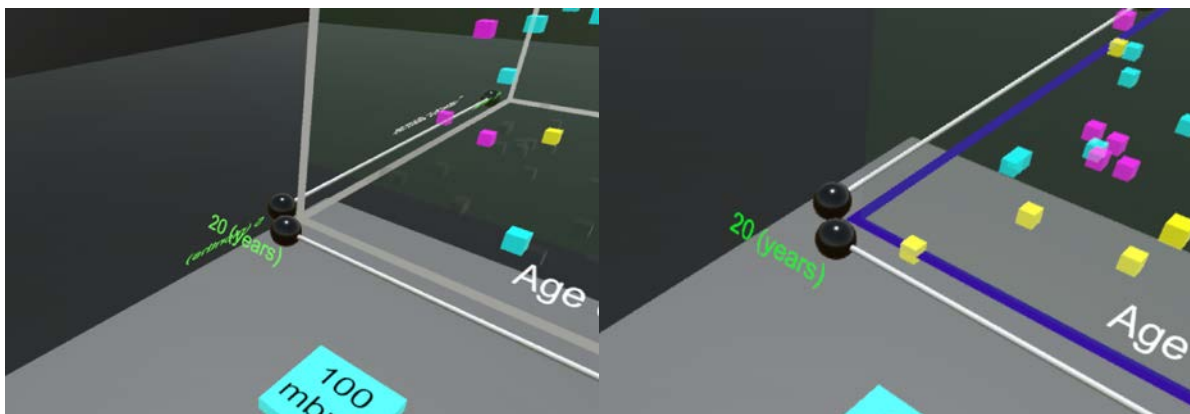


Figure 6. Readability issues. First iteration on the left, second iteration on the right

- **Problem:** It is hard to compare two customer groups, you must calculate the ratio yourself.
 - **Explanation:** A common operation during the tasks was to compare two customer groups. The first design iteration off-hand display was limited in the sense that it only contained the number of customers visible compared to the total number of customers.
 - **Solution:** The off-hand display was upgraded to contain information about the total number of customers visible, as well as the number of customers within each product category currently visible. Instead of always showing the total number of data points in the data set, a number showing the percentage of the currently visible customers

compared to the total number of customers was implemented, as seen in figure 7. A semitransparent background was used to not occlude the data points.



Figure 7. Off-hand display. First iteration to the left, second iteration to the right.

- **Problem:** Resetting the filters requires the user to manually reset each filter to the starting position.
 - **Explanation:** Some users asked if there was some way to reset all the filters to their starting positions, showing all customers. Suggestions were received to implement a reset button on the controller.
 - **Solution:** A reset button was implemented and bound to a button on the dominant hand controller. When pressed, the filters automatically reset themselves to show all customers with all customers.

Other changes that were not specifically identified by the participants during the first test round were also implemented in the second design iteration:

- Faded customers received a shade of their product color, to be able to distinguish also the faded customers.
- The axes which had sliders attached to them were colored blue to help users spatially navigate themselves, had they moved around a lot.
- The graph container was moved up slightly to better suit the average length of the participants.
- Slider handle labels for the vertical NPS slider were made to always be rotated in one axis towards the user's eyes in order to increase readability, as seen in figure 8.

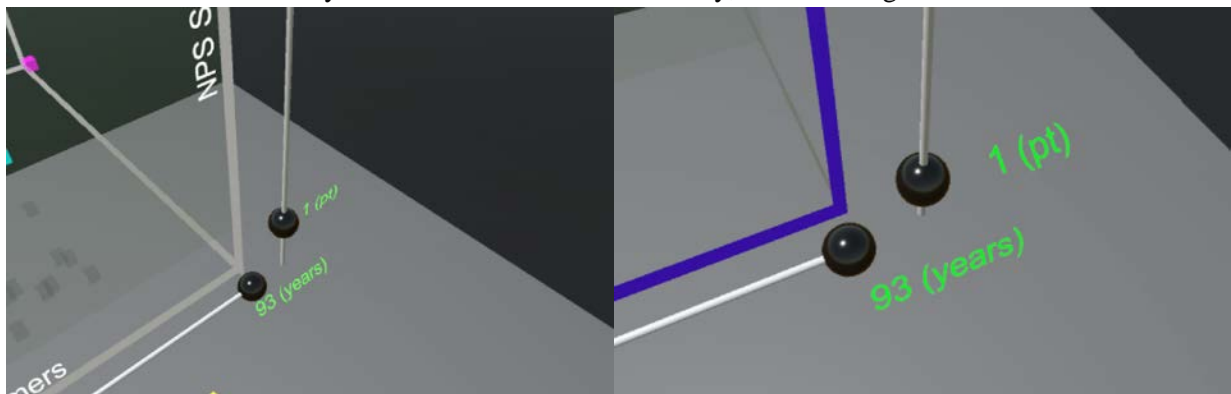


Figure 8. NPS slider label rotation. First iteration to the left, second iteration to the right.

6 Results

6.1 Participants

All participants voluntarily participated in the study. Table 2 shows the outcome of the desired test participant characteristics. For the second test round, one additional participant was recruited as time allowed for it. The demographic was close to what was initially desired, with a slight skew towards experienced VR users. The outcome of the data filtering experience characteristic was as close to the desired distribution as possible.

Characteristic	Actual number of participants
Participant type	
pilot	2
session #1	6
session #2	7
Total number of participants	13 (+2 in pilot)
VR experience	
<i>none</i> : never used VR	0
<i>minimal</i> : 1-3 times used VR	4
<i>intermediate</i> : 4-9 times used VR	2
<i>expert</i> : 10 or more times used VR	6
VR experience with motion tracked hand controllers	
<i>none</i> : never used VR with motion tracked hand controllers	1
<i>minimal</i> : 1-3 times used VR with motion tracked hand controllers	3
<i>intermediate</i> : 4-9 times used VR with motion tracked hand controllers	4
<i>expert</i> : 10 or more times used VR with motion tracked hand controllers	5
Data filtering experience	
<i>minimal</i> : use filtering operations once of a few times per month	2
<i>intermediate</i> : use filtering operations once or a few times per week	7
<i>expert</i> : use filtering operations daily	4

Table 2. Actual outcome of participant characteristics.

6.2 Presence Questionnaire

The form was given to the participants directly after finishing the tasks in the application.

Conducting a cluster analysis on the results of the Presence Questionnaire allows scoring of the different subscales identified by Witmer & Singer (1998). Each question can be found presented separately in the appendix. Here follow the subscales analyzed in this study:

- INV/C: Involvement/Control

- NATRL: Natural
- HAPTC: Haptic
- RESOL: Resolution
- IFQUAL: Interface Quality

In figure 9 are the calculated values for each subscale, divided between the two design iterations while figure 10 contains the standard deviation.

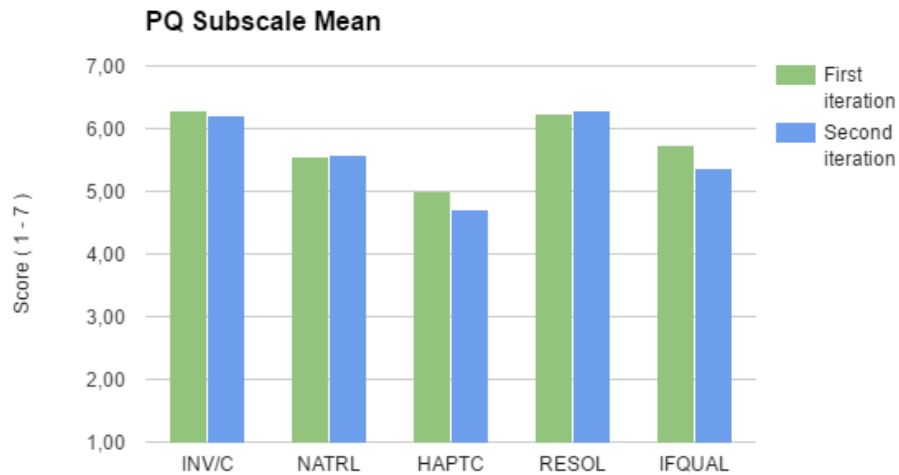


Figure 9. Presence Questionnaire subscale mean.

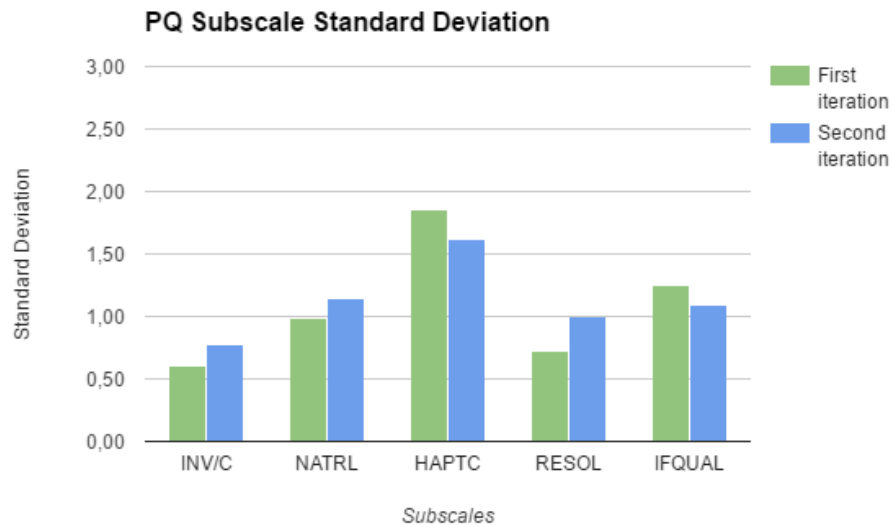


Figure 10. Presence Questionnaire subscale standard deviation.

The cluster analysis shows that the scores for the subscales are very close between iterations, which indicates that the second design iteration did not significantly affect the perceived presence for the application.

6.3 Predetermined tasks

The predetermined tasks were the first eight tasks the participants were given. Each task except task #2 had three possible outcomes:

- Correct: participant read the correct numbers and set the filters correctly for the task
- Wrong (filters): participant set the filters incorrectly, resulting in a wrong answer
- Wrong (read): participant set the filters correctly, but gave the wrong answer. This option was not an alternative for task #2 as the participant was not asked to read a number.

All participants attempted all tasks. Listed below are the results for the tasks which did not have a 100% success rate.

#2 Filter out customers who are 50 years old and older, with an NPS score from 6 to 10		#3 What is the total number of customers within category 1 (100 mbps)?	
	Count		Count
CORRECT	11	CORRECT	13*
WRONG (FILTERS)	2	WRONG (FILTERS)	0
		WRONG (READ)	0

Table 3. Predetermined tasks #2 and #3.

* Participant 13 corrected himself after first giving a wrong answer, as he realized in the following task that he did not reset the filters before reading the number.

#6 Are there more customers with an NPS score of 8 and above, compared to 7 and below, for customers within product category 2 (250 mbps)?		Count
CORRECT		10
WRONG (FILTERS)		1
WRONG (READ)		2

Table 4. Predetermined task #6.

The eight tasks were completed in between approximately four and ten minutes with a mean completion time of approximately six and a half minutes.

The two read errors were due to participants reading the percentage of the total number of participants shown, not the percentage of the customers with the 250 mbps connection. The three filter errors were caused by participants not resetting the filters when they got the instructions for the task.

6.3.1 Task paths

The desire was to evenly distribute the participants on the three task paths. The actual distribution along with the number of wrong answers in the first eight tasks is presented in table 5 and table 6.

The reason why the distribution was uneven was forgetfulness during the testing, as well as a discovery which made one task in the reversed task path redundant. The task in question was task #3, which was already answered in task #4 which came directly before task #3 in the reversed task path.

First test round

The first test round contained six participants.

Task path	Count	Number of errors
Path #1 (NORMAL)	5	0
Path #2 (REVERSED)	1	0
Path #3 (SEMI-RANDOM)	0	0

Table 5. Task path distribution and number of errors for the first test round.

During the first test round, there were zero errors recorded during the tests.

Second test round

The second test round contained seven participants.

Task path	Count	Number of errors
Path #1 (NORMAL)	2	0
Path #2 (REVERSED)	1	1
Path #3 (SEMI-RANDOM)	4	4

Table 6. Task path distribution and number of errors for the second test round.

The second test round contained all five wrong answers. Looking at the number of errors measured with each task path, 80% of all wrong answers were measured in the semi-random task path while none of wrong answers were measured in task path #1. The total number of tasks attempted was 104 which gives an error rate of approximately 4.8% over the two test rounds.

6.3.2 Data logs

The automatic data logging consisted of five data sources during the first test round, and seven during the second test round as interactions were added. The data logging was split over the two parts of the testing process: the predetermined tasks, and the open task. Presented below are the logs for the predetermined tasks.

Due to a mistake during the testing, one participant's results in the second test round were not recorded during the predetermined tasks.

Data source	Test round	Min	Max	Avg.	Std. dev.
Product button clicks	1	22	47	32.5	9.1
	2	4	68	24.3	22.2
Slider usages	1	18	48	31.8	12.7
	2	7	34	19.2	9.7
Total slider usage time	1	34.3s	94.1s	62.2s	24.1s
	2	30.9s	77.7s	49.6s	19.7s
Container side changes	1	2	12	4.2	4
	2	1	6	3	2.1
Time to complete (all 8 tasks)	1	245.4s	521.7s	358.7s	99.7s
	2	350.1s	582.9s	438.2s	84.4s
Reset button clicks	1	N/A			
	2	3	7	4.7	1.5
Detail on demand clicks	1	N/A			
	2	1	15	5.7	5.0

Table 7. Quantitative data logs during the predetermined tasks.

Below are the logs for the open task.

Data source	Test round	Min	Max	Avg.	Std. dev.
Product button clicks	1	31	218	86.8	68.3
	2	10	115	40.9	37.7
Slider usages	1	21	51	34	11.8
	2	15	80	46	26
Total slider usage time	1	59s	122.4s	88s	25.4s
	2	44.1s	255.3s	126.6s	77.8s
Container side changes	1	5	30	14.2	8.4
	2	8	48	22.3	14.7
Time to complete	1	438.3s	832s	561.8s	144.9s
	2	312.4s	1222.2s	846.2s	313s
Reset button clicks	1	N/A			
	2	0	5	2.3	1.6
Detail on demand clicks	1	N/A			
	2	0	49	10.6	18.1

Table 8. Quantitative data logs during the open task.

As seen in table 7 and table 8, all average usage statistics except for reset button clicks are significantly higher during the open task. Reset button clicks were almost halved in the open task, even though an average time to complete time that was approximately 75% higher during the open task.

Comparing the two test rounds, the second test round had generally less interactions during the predetermined tasks, even though a longer average time to complete the tasks. This may indicate that due to the changes and functionality introduced in the second test round, the same amount of filtering interactions was no longer needed in order to solve the tasks.

6.4 Semi-structured interview

Here, participants' feedback and answers during the interview are presented. For the sake of conciseness, key points regarding the research questions presented in the test plan will be aggregated, presented along with a few citations from the interviews.

6.4.1 Button interaction

All participants agreed that the product buttons were easy to understand and use. Eight participants said that the buttons felt real to a certain degree. All participants noted the visual feedback of the buttons and agreed that it helped them to understand when a button was used and which state the button currently was in. Regarding the haptic feedback implemented on the buttons when the controllers touched them, only seven out of the 13 participants said that they experienced any haptic feedback.

P2: If I recall correctly, [the buttons] vibrated when I clicked them also, which was a very good feature as you understand that it really worked, that you pushed down the button so that you don't have to assume that you did.

Participants' common reactions to the functionality of the buttons were that the button interaction felt natural in general. About half of the participants mentioned that initially, they were unsure exactly how to interact with the buttons. The most common factor which confused them was whether they were supposed to press a button on the controller to interact with the buttons or not. After realizing they did not have to press anything on the controller to interact with the buttons, the interaction was mainly described as intuitive and natural.

P4: At first, I was surprised, because [the buttons] did not react as I had thought. From previous VR experience, I thought that I was supposed to use the trigger, hover [the buttons] and use the trigger, but you told me that the grip button was used so I thought I was supposed to hover them and press the grip. But I noticed partly haptically and visually that I had pressed [the button] so there were no problems understanding what had happened, and after that I think it worked really well when I knew how to use [the buttons].

One participant did not feel the buttons did what he wanted. After resetting the filters, effectively turning all buttons to the "on" state, making all data points visible, the participants pressed one of the buttons with the intention of only showing that product. Instead, the button push did the opposite of the participant's desired effect, hiding the customers with the product which he pressed.

P12: I would say that I never really got used to it, because each time I tried to push one, I thought that it would do what it didn't do, that it would filter "on" [the product] instead of filtering "off" [the product]. [...] I understand the thought, but I never really got used to it.

6.4.2 Slider interaction

All participants understood the interaction method of the sliders without any trouble. The outline highlight that activated when touching the slider handles with the controllers was described as helpful and positive. The fact that the handles were attached to the slider with only one axis of movement felt natural and intuitive. One participant described the interaction similar to that of an abacus.

P1: I thought of those abacuses one had as a child, learning how you count. That was my reference when I used [the sliders]. So, the only weird thing was that the marble didn't fall down on [the slider] that was up and down, but it would have sucked if it did. [...]

Q: So, the sliders reacted sort of as you thought they would?

P1: Yes, they reacted absolutely as I thought they would.

Participants generally felt that the vertical slider was the easiest to use, with the motivation that it had the fewest steps on the axis. The scale of zero through ten is a common one to use, which according to some participants also made it easier to keep the values in their short-term memory during comparisons.

The fact that the highlight area followed the slider handles in real-time was described as intuitive. Having the highlight area helped the participants to get an overview of their filtered data and set the limits they wanted to.

One aspect of the sliders that was noted was that participants experienced it difficult to set precise values of the sliders if the handles were near each other. If one handle was dragged into the other one, the other one would also be moved along the slider which affected the operation. Another discovery made during the testing was that on the “Age of customer” slider, participants could not set an interval containing just one age. This was due to the slider handles colliding with each other at a distance where the minimum age interval was three years, meaning that if the minimum handle was as age 20, the maximum handle could not go lower than 23 as the two handles collided at that distance.

Regarding two-handed interaction, most participants only used one hand (usually their dominant hand) to control the sliders, while looking at the off-hand display at the same time. No major difficulties to set a precise value on the sliders using one hand was observed during the testing. A few participants tried to interact with the sliders by controlling each handle with one hand, however, in accordance to the findings of Kabbash et al. (1994), this seemed to be a challenging task as the participants said that it was challenging to be accurate (setting the desired value) while interacting with both slider handles at once.

The sliders did not have any haptic feedback during the first test round, a feature that was brought up by several participants during the first round. After implementing the haptic feedback for the second iteration, the feedback on the sliders was described by several participants as an enhancement to the physical illusion of the sliders, making them feel more real.

P10: I was a little surprised about the haptic feedback, but I thought it was nice.

Q: Do you feel like it made [the sliders] feel more natural, more real, physical?

P10: It felt sort of more natural in a VR environment to make it clear that you are moving [the handles], perhaps not natural in [real life], but I thought they felt natural in the VR environment.

When asked if the sliders reacted the way they expected them to, all participants agreed that they did in fact react as they expected them to. One participant added that it was a nice surprise that the sliders and their filtering operation were so responsive, but also that it was rather obvious for it to work that way when giving it a second thought.

6.4.3 Room scale immersion influence

Most participants agreed that VR helped them to explore the data set. Common answers to the question “In which way did you feel that VR affected the visualization?” were that it felt like exploring data in VR is more fun compared to if they would have used a normal computer monitor with a keyboard and mouse.

The explorative part of the data analysis process is what most participants found to be the strength of this sort of VR visualization; doing quick filtering and looking for hypotheses in the data.

One participant compared the VR application’s workflow to what he had used previously in Microsoft Excel, explaining the strength of VR when doing these tasks:

P12: If you stare blindly at just numbers and maybe do some scatter plots in 2D or line charts or something, then it's very difficult to find correlations if you don't know what you are looking for. [The VR application] gave me the tools to determine "what am I looking for?".

7 Discussion

7.1 Buttons and sliders in VR

The results, both from the task completion statistics as well as from the semi-structured interviews, indicate that the main interaction methods worked well for these sorts of tasks. The consensus was that the interactions were easy to understand and effective for filtering the four dimensions included in this interactive information visualization. The time it took from the first interaction with the filters until the participant understood how it worked and what affected the filter was for every participant a matter of seconds. Many of the participants mentioned that they recognized the interaction methods from other implementations such as web interfaces, which was the thought behind the implementations in this study. The reasoning behind this was to achieve a high recognition factor regarding the interaction methods, minimizing the time at which a first-time user would feel comfortable using the filters.

When asked about which interaction method they preferred, most participants answers indicated that both buttons and sliders were equally useful and essential for the tasks. A common opinion was also that the interaction methods helped the participants to understand the data. By filtering, participants could break the data set down into subsets, which was said to increase the apprehension of the data.

7.1.1 Button issues

The buttons did however suffer from two observed drawbacks in the form they were implemented in the application. First, the buttons occasionally “double clicked”. The controllers pushed the button down until the button reached its lowest position, toggling the filter. Although, after the button had reached its lowest position, the controller started passing through the button instead. When pushed down far enough, the controller no longer pushed down the button, which made the button return to its initial position. If the controller then was pulled up through the button, the pushing operation was triggered once more, making the button “double click”. A technical solution to this issue was not found during the study, however participants who experienced this issue noticed that by not pushing the controller down as far, the issue was effectively avoided.

Second, some participants experienced an issue with involuntary button pushes. These happened mainly when the participants switched side and the button set popped up in front of them as they accidentally had one or both controllers positioned on top of a button. A possible solution to this problem could have been to implement an animation for the movement of the button sets, or remove the button set movement functionality completely, always having multiple button sets around the graph visible. Another possible solution could have been an alternative placement for the buttons. The current implementation was chosen mainly because of ergonomics, making the buttons easy to reach. However, it is possible that the placement was too close to the hands of the user, indicating that an alternative position could have been favorable.

7.1.2 Slider issues

The main observed issue with the sliders was that participants could not use all sliders from one position - they had to move around the graph container to set all filters. A suggestion was to solve this issue by implementing a similar movement functionality found in the buttons, making the sliders follow the user wherever the user walks.

Other minor issues identified were for instance the previously mentioned problem with defining small ranges on the sliders representing a big data range. As collision of the slider handles was the culprit of the issue, a redesign of the slider handles could solve the issue.

7.2 Confusing data dimension

Naturally, as this was an explorative study, it was bound to find some usability issues. A recurring issue was the “Time as customer” dimension. Noted as early as in the pilot study, this dimension took the longest for the participants to understand. In fact, one of the participants in the pilot study could not finish one of the tasks because of confusion caused by the definition of said dimension. Using the feedback received during the pilot study, a few tasks were reformulated for clarification. Even after this clarification, some participants still had difficulties understanding task #8, “Has more customers registered in the last 10 months, or before?”. This may have been caused due to the Swedish translation of the task which subjectively is harder to understand, or simply because the dimension is not the most common way to handle a time span. Some participants needed further explanation of the task in question to complete it, although as soon as they realized what was being asked, there were no major difficulties carrying out the task.

7.3 Haptic feedback

An interesting observation during the semi-structured interviews was that more than half of the participants said that they did not experience any haptic feedback on the product buttons, and some participants in the first test round even said that they did in fact experience haptic feedback on the sliders, even though it was not implemented at the first test round. The reason why participants did not experience any haptic feedback when using the buttons could have been related to how the haptic feedback was implemented. Haptic feedback was only given at the first touch of the buttons, there were no additional haptic pulses when the buttons were pushed down. It is possible that more participants would have noticed haptic feedback if the controller vibrated as the buttons were activated, i.e. pushed all the way down, giving the participants an indication that an operation was executed. Another reason why more than half of the participants did not experience any haptic feedback could be that they were expecting a reaction when touching what seemed like a physical object, just as you would in real life. Since this form of virtual environment is so immersive, users sometimes “forget” that they are in VR, which could remove barriers between interactions in VR and interactions in real life. This could mean that they expected to feel the buttons as they were touched, therefore not noticing the haptic feedback as anything out of the ordinary.

7.4 Real-time interactions

The fact that all filtering operations were carried out in real-time in the implementation was highly appreciated by the participants, indicating that real-time filtering is useful for interactive information visualizations in VR.

7.5 Comparison between data subsets

One often desired feature not implemented in the second design iteration due to time constraints was the ability to compare different subsets of the data. A common scenario was setting a range on one filter, for instance customers older than 50 years of age, and then wanting to compare NPS ranges with each other. The desire was that the full range of the NPS slider would be shown as 100% of the current customers on the off-hand display, while keeping the “Age of customer” filter set at 50+ years of age. Setting the NPS slider to a smaller range would then be compared to that specific subset of customers, instead of comparing it to the entire data set which is the functionality of the implementation for the study. Participants mentioned that they would like to be able to carry out these comparisons without having to always compare a subset to the entire data set.

7.6 Error rates and design iterations

As more information was added to the off-hand display in the second test round, more errors were also registered during the tasks. The read errors were first introduced in the second test round, with the explanation that participants read the wrong percentage number from the off-hand display. Instead of looking at the percentage regarding the specific product they were asked about, they looked at the percentage regarding the total number of customers filtered. This was however not correlated to their opinion of the off-hand panel. Six out of seven participants in the second test round said that the off-hand display was useful, helping them to carry out their tasks. The most common criticism regarding the display was confusion about the percentages, as well as a wish to be able to compare two subsets with each other using the display.

Looking at error rates and task paths, the semi-random task path contained four out of the six errors in total, which could mean that learning transfers could have affected the task paths. Three task paths were chosen to avoid potential biasing effects. Taking into consideration that the tasks were originally created in the order of task path #1 and there was only one error registered within that task path even though most of the participants carried out the tasks in that order, biasing effects could have affected the results. The tasks, carried out in that specific order, could therefore have given rise to learning transfers for the participants. However, this cannot be statistically proven given the number of participants of this study.

7.7 Controller buttons

Finding the right button to do the correct operation is a common problem with hand controllers that have multiple buttons. During the first test round, only one button was used for the interactions - namely the grip button on the VIVE controllers. Applications and games on the VIVE commonly use the trigger button as the main interaction button, which made almost all participants who had used the VIVE before

react in a similar way when using the implementation for the study. Those participants first tried the trigger button, and explained that they assumed the interaction button to grip the slider handles was the trigger. However, this reaction seems to be highly correlated to having previous experience with the VIVE, since participants with little or no experience using the VIVE did not react to using the grip button as the main interaction button.

In the second test round, functionality was added to the dominant hand controller, making use of three different buttons on the controller: the grip button (moving sliders), the trigger (details on demand by clicking a customer) and the thumb touchpad (reset filters). Having three buttons for interactions started to confuse participants, as they rather often used the wrong button for an interaction at first, following up with the correct button after a few tries. Considering this behavior, keeping the number of interactive buttons on the controllers to a minimum seems to be favorable, although this could also be a matter of getting used to the application. The participants did not spend more than an average of 22 minutes in the application, which means they may not have had enough time to fully get used to the controllers during their test.

7.8 Translating web-like interactions

The interaction methods designed for this thesis were based on the functionality of buttons and sliders commonly found in web interfaces. For instance, the functionality and design of the sliders was adopted to the 3D virtual environment, although not specifically designed to utilize the full potential of the VR hardware. The sliders were designed to be “physical” and static in the study, only being interactable from each side of the graph container. As an alternative more native to VR and motion tracked hand controllers, a few participants mentioned how the slider functionality did not have to be bound to the sliders, but could rather be carried out by directly interacting with the edges and corners of the highlight area instead of the slider knobs. This would allow the user to easily interact with two dimensions at once, using only one controller – an interaction impossible with the current implementation of the filtering functionality. In addition, this could potentially solve the issues stated in section 7.1.2.

7.9 Method critique

In this section, the identified shortcomings and limitations of the study are discussed in order to suggest improvements for future similar studies.

7.9.1 Think-alouds

A lot of feedback was given during the think-alouds while the participants carried out the predetermined tasks. This feedback was written down, although only partly. In hindsight, it would have been favorable to have recorded these conversations as well, in the same way the semi-structured interviews were recorded. The think-alouds contained a vast amount of first impressions and feedback during the tasks, which is of significance for the study. Unfortunately, analysis of these were partly hindered by the extent at which the feedback was written down.

7.9.2 Task paths

As mentioned in 6.3.1, there were some issues regarding the three task paths. First, the different task paths were entirely forgotten during the first five test sessions, meaning that the first five participants did the tasks along task path #1, the order at which the tasks were created. Second, all of task paths were not tested beforehand, resulting in a strange order of two tasks in the reversed task path. Both issues could have been resolved by doing a more extensive pilot study, trying out all task paths and getting more used to the testing environment in order to make less mistakes similar to forgetting about the task paths.

8 Conclusions

Using web-inspired interaction methods to carry out filtering operations works very well in an IVE with motion tracked hand controllers. By implementing haptic and visual feedback, natural interactions can be imitated which according to the results of the study generally is perceived as helpful while making the interactions feel more natural. Giving clear visual and haptic feedback to help guide users towards interactive elements was also something that was identified as helpful during the tests.

Designing the interaction methods to function like previously known interactions (such as ones found in web interfaces) helped the participants to understand the functionality of the filters. The participants became proficient in using the main interaction methods in a matter of seconds from when they first interacted with them. This partly had to do with the participants recognizing both the operation (what happened when buttons and sliders were used) and the interaction (buttons and sliders), although it being implemented in VR.

Participants generally felt like real-time filtering was a good thing, which also helped them in setting their filters correctly as they instantly could see what they had filtered. Visual tools such as the highlight area helped the participants to set the filters correctly as well as to get a clear overview of the filtered data by distinguishing between filtered and unfiltered data points. Furthermore, having an easily accessible display which holds information about the filtered data set was perceived as useful. However, the results indicate that keeping the amount information shown on the display to a minimum could reduce the risk of incorrectly read information by users.

Presenting data in a three-dimensional space was perceived as easy to understand and participants generally felt and demonstrated during an open explorative task that it was possible to find correlations across several dimensions in the data set used. Most participants also agreed that this form of interactive visualization was more fun to use compared to desktop based 2D-applications.

During this study, the participants have identified some strengths of interactive information visualizations in IVE's, indicating that applications of this sort, in combination with VR hardware, are highly viable for identifying correlations and finding patterns in multidimensional data sets.

9 Future work

During the second iteration, functionality beyond the scope of this study was introduced. For instance, a way to reset the filters was introduced. This interaction was carried out by pushing a button on the hand controller, not by using anything in the virtual environment. The introduction of this functionality thus increased the number of buttons used on the hand controllers. An interesting study would be to see how an increased number of buttons on the controllers affects task performance as well as user preference. Some observations were made in this study, indicating that an increased number of buttons may confuse the users, making them have to click several times to find the correct button to use. How this affects the task performance is however unknown, making more quantitative measurements in terms of performance a relevant suggestion for future work.

Furthermore, comparing interactions such as the ones used in this study, which were mainly “physical” in the virtual environment, to interactions focused around buttons on the hand controllers could be a subject for future work. Does it affect the sense of immersion? How does it compare in terms of task performance? What users prefer in terms of interaction would be an interesting subject to explore. How fun compares to effectiveness, for instance.

Finally, other ways of interacting with the data should be explored and compared. For instance, one of the most common feature requests was a way to compare two data subsets with each other. Exploring ways to carry out this type of operation would be highly relevant regarding data interaction in VR.

10 Bibliography

- Alger, M. (2015) 'Visual Design Methods for Virtual Reality'. Available at: <https://drive.google.com/file/d/0B1917cJ7tVJyRkpUM0hVYmxJQ0k/view>.
- Bayyari, A. and Tudoreanu, M. E. (2006) 'The impact of immersive virtual reality displays on the understanding of data visualization', *Proceedings of the ACM symposium on Virtual reality software and technology - VRST '06*, 3, p. 368. doi: 10.1145/1180495.1180570.
- Cairo, A. (2013) *The Functional Art: An introduction to information graphics and visualization*.
- Garcia-Hernandez, R. J., Anthes, C., Wiedemann, M. and Kranzlmuller, D. (2016) 'Perspectives for using virtual reality to extend visual data mining in information visualization', in *2016 IEEE Aerospace Conference*, pp. 1–11. doi: 10.1109/AERO.2016.7500608.
- Kabbash, P., Buxton, W. and Sellen, A. (1994) 'Two-handed input in a compound task', in *Proceedings of the SIGCHI conference on Human factors in computing systems celebrating interdependence - CHI '94*. New York, New York, USA: ACM Press, pp. 417–423. doi: 10.1145/191666.191808.
- Kiltner, K., Bergstrom, I. and Slater, M. (2013) 'Drumming in immersive virtual reality: The body shapes the way we play', *IEEE Transactions on Visualization and Computer Graphics*, 19(4), pp. 597–605. doi: 10.1109/TVCG.2013.29.
- Koutek, M. (2003) 'Scientific Visualization in Virtual Reality: Interaction Techniques and Application Development'. Available at: <http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.110.682>.
- Loomis, J. M., Blascovich, J. J. and Beall, A. C. (1999) 'Immersive virtual environment technology as a basic research tool in psychology', *Behavior Research Methods, Instruments, & Computers*, 31(4), pp. 557–564. doi: 10.3758/BF03200735.
- Nielsen, J. and Landauer, T. K. (1993) 'A mathematical model of the finding of usability problems', in *Proceedings of the SIGCHI conference on Human factors in computing systems - CHI '93*. New York, New York, USA: ACM Press, pp. 206–213. doi: 10.1145/169059.169166.
- Norman, D. (1988) 'The Design of Everyday Things (Originally published: The psychology of everyday things)', in *The Psychology of Everyday Things*, pp. 1–104. doi: 10.2307/1423268.
- Rubin, J., & Chisnell, D. (2008) *Handbook of usability testing [electronic resource] : How to plan, design, and conduct effective tests (2nd ed.)*, Indianapolis, IN: Wiley Pub. doi: 10.1007/s13398-014-0173-7.2.
- Schultheis, U., Jerald, J., Toledo, F., Yoganandan, A. and Mlyniec, P. (2012) 'Comparison of a two-handed interface to a wand interface and a mouse interface for fundamental 3D tasks', *IEEE Symposium on 3D User Interfaces 2012, 3DUI 2012 - Proceedings*, pp. 117–124. doi: 10.1109/3DUI.2012.6184195.
- Slater, M. and Wilbur, S. (no date) 'A Framework for Immersive Virtual Environments (FIVE): Speculations on the Role of Presence in Virtual Environments'. Available at: <http://publicationslist.org/data/melslater/ref-232/pres5.pdf> (Accessed: 17 May 2017).
- Steuer, J., Breitrose, H., Cool, J., Detenber, B., Johnson, G., Levine, S., Lombard, M., Melwani, G. and Voelker, D. (1992) 'Defining Virtual Reality: Dimensions Determining Telepresence', *Journal of Communication*, 42(4), pp. 73–93.
- Unity (2015) *Unity - User Interfaces for VR*, Unity3D.Com. Available at: <https://unity3d.com/learn/tutorials/topics/virtual-reality/user-interfaces-vr> (Accessed: 17 May 2017).

Wang, N., Paljic, A. and Fuchs, P. (2012) 'An evaluation of rendering and interactive methods for volumetric data exploration in virtual reality environments', in Wong, P. C., Kao, D. L., Hao, M. C., Chen, C., Kosara, R., Livingston, M. A., Park, J., and Roberts, I. (eds). International Society for Optics and Photonics, p. 82940W. doi: 10.1117/12.912312.

Witmer, B. G. and Singer, M. J. (1998) 'Measuring Presence in Virtual Environments: A Presence Questionnaire', *Presence: Teleoperators and Virtual Environments*. MIT Press 238 Main St., Suite 500, Cambridge, MA 02142-1046 USA info@mit.edu , 7(3), pp. 225–240. doi: 10.1162/105474698565686.

11 Appendix

Appendix A. Presence Questionnaire

How much were you able to control events?	Count
1 - NOT AT ALL	0
2	0
3	0
4 - SOMEWHAT	0
5	0
6	8
7 - COMPLETELY	5
Average	6.4
Standard deviation	0.51

How responsive was the environment to actions that you initiated (or performed)?	Count
1 - NOT RESPONSIVE	0
2	0
3	0
4 - MODERATELY RESPONSIVE	0
5	4
6	5
7 - COMPLETELY RESPONSIVE	4
Average	6.0
Standard deviation	0.82

How natural did your interactions with the environment seem?	Count
1 - EXTREMELY ARTIFICIAL	0
2	0
3	0
4 - BORDERLINE	2
5	5
6	4
7 - COMPLETELY NATURAL	2
Average	5,5
Standard deviation	0.97

How much did the visual aspects of the environment involve you?	Count
1 - NOT AT ALL	0
2	0
3	0
4 - SOMEWHAT	5
5	2
6	3
7 - COMPLETELY	3
Average	5.3
Standard deviation	1.25

How natural was the mechanism which controlled movement through the environment?	Count
--	-------

How compelling was your sense of objects moving through space?	Count
--	-------

1 - EXTREMELY ARTIFICIAL	0
2	0
3	0
4 - BORDERLINE	0
5	3
6	4
7 - COMPLETELY NATURAL	6
Average	6.2
Standard deviation	0.83

1 - NOT AT ALL	0
2	0
3	0
4 - MODERATELY COMPELLING	0
5	6
6	5
7 - VERY COMPELLING	2
Average	5.7
Standard deviation	0.75

How much did your experiences in the virtual environment seem consistent with your real world experiences?

	Count
1 - NOT CONSISTENT	0
2	0
3	2
4 - MODERATELY CONSISTENT	3
5	3
6	3
7 - VERY CONSISTENT	2
Average	5.0
Standard deviation	1.35

Were you able to anticipate what would happen next in response to the actions that you performed?

	Count
1 - NOT AT ALL	0
2	0
3	0
4 - SOMEWHAT	0
5	2
6	6
7 - COMPLETELY	5
Average	6.2
Standard deviation	0.73

How completely were you able to actively survey or search the environment using vision?

	Count
1 - NOT AT ALL	0
2	0
3	1
4 - SOMEWHAT	0
5	1
6	4

How compelling was your sense of moving around inside the virtual environment?

	Count
1 - NOT COMPELLING	0
2	0
3	0
4 - MODERATELY COMPELLING	0
5	1
6	3

7 - COMPLETELY	7
Average	6.2
Standard deviation	1.17

7 - VERY COMPELLING	9
Average	6.6
Standard deviation	0.65

How closely were you able to examine objects?	Count
1 - NOT AT ALL	0
2	0
3	0
4 - PRETTY CLOSELY	1
5	3
6	2
7 - VERY CLOSELY	7
Average	6.2
Standard deviation	1.07

How well could you examine objects from multiple viewpoints?	Count
1 - NOT AT ALL	0
2	0
3	0
4 - SOMEWHAT	0
5	1
6	6
7 - EXTENSIVELY	6
Average	6.4
Standard deviation	0.65

How involved were you in the virtual environment experience?	Count
1 - NOT INVOLVED	0
2	0
3	0
4 - MILDLY INVOLVED	1
5	0
6	8
7 - COMPLETELY ENGROSSED	4
Average	6.2
Standard deviation	0.80

How much delay did you experience between your actions and expected outcomes?	Count
1 - NO DELAYS	11
2	2
3	0
4 - MODERATE DELAYS	0
5	0
6	0
7 - LONG DELAYS	0
Average	1.2
Standard deviation	0.38

How quickly did you adjust to the virtual environment experience?	Count
---	-------

How proficient in moving and interacting with the virtual environment did you feel at the	Count
---	-------

1 - NOT AT ALL	0
2	0
3	0
4 - SLOWLY	0
5	0
6	1
7 - LESS THAN ONE MINUTE	12
Average	6.9
Standard deviation	0.28

end of the experience?

1 - NOT PROFICIENT	0
2	0
3	0
4 - REASONABLY PROFICIENT	1
5	0
6	6
7 - VERY PROFICIENT	6
Average	6.3
Standard deviation	0.85

How much did the visual display quality interfere or distract you from performing assigned tasks or required activities?

1 - NOT AT ALL	Count 4
2	5
3	2
4 - INTERFERED SOMEWHAT	0
5	2
6	0
7 - PREVENTED TASK PERFORMANCE	0
Average	2.3
Standard deviation	1.38

How much did the control devices interfere with the performance of assigned tasks or with other activities?

1 - NOT AT ALL	Count 1
2	6
3	3
4 - INTERFERED SOMEWHAT	3
5	0
6	0
7 - INTERFERED GREATLY	0
Average	2.6
Standard deviation	0.96

How well could you actively survey or search the virtual environment using touch?

1 - NOT AT ALL	Count 1
2	2
3	2

How well could you move or manipulate objects in the virtual environment?

1 - NOT AT ALL	Count 0
2	0
3	1

4 - SOMEWHAT	2
5	3
6	0
7 - COMPLETELY	3
Average	4.2
Standard deviation	2.01

4 - SOMEWHAT	3
5	1
6	5
7 - EXTENSIVELY	3
Average	5.5
Standard deviation	1.33

Appendix B. Regarding development and testing

The application used for this study was developed in collaboration with one other student, Anton Sivertsson, who also carried out his Master's thesis during the same period. Anton's thesis focused on the visual aspect of the visualization, exploring how to visualize data sets, as the one used in this study, in VR. While sharing the workload of coding the application, design decisions regarding each research area were done separately. This means that all decisions regarding the interaction methods explored in this study, as well as the design of the interface, were done by me. Respectively, any decisions regarding the visual aspects of how the data was visualized, were done by Anton. We did however work together to create the application's general and shared functionality which did not have any specific bias to one of the two research areas. Those parts included the set up and cleaning of the database, designing the backend API service, setting up the communications between the frontend and the backend, parsing the HTTP response in the frontend, logging of in-application events and usage statistics in the frontend application, as well as optimizing code for better performance.

As a result of evaluating the same application, the user tests were shared sessions between the two of us at which I handled the communication with the participants and Anton took notes during the sessions. Therefore, our respective results are based on the same participants and the same test sessions. However, we both had our own parts with separate questions in the semi-structured interview and the tasks were created to be beneficial to both of our studies, focusing on two entirely separate research areas. The decision to carry out shared test sessions was based entirely on the practical reason of having only one set of hardware compatible with the software.

