Magnus Winther Warvik

Visualizing climate change in Virtual Reality to provoke behavior change

Master's thesis in MiT

June 2019

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Abstract

Climate change is an important societal problem, both globally, and on a local scale. The objective of this research is to discuss the use of a Virtual Reality (VR) application as a tool to provoke empathy and modify environmental behavior among users. It also tries to answer questions regarding using VR to visualize climate data, and how best display menu interfaces in the same context. The research have been grounded in design science, with the final application developed through several implementation and evaluation cycles. The result is an application displaying climate change in the city of Trondheim. The user can look at how an increased sea level affects different parts of the city, and visualizations of climate data can be augmented on top of the ground. In the end, any definite conclusions regarding the specific application are hard to draw, with more research needed. The results are positive towards VR in general to visualize and make users empathize with climate change.

Keywords: Virtual Reality, climate change, empathy, behavior change, geographic information system, user experience

Preface

I declare that the work performed in this master thesis has been done independently, and in accordance with the rules and regulations at the Norwegian University of Science and Technology (NTNU). It was carried out during the autumn and spring of 2018/2019.

The thesis marks the end of five years of study at NTNU, and my major in Informatics, specializing in Interaction Design, Game and Learning Technology. The years leading up to the thesis has been a journey to obtain the knowledge and skills required, with the last year providing plenty of new challenges along the way.

For guidance and motivation, and the possibility to write about this interesting topic, I especially want to thank my supervisor Ekaterina Prasolova-Førland at the department of Education and Lifelong Learning at NTNU. She is also the head of the Innovative Immersive Technologies for Learning (IMTEL) research group, and the leader of the VRLab at Dragvoll, NTNU, where most of the work in this master thesis took place. I also want to thank my supervisor Simon McCallum at the department of Computer Science and Jan Ketil Rød at the department of Geography. Also, thanks to everyone who tested the application, and gave me feedback.

Finally, I want to thank my parents, and my girlfriend, for always being there for me.

Magnus Winther Warvik
Trondheim, 07.06.2019

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Glossary

City model	When referencing to *the city model*, this represents the three-dimensional model of Trondheim and the surronding region, developed by Rambøll in 2014.
GIS	A method to collect, analyze, and visualize location-based information.
Git	Distributed version control system for tracking changes to files during software development, especially useful for coordinating work in teams.
Risk and vulnerability analysis	Used to prioritize risk areas and planning prevention, by mapping the probability and consequences of undesirable events. (Norwegian: Risiko- og sårbarhetsanalyse)
Trondheim Municipality	The third largest municipality in Norway by population.
Unity	A game engine for creating two- and three-dimensional games and simulations.
Virtual Reality	An artificial environment generated by a computer, experienced through sensory stimuli.

Abbreviations

GIS	=	Geographic Information System
HMD	=	Head-mounted display
RCP	=	Representative Concentration Pathway
VR	=	Virtual Reality

Chapter 1

Introduction

This introductory chapter is divided into five subsections, and will give an overview of the project, including the context and purpose. It will then introduce the research methods used, and the tangible outcome that resulted from the thesis. Lastly, a guide to the rest of the report will round off the chapter.

1.1 Context

In the last 10 years, temperature has risen by 0.98°C globally, we have seen more instances of extreme weather, and all of this is with a high probability connected to human activity. [16] There are still those who doubt that climate change is an important issue, and those who do are usually the ones with the highest CO_2 emissions. [28] In general, it's hard to empathize with polar bears on melting ice sheets at the other side of the globe. [14]

VR is one of the technologies that might solve these problems. When people take on these head mounted displays, they show a higher level of empathy, and with relevant simulations, they can also look at the effects on a local scale to see how it affects their home environment.

1.2 Purpose

The purpose of the study done in this thesis, is mainly to look at the combination of VR and climate change, and if people exposed to climate change visualizations and scenarios in their local community, empathize and change their environmental behavior.

Climate is the statistics of weather over a long period of time, and includes the patterns of variation in variables such as temperature, humidity, atmospheric pressure, wind and precipitation. Climate is affected by numerous factors, such as oceans, mountains, and the latitude of the area. [8] This makes it relevant to be able to visualize relevant GIS layers, to show both the causes and effects of climate change.

Lastly, with several different layers, as well as other features, the application will need some sort of menu system to navigate in, that should be easy to use. Menu interfaces in VR are completely different from menus in applications and games, and there are still a lot of questions on how to best implement them.

With this in mind, the three research questions this thesis tries to answer are:

RQ1 To what extent can VR exposure to local climate change provoke empathetic response to modify environmental behavior?

RQ2 How can you implement and visualize two-dimensional climate data in VR to increase understanding of climate change?

RQ3 What is an efficient way to interact with menus in VR when visualizing climate change?

1.3 Research method

To answer the research questions posed in the thesis, multiple research methods have been utilized. The application was developed through an iterative process, with user tests and questionnaires conducted throughout to gather both quantitative and qualitative data. Users were observed, and log files generated during usage of the application were analyzed. After the last iteration, a semi-structured group interview was performed, with the answers recorded and transcribed. The process was approved by the Norwegian Centre for Research Data (NSD). A simplified expert interview was also performed.

The research has been grounded in the design science methodology. Here, the focus is on the development and improvement of a specific artifact [26]. The artifact will be explained in the next section. The research is also in line with Oates' information systems and computing research [19], with a focus on both the social and technological aspects of the developed application.

1.4 Tangible outcome

As tangible outcome after this master thesis, a VR application visualizing climate change has been developed. The application consists of a model of the city of Trondheim (and surrounding areas), with the user able to control certain aspects of the environment.

When starting the application, the user is guided through a tutorial, showing how to use the application with animations, text, and a synthesized voice.

After the short introduction, the user is free to use the application as she pleases. Movement can be done by ”teleporting” (pointing the controller towards a target), or by inputting any address in the city of Trondheim, for example a home address.

The sea level can be raised (or lowered back to today's level), and the application will show if this is a realistic level in the near future. The sea level can either be raised/lowered in small increments, or directly set to 7 meters. This is the approximate sea level if all of the Greenland ice sheet melts. [13] Altering the sea level will in turn change the amount of rain and clouds, as well as the intensity of the rain ambience sounds.

It is also possible to show additional layers on top of the city model. The user can view where the water will flow and collect in case of extreme rainfall, and the locations of quick clay. These layers can be toggled on and off at will, and a short audible description can be activated if the user is unsure of what the layers are representing.

For developers, the three-dimensional model can be changed out with a model of any other city, and the layers changed to something relevant to that particular city. The application can easily be localized to any language. With small changes, this will make the application relevant for any community.

1.5 Thesis outline

Including the introduction, this thesis is structured into 6 chapters.

The next chapter will be discussing the background research of this thesis, including information about VR, data visualization, climate change, and empathy, as well as the state of the art in the field of VR climate applications.

Chapter 3 will elaborate on the planning of the application, including a list of stakeholders, and the initial requirements developed during this process. A short section on the most relevant software architecture principles is presented.

Chapter 4 will discuss the user-centered design process that took place, as well as sections about the tools and technologies used during development, and the testing setup.

Chapter 5 is a conclusion to the process, with discussion about the final evaluation. Limitations, some unimplemented features, and reflections on the work is presented.

Chapter 6 is a conclusion of the thesis, and connects back to the introduction chapter. The application is compared to the state of the art discussed in chapter 2, and a list of contributions is included. A section regarding future work rounds off the report.

Chapter 2

Background

In this section, background literature relevant to the project is presented. It will first go into VR, climate change, and data visualization. Then, the next section combines som discussion about climate change and immersive technology with empathy. Section 2.5 references four existing climate change VR applications.

2.1 Virtual Reality

There are several ways to describe VR. One definition can be taken from the Merriam-Webster dictionary: *"an artificial environment which is experienced through sensory stimuli (such as sights and sounds) provided by a computer and in which one's actions partially determine what happens in the environment."* [25]

VR is one of the realities under the umbrella term of Cross Reality (XR), in this case replacing the entire reality of the user with a computer-generated one. Through mainly visual and auditory cues (but also other possibilities, like haptics), the user is immersed in a world that can have completely different rules from the real world.

Because of technological development, VR is now available cheaper than ever. In fact, every modern smartphone is a VR capable device. This makes it possible for content creators to develop applications to be experiences by a large percentage of the world population. More advanced HMDs in the form of HTC Vive (figure 2.1) or Oculus Rift are

Figure 2.1: The HTC Vive controllers, headset, and base stations. Source: Bestbuy.com

also beginning to get into an affordable territory, though a powerful computer is required.

The possibilities with VR are huge, and disruptions in almost all industries are possible. Imagine surgeons performing a virtual surgery as training before doing it to a real patient, becoming a super-hero and saving the world with your friends, or being able to visit the entire world from your couch. All of these experiences already exist, so just wonder where we are in 2, 5 or 20 years.

2.1.1 History of VR

The term *Virtual Reality* was coined in 1985, but have a much longer history. [11] argues that it can be tracked back to the original magicians performing illusions to trick the brain into what is actually present. The original precursor to the VR of today can be said to be the stereoscope from 1832, with a line of improvements leading up to today, including the View-Master and Google Cardboard. As with many other technologies, interest in VR has had its peaks and valleys. The current surge came in 2012, after Palmer Lucky as the head of Oculus shared his idea on the crowd-funding website Kickstarter. This new VR headset kick-started a new interest by the media and general public. The company was sold to Facebook for $2 billion in 2014.

2.1.2 Immersion and presence

Two very relevant concepts when it comes to VR are *immersion* and *presence*. Immersion is an objective measure of how well a VR ”tricks” your body and senses into believing you are somewhere else. This by replacing sensory input (e.g. visual and audio), letting you interact with the world, and having a world with a consistent flow of events. Presence is the subjective sense of ”being there”, and breaking this illusion should be avoided at all cost. Presence is limited by the provided immersion of a system. [11] It’s not just entertainment experiences that should strive for better immersion, as immersion leads to better data understanding, and relationships in the data are better retained [6].

Because of technologies such as head tracking and the use of separate images for each eye, another proposed benefit of immersive VR is a better spatial understanding. [3] Immersion however, is not always a must, with previous research finding small or no differences between emotional response to different levels of immersive VR [1] [10]

Audio and haptics

Humans have a multitude of sensors, including the five basic senses of hearing, sight, smell, taste, and touch. As smell and taste is seldom utilized in VR, and controllers are usually in the users hands, the last two senses of hearing and sight becomes extra important for improving immersion. Some of the important roles sounds are used for are ”adding awareness of surroundings, adding emotional impact, cuing visual attention, conveying a variety of complex information without taxing the visual system, and providing unique cues that cannot be perceived through other sensory systems”.[11, p. 239] This is true in VR environments as well as in real life.

Spatial audio, with the user being able to hear where the sound comes from, makes it easier to understand how the environment is built up and structured. This is also a way to grab user attention, as the user would naturally look down if hearing a sound from the controller. According to [21], background sounds (ambience) are important for a sense of atmosphere.

Even if the user has controllers in both hands, a VR application can simulate the feeling of touching an object through *haptic feedback*. It can be used as an alternative, or in addition to sound. With different frequencies and intensities, the feeling of the feedback can be altered for different use cases.

2.1.3 VR interactions

To get a better overview of how implementation should be done, previous research on menu interaction, movement, and scale, has been studied.

Menu interaction

When designing menu systems and heads-up displays for VR applications, rules for normal 3D applications are not recommended. This is mainly because of *occlusion*. This is a type of pictorial depth cue that lets you see the relative distance of objects by closer objects hiding farther away objects. In a normal graphical application or game, the heads-up display would occlude all other objects. In VR applications, these menus should be transformed to 3D geometry that is properly occluded [11, p. 116, 173]. In VR, there are usually three methods of showing menus and user interface, discussed in [11]:

1. Interfaces on actual objects. An example of this is a menu on a virtual computer screen. Another example is a picked up object augmented with information about its state.
2. Interfaces floating in front of the user. To not be in the way, these menus are often displayed only when needed, activated by a button press or contextually.
3. Interfaces on body parts/hands.

Movement

Movement in VR can be done in multiple ways, depending on the user group, the size of the virtual and real space, and what the focus of the application is. One way of moving around in the virtual world is *teleportation*, where the user instantly moves from his current location to a new one, usually by pointing the controller. This makes it easy to move around without needing a large physical space. Compared to a continuous movement, it reduces motion sickness at the cost of reduced immersion and spatial orientation [11, p. 344].

Scale

Scale can be defined as ”the projective size of the place relative to the human body” [32]. Immersive technologies, such as VR has the possibility to change this variable, to overcome what is possible in the physical world. In a study on virtual field trips, it was found that using 360 degree cameras at an elevation of 27 feet had positive effects on subjects spatial sitution model. More information is accessible without obstructions, giving a better picture of spatial relations and larger features [32]. This is relevant for this thesis, especially when visualizing data sets that should be easy to see and understand.

2.2 Data visualization

In today’s information society, an increasing amount of data is generated and available. As such, new methods for representing and interacting with the data is required to find meaningful patterns and increase understanding. This is true for both climate data, as well as all other types of data. [6] argues that effective visualization is the bridge between raw data and human intuition, thus leading to knowledge and understanding if done correctly. Humans arguably need information visually to be able to comprehend it.

Immersive technologies such as VR are suggested as one possible solution to visualization, particularly when the data is spatial in nature [6], such as geographical information. To best design the data representations and interactions, disciplines such as interaction design and human-computer interaction are needed. This is especially true in contexts such as education and citizen empowerment. [20]

2.2.1 Three-dimensional geographic modeling

With the world existing in three dimensions, converting representations of the world to the same amount of dimensions is beneficial. This makes it possible to more easily understand information such as the height of mountains and grade of hills, and analyze contextual relationships. For a long time, maps and geographic information was largely 2D, with 3D models consisting of physical miniatures instead of being computer generated [12, Lesson 1.4]. Creating virtual instead of physical models makes them easier to augment and modify, as well as being easily shareable.

Geographic Information System

GIS is used to collect, analyze, and visualize location-based information. [9] To organize and encode geographical information, some sort of file format has to be used. One example of this is *GeoJSON*, with pairs of keys and values representing both the spatial features (such as points, lines, and polygons), and the non-spatial attributes (descriptive information about the data set).

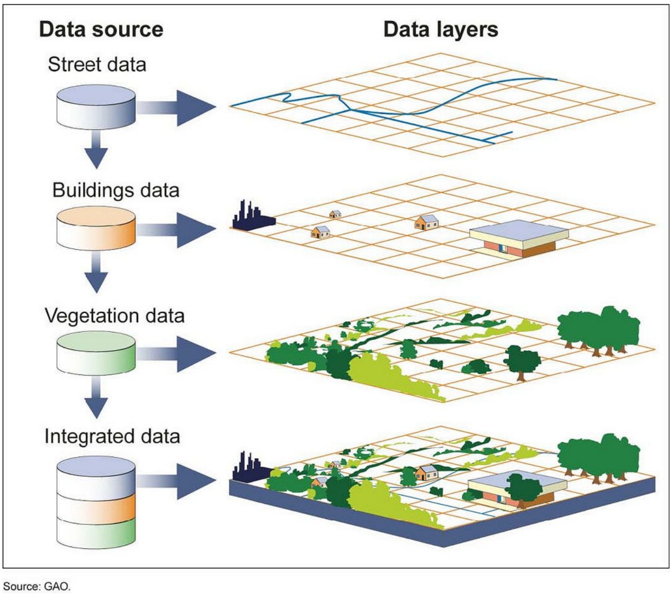

Figure 2.2: An example of GIS layers. Source: [9]

2.3 Climate change

The Earth's climate has been in constant change since its formation over 4.5 billion years ago. According to NASA, there has been seven cycles of glacial advance and retreat in the last 650,000 years [18]. The end of the last ice age, 7,000 years ago, marks the beginning of the modern climate era. While earlier changes are attributed to small changes in Earth orbit (and therefore the amount of received solar energy), most of the later trends are with

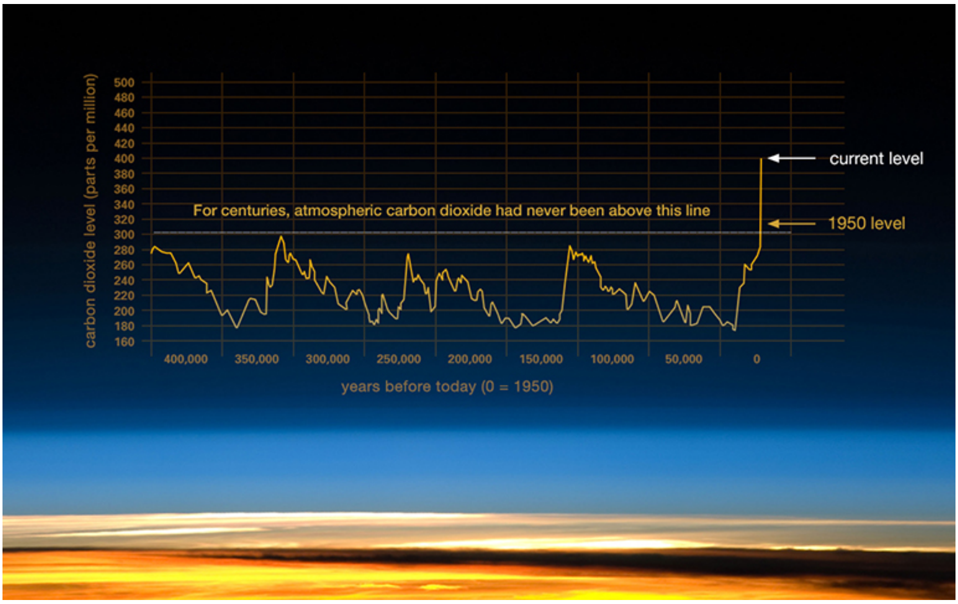

Figure 2.3: Levels of carbon dioxide in the atmosphere are higher than they have been at any time in the past 400,000 years. Source: [17]

high probability (>95 percent) the result of human activity [16].

The ”greenhouse effect”, with more and more heat radiating from Earth trapped in the atmosphere, is caused by several gases blocking the escape. These gases include water vapor, carbon dioxide, methane, nitrous oxide and CFCs [16]. The increased concentration of most of the greenhouse cases seem to have a direct correlation with human activity. As figure 2.3 shows, the carbon dioxide concentration in the atmosphere has fluctuated throughout history, but only increased in the last decades. In 2013 it reached the highest level in recorded history of 400 ppm (parts per million) [17], and in 2019 it reached 415 ppm. [5]

George Marshall, climate change author, and the director of the Climate Outreach Network, says most people do not accept climate change because ”we wish to avoid the anxiety it generates and the deep changes it requires.” [14]. Most people underestimate the scale of the threat, not because of individual differences, but because of how our brains are wired. Studies have been done, finding that a majority of people think climate change is a serious issue, with 54 percent believing it to be a *very* serious problem. [28] The same study found people in countries with higher emissions to be less concerned. Therefore, it seems people still needs convincing.

Representative Concentration Pathway

A Representative Concentration Pathway, or RCP, is a trajectory that describes current and future concentration of greenhouse gases in the atmosphere. When doing climate modeling and research, four different pathways are used; RCP2.6, RCP4.5, RCP6, and RCP8.5. The numbers represent the predicted difference between the amount of sunlight the Earth absorbes, and sunlight radiated back to space in or after year 2100. As an example, RCP6.0 will have an energy surplus of 6 Watts per square meter, equivalent to a CO_2 concentration of 490 ppm. [27]

To get a response from users, while still grounding the application in reality, RCP8.5 was selected as a grounds for sea level rise. This is the harshest pathway, with a CO_2 equivalent of 1370 ppm in 2100.

2.4 Empathy, climate change, and immersive technology

VR has been dubbed ”the ultimate empathy machine”. The prolific music video director, and co-founder of the VR production company Within, Chris Milk, claims that VR puts you in the world, instead of watching through a window. This makes you empathize, and is a way to use VR for good. [15] Climate change is not just happening elsewhere. It's happening everywhere, and right now. By utilizing virtual environments, it is possible to make simulations and scenarios that are relevant to local inhabitants, to make them understand that changes are happening in their backyards.

A question you can ask is if this empathy will still be there back in the real world, and when the technology is a normal part of everyday life. One study on empathy (and homelessness) found that VR exposure had a longer-lasting positive effect than in a traditional perspective-taking task [10]. The same article found a higher number of participants in the VR condition signed up for a relevant petition, compared to less immersive experiences. Another study found the less immersive formats being a equal or larger motivation driver for social or political action. [1] It also found that the novelty of either the source material or technology increases empathetic responses, making VR suitable for introducing new topics.

By having participants take a shower in a virtual environment, one study found that vivid feedback was effective in promoting behaviour positive for the environment, while personalized feedback displayed little effect. [2] In another study, participants experienced a virtual coral reef with different levels of immersion and navigational capabilities. They found that high levels of both immersion (using a HMD) and navigation (free translational movement) actually decreased the behavioral change intention of participants. [31] Therefore, if the intention is to elicit behaviour change, designers need to be aware of design decisions.

2.5 State of the art

In this section, the following state of the art experiences will be discussed briefly: *The Standford Ocean Acidification Experience*, *Greenland Melting*, *Look Ahead – San Francisco*, and *This is Climate Change*. In the last chapter, the experiences will be compared to the developed application.

2.5.1 Stanford Ocean Acidification Experience

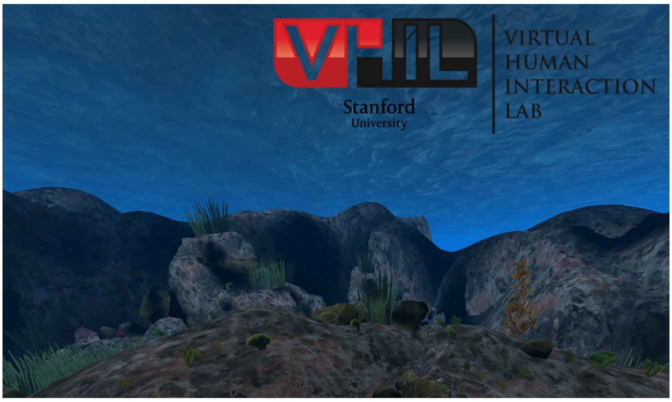

Figure 2.4: The Stanford Ocean Acidification Experience. Source: [24]

The most widely known VR application regarding climate change was created at Standford at the Virtual Human Interaction Lab. As a virtual storytelling application, it takes the user through an experience in coral reefs outside Italy, where the ocean is being polluted by carbon dioxide from the atmosphere. This *Ocean Acidification* is a huge problem for the coral reefs and its inhabitants.

The player is guided through the entire experience by a narrator, with a combination of videos and virtual environments. It starts in a busy and CO_2 filled city street, then to the deck of a ship, where CO_2 molecules are disappearing into the ocean. The user is transported to the sea floor, with a 360° video showing a coral reef in its current state. Tasked with doing a count of the number of sea snails in the area, the user places flags beside each snail. Finally, the reef is transformed to a dying reef, with all sea snails dead. The narrator tells us that this is the future in we continue our current trajectory.

2.5.2 Greenland Melting

Figure 2.5: Greenland Melting. Source: [7]

Greenland Melting is an experience where you get a look at the effects of climate change on the glaciers in Greenland. In addition to being informed by a narrator, the VR documentary follows two scientists from NASA, and their research into how the warming of the ocean water melts the ice. This is very relevant, as it was recently found that the Greenland ice is melting four times faster than previously thought. [13]

The 12 minute experience has no user interaction, except for the ability to teleport around to change view point. In addition to utilizing 360 degree videos and photogrammetry, animations and overlays are used to further inform the user. As an example, the application displays the current state of the Fimbul Glacier, then representations of where it was 15, 30, and 120 years ago. According to the researchers, the glacier retreated more in the last 15 years than the previous 70 years.

2.5.3 Look Ahead – San Francisco

Figure 2.6: Look Ahead – San Francisco. Source: [23]

Climate Access' *Look Ahead – San Francisco* is a mobile phone application that let you see the impacts and solutions to sea level rise on three sites in San Francisco. It first displays the current situation, then two possible situations: one where the sea level is raised, and one where climate solutions have been deployed.

The app can either be viewed as a 2D application, or through Google Cardboard or similar HMDs. With a stationary 360-video for each location, you are not able to move around. You can instead answer questions about your concern level, quizzes about the area, and if you are interested in helping out. It is especially geared towards those living in the area.

2.5.4 This is Climate Change

Figure 2.7: This is Climate Change. Source: [29]

This is Climate Change is a VR documentary series. Compared to a normal TV series or movie, watching something in VR is much closer to experiencing it, as you aren't just looking at it through a window. As the series is heavily reliant on the story, it is a powerful way to affect understanding, and as you are placed in the middle of the action, you are easily emotionally invested.

The series is divided into four parts, each focusing on different unfortunate effects of climate change. *Famine* focuses on how drought caused by rising temperatures has turned fertile land in Somalia into deserts. In *Fire*, the focus is on the increased amount of wildfires due to climate change. In *Feast*, you can witness how loggers destroy the Amazon to make space for cattle ranches. The series also has an episode on the melting ice of Greenland.

Chapter 3

Problem definition process

In this chapter, the planning that took place before the start of the development process will be discussed. This includes a section on Trondheim Municipality, stakeholders, requirements, and the planned overarching architecture of the application.

3.1 Trondheim Municipality

Trondheim is a city and municipality in central Norway, and the third most populous municipality of the country. Laying on the south shore of the Trondheim Fjord and having the Nidelva river running through the city centre, it is affected by floods and sea level rise.

Different areas are affected by different causes, and to analyze a specific area, a *climate profile* is usually made, as an aid for planning and decision makers. The profile discusses current climate, as well as expected changes and challenges. The last profile for Sør-Trøndelag (the location of Trondheim) was created in January of 2016. With an estimated temperature increase of around 4°C before the end of the century, potential changes can be massive.

At the same time as the climate profile is developed, a *risk and vulnerability analysis* is also created. By listing all climate change areas, and multiplying the probability by consequence in different areas, a risk factor is found. The analysis of Sør-Trøndelag found several risks to be pressing, including flood, landslide, storm surges, and sea rise.

Appendix C shows the entire analysis table from 2016. As an example, sea level rise is likely, and has a factor of 4. The consequences for life and health is low (1), with a calculated risk of $4 * 1 = 4$. The consequence for material value is much higher (3), for a risk of $4 * 3 = 12$. Another high-risk element that is especially relevant for Trondheim (and Trøndelag), is quick clay. To conclude, such an analysis makes it possible to focus on the most pressing risks in an specific area.

3.1.1 Three-dimensional model

In 2014, Trondheim Municipality had a 3D model of Trondheim developed. The model includes the city centre, and surrounding areas of of approximately 36 km^2. By using several different techniques (including map information and aerial photos), the model includes terrain, textured buildings, and a few manually modeled objects including the Old Town Bridge, and the Tyholt Tower (see figure 3.1 for an example). [4]

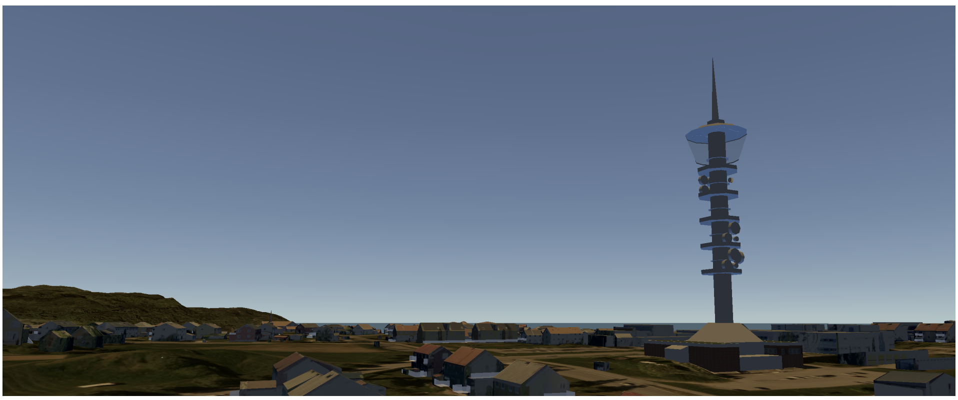

Figure 3.1: The Tyholt Tower represented in the city model

This model has been 3D printed, and is available as a physical representation in the offices of Trondheim Municipality. By using multiple projectors and custom software, different map data can be projected on top of the model (see figure 3.2). Seeing this model was a source of inspiration for possibilities in this project. A normal desktop application is also available [4], with basic navigational functionality.

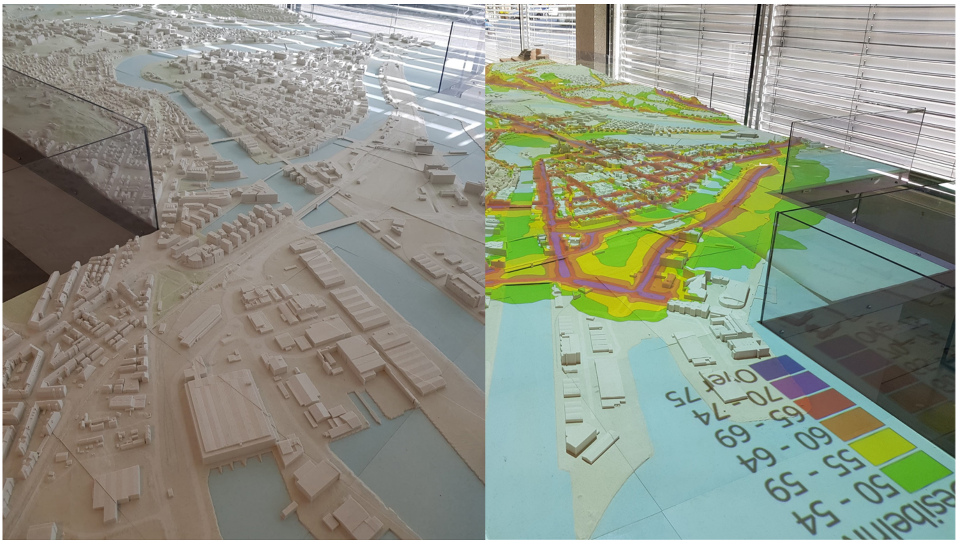

Figure 3.2: A physical model as a counterpart to the three-dimensional virtual model. This shows the model without (left) and with (right) augmented images layered on top.

3.1.2 First meeting

Because of the idea to use the 3D model as a foundation for the application, it was logical to start the planning process with a meeting with representatives from the municipality, discussing what they were interested in. In short, they were interested in a product that could be displayed at the municipality building to interested parties, showing different climate effects, and how they would affect the city. By using the aforementioned risk and vulnerability analysis, the focus should be on developing visualizations for the most pressing areas.

As discussed in the previous section, they already had a physical model developed, but such a model has several drawbacks (some discussed in section 2.2.1). The model was split into multiple squares, and when there was a change to the city, like a new building, that square had to be re-printed. A VR station would also make visitors much more immersed in the experience compared to just seeing the miniature from above.

As there are few similar VR applications, experimentation had to be done to see what would work. With other municipalities in Norway also exploring the topic, it would be ideal if a solution could be used in multiple locations with minimal changes.

3.1.3 Alternatives

During the planning of the project, interesting ideas were written down regarding alternative solutions. If it wasn't already decided on using fully immersive VR, an alternative could have been to develop an Augmented Reality application for mobile phones. When walking around in Trondheim, the user would be able to take his phone up, and look at the area around him. By fetching his location, the application would show relevant climate information for that area, for example scenarios for the sea level, or the location on quick clay. All of this could be layered on top of the camera view.

3.2 Stakeholders

By researching the topic, three main stakeholders were discovered:

- The general public in Trondheim would be able to see how the city and their neighborhood are affected by climate change.
- Geography students could analyse data sets, either those included in the application, or by importing their own GIS data. This would create a new dimension compared to traditional mapping applications.
- Politicians could use the application as a tool for city planning, to see how different areas are affected by climate, and potentially modifying their plans based on this.

3.3 Requirements

After the meeting with Trondheim Municipality, initial requirements were developed. Because of the iterative approach, and the many unknowns in the field, the list of requirements in the start of the project was quite short. Just the most pressing requirements were included, with more to be discovered through iterations and user-testing. Table 3.1 lists the initial requirements, with the IDs being used to reference the requirements later.

The requirements that was found later are discussed in subsequent chapters.

ID	Requirement	Priority
R1	The application should use the three-dimensional model distributed by Trondheim municipality.	High
R2	The application should support the HTC Vive.	High
R3	Users should be able to walk around freely in the model.	High
R4	The application need to be able to show GIS data.	High
R5	GIS data should be able to be imported with no changes to the structure.	Medium
R6	Advanced users should be able to import their own GIS data.	Medium
R7	Users should easily be able to find their home or neighborhood.	High
R8	Three-dimensional map information should be animated and realistic.	Medium

Table 3.1: Initial requirements

3.4 Architecture

When working in Unity and C#, a object-oriented and component-based architecture is usually chosen. In this section, the overarching architecture will be very discussed briefly.

3.4.1 Object-oriented

Object-oriented programming is a paradigm based on programming with objects containing data and procedures. As the project uses the programming language C# where everything is built up from objects, there is no way around OOP.

3.4.2 Component-based

In addition to object-oriented, programs developed in Unity are component-based, or at least should be. A *component* is a very small piece of programming, that does one specific thing. One example can be a script that follows an object. As games are visual, Unity uses a visual interface to create games, where components easily are added and removed from objects, even when the application is running. Figure 4.1 shows the Unity window, with example components on the right side of the window.

Chapter 4

The process

Chapter 4 discusses the entire process after the initial requirements were formulated. First the design process in section 4.1. Then, section 4.2 will go through the tools used, and section 4.3 the testing setup. Sections 4.4-4.6 will discuss each iteration of the project.

4.1 User-centered design

This project was done from start to finish as a user-focused iterative process. To be able to answer the research questions, the user tests had to focus on several different aspects. Some tests had a focus on the usability of the application to see how users understood how to interact with the application and menus (RQ3), and see if the map information was visualized in a way so that the users understood what they saw (RQ2). Some tests focused more on the emotional impact of the application (RQ1). Most of the questionnaires, especially in the middle, also asked for feedback on what features and enhancements should be focused on for further development.

Though out the project, a total of 7 user tests with following questionnaires were completed, and as different user groups tested the application, the focus of the questionnaire were also affected by this. Some shorter tests were performed, to quickly change and improve certain aspects of the application before the more substantial tests. Between 7 and 10 people tested the application each time, with no repeated testings. An overview of tests can be seen in table 4.1.

#	Date	Testers	Description
1	October 3rd	8	Teacher students
2	January 14st	12	Teacher students
3	January 25th	7	Computer science students
4	February 14th	10	Teacher students
5	Febuary 15th	10	Teacher students
6	February 25th	7	Teacher students
7	April 29th	9	Geography students

Table 4.1: All user tests performed in the project

4.2 Tools and technologies

There exists a handful of tools for developing VR applications. In this section, the most important technologies used in this project will be presented.

4.2.1 Unity

Unity is one of the most popular game engines for developing 2D and 3D games, as well as other graphical applications. Unity can be used to develop for a wide variety of platforms, including computers, phones, TVs, and game consoles. In addition to developing VR for normal desktop computers, the software can be used for VR and AR development for PlayStation 4, Android, and iOS, among others.

Figure 4.1 shows a possible configuration of Unity, with five different views displaying different information. In this setup, it displays the Scene, Game, Hierachy, Project and Inspector views. In combination, these views are used to develop applications in a visual way, using a combination of object oriented (section 3.4.1) and component based (section 3.4.2) architecture.

The product developed in this master thesis is created in Unity, and available for Win-

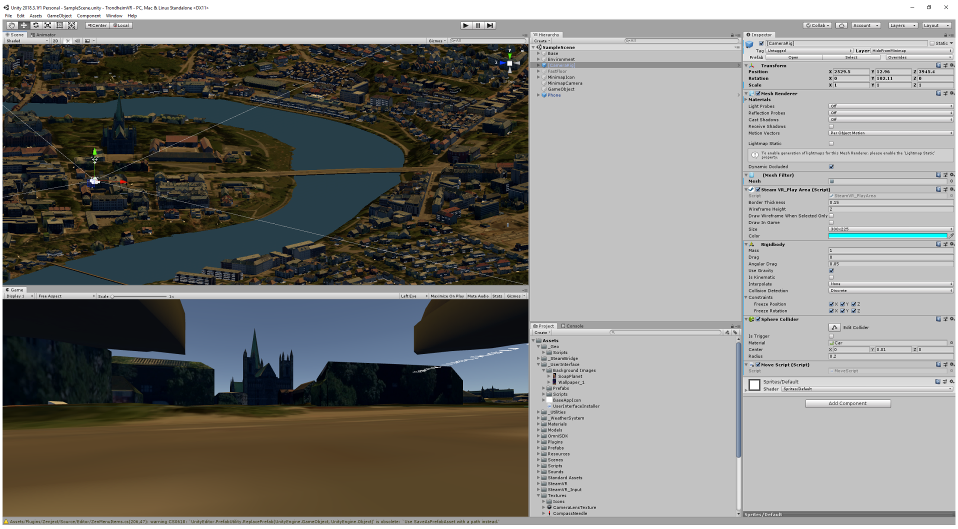

Figure 4.1: The Unity application

dows. There are multiple reasons for this choice. Most importantly, I am used to the software from both earlier school projects and work. The city model is easily imported into Unity.

SteamVR Plugin

The SteamVR Plugin is used to make development across different VR headsets easier. The plugin supports most VR headsets for PC, with three main goals: Loading the correct 3D model based on the controllers that are being used, handling the input, and estimating hand position on the controllers.

The input system is a central part of the plugin, making it easy to enable support for a wide variety of controller types. Instead of focusing on the button or trigger the user should use to perform an action (eg. A to jump), it instead puts the focus on the action (eg. jump). With such a variety of controller schemes that exists, this makes it easier for the developer. Instead of first checking what controller is being used, and then checking what button is being pressed, the program just listens for a specific action. The application developer can then create a default control scheme for each controller, which the user can override if he wants to. Figure 4.2 displays the interface, which can be accessed through the headset or a a web browser.

There exist several frameworks for speeding up development of VR applications in Unity, such as VRTK (Virtual Reality Toolkit). In this project, it was decided against using one of these. Using a framework would focus more of the learning on the framework, instead of basic VR development.

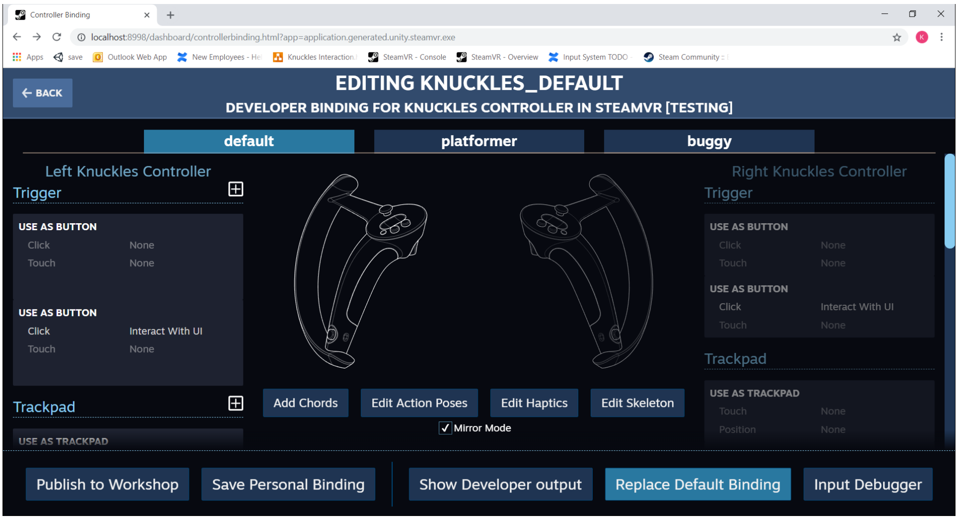

Figure 4.2: Controller bindings with SteamVR

Unity Collaborate

A VCS (version control system) is a system used to track file changes, and have a history of previous versions. This makes it possible for multiple people to work on the same file at the same time, or to revert back to an old version of a file or project. It also makes it easy to continue development on any computer. The original plan was to have the project on Github, but the city model made the project too large, and another solution had to be found.

Initially, a USB flash drive was used to copy files between computers. This quickly became a chore, with the action of copying taking at least 30 minutes. Unity Collaborate became the solution. Built right into Unity, this alternative to Github uses Git under the covers. Github was used on the side to keep track of bugs and features to be implemented

Figure 4.3: The IMTEL VRLab at Dragvoll.
Image downloaded from https://www.ntnu.edu/ipl/imtel in June 2019.

via an Issue tracking system.

4.3 Testing setup

During six out of seven testing sessions, the HTC Vive Pro and Vive controllers (figure 2.1) were used to test the application. The HTC Vive Pro is one of the most advanced VR headsets available on the market, with users being able to freely walk around in a room, and their movements reflected in the virtual environment (”room scale”). The Vive Pro has built in headphones for directional sound, and the controllers are built in with haptic feedback. The computers used during the tests had top of the line hardware.

The testing took place at the VR lab at Dragvoll in Trondheim. The lab is founded by the IMTEL group, which focuses on research around technology-enhanced learning. The lab is lead by one of the supervisors of this project; Ekaterina Prasolova Førland.

One test was performed outside the laboratory, using the HP Windows Mixed Reality Headset and Windows MR controllers. Instead of using room tracking, the headset tracks the controllers. The headset was connected to an Alienware Gaming laptop built for VR, receiving very similar frame rate to the desktop setup.

4.4 First iteration

The rest of the chapter will discuss the iterative process that took place. In reality, it is hard to divide development between specific iterations, with the following sections split into three logical sections to make reading easier. This section will discuss the initial prototype development, the user test that followed, and a discussion of the process and results. Refer to figure 4.4 for the different input methods mentioned.

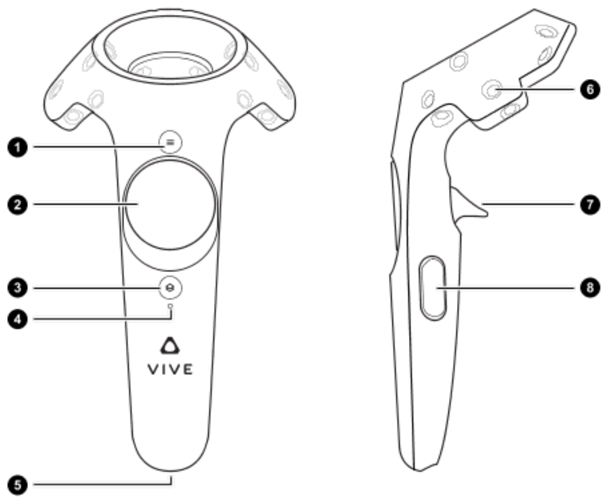

Figure 4.4: HTC Vive controllers. 1 = Menu button, 2 = Trackpad, 3 = System button, 4 = Status light, 5 = Micro-USB port, 6 = Tracking sensor, 7 = Trigger, 8 = Grip button.
Image downloaded from https://www.vive.com/us/support/vive/category_howto/about-the-controllers.html

4.4.1 Implementation

The prototype version of the application was developed in September as a base to get feedback from users. It included the 3D model of the city (discussed in section 3.1.1), and basic movement. By importing the SteamVR plugin, the application could already be viewed in the HTC Vive headset. This satisfied requirements R1-R3. The input system that was discussed in section 4.2.1 was just released, with documentation being sparse. Quite a lot of trial and error had to be done to figure everything out. In addition to moving around, three analogue interactions were implemented: Sea level, avatar height, and time of day.

Movement

To move around in the environment, the user could click on the trigger button on the back of the controller to teleport around. This type of movement is discussed in section 2.1.3. If using a room scale setup, movements in real life would also be reflected in the virtual environment. When using the SteamVR plugin, teleportation is generally easy to implement, but because of how the city model terrain was created, the teleportation had to be recreated from scratch. After implementation, this allowed users to freely move around in the city.

Sea level

After researching relevant works, and also seeing how sea level has a high risk factor in Trondheim (section 3.1), being able to see the effects of sea level rise seemed like a good idea to explore. The user would be able to increase and decrease the level, to see how a potential future Trondheim would look. The implementation was simple: a blue plane represented the water, with the user adjusting the height of the plane relative to the city model.

Avatar height

As discussed in section 2.1.3, the manipulation of scale can be useful for immersive field trips. When walking around in the city model being as tall as a normal person, it was quite disorienting and hard to navigate. A simple way to freely adjust the scale of the user was therefore implemented. As in the study on scale, this would theoretically be a good fit for this sort of application. On figure 4.5, the user is positioned at the same place, but scaled differently.

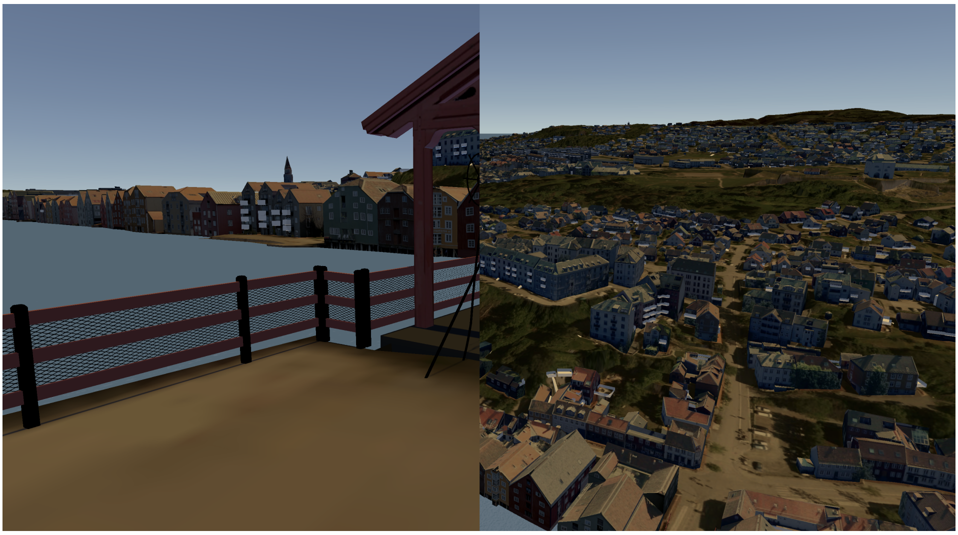

Figure 4.5: Perspective from street level (left) and from a bird's-eye view (left)

Time of day

To have a more realistic simulation, a light source representing the sun was created, with a day-/night-cycle of around 10 minutes. In addition to the automatic cycle, the user could adjust the time of day manually. This was in part inspired from the simple demo application developed in conjunction with the city model, as that also allowed the user to change time of day (section 3.1.1).

Menu interface

In section 2.1.3, three different types of menu interaction in VR was discussed. In the first prototype of the application, a simple floating menu was selected, as this was thought to be the easiest option to implement quickly. This menu would make it possible to change between the aforementioned interactions, and read the current values (for example time of day, see figure 4.6). The user would select a setting to change by pointing the controller to the button, and using the trigger button. She would then adjust the value by clicking on the top or bottom of the right controller trackpad.

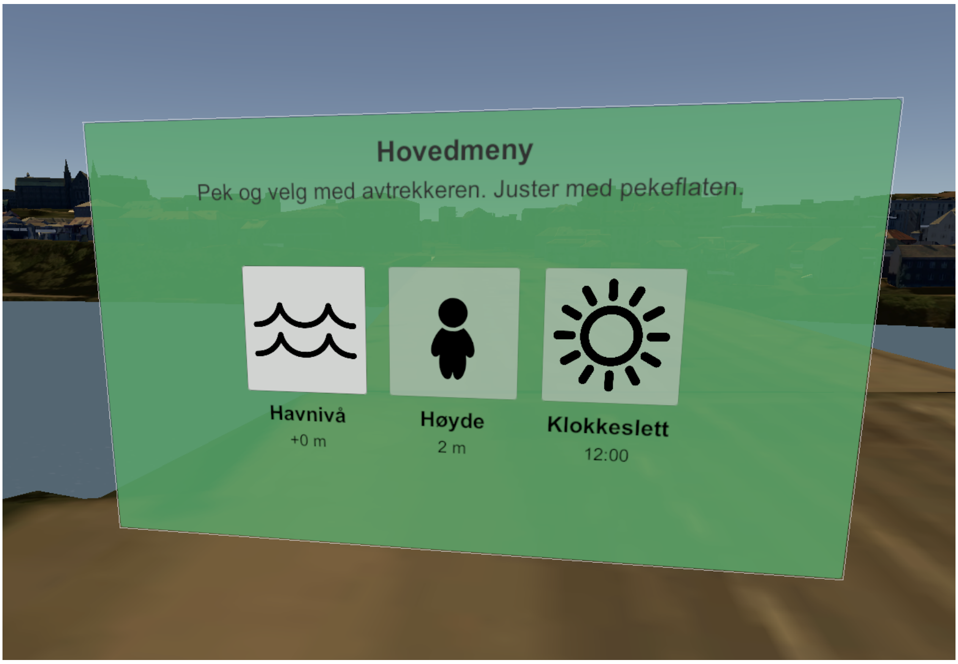

Figure 4.6: Floating interaction menu

4.4.2 Evaluation: User test

The first test was performed around one month after the application development started, to get initial feedback from users. 8 students at the teacher line at NTNU tried the application, and afterwards filled out a questionnaire. Before the testing, the application was introduced, with the general plan for the research. Any observations during testing were written down. In addition to age and gender, the questionnaire had seven questions the user would fill out on a Likert scale (strongly disagree to strongly agree). The answers were then coded from 1-5. The full questionnaire can be found in appendix A.1.

Most respondents believed that climate change is an important societal problem (table 4.7). The questionnaire compared the application to The Stanford Ocean Ocidification Experience (section 2.5.1), which the users had tried the same day. This should be a less relevant experience to most users, as it don't affect them directly. On the question ”I get a better understanding of climate change when I see it on a local level” (translated from Norwegian), 4 of the respondents answered with ”Mostly agree”, and 3 with ”Strongly

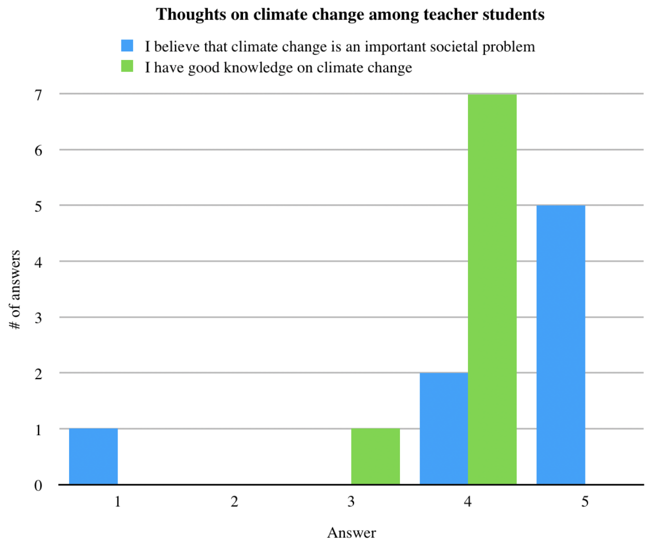

Figure 4.7: Thoughts on climate change among teacher students

agree".

The user group in this test were studying to become teachers. It was therefore interesting to get their feedback on VR as teaching tools. One question on the specific Trondheim application ("I would use the Trondheim application in teaching (when it's done)") and one on general VR ("Such VR applications should be included as part of the curriculum at NTNU") was included. The result can be seen in figure 4.8).

To get user feedback regarding features, one question let the participants rate potential features as important (1), no opinion (0), or not important (-1). Options included sea level rise, vegetation, climate data integration, navigation, game elements, information boxes, and visualization of historical data. By rating the options, the following ranked list was gathered (scores in parenthesis):

1. Sea level rise / information boxes / Visualization of historical data (5)
2. Climate data integration / vegetation and trees (4)
3. Navigation (3)
4. Game elements (-1)

The respondents could also add their own idea. Only three of the participants did this.

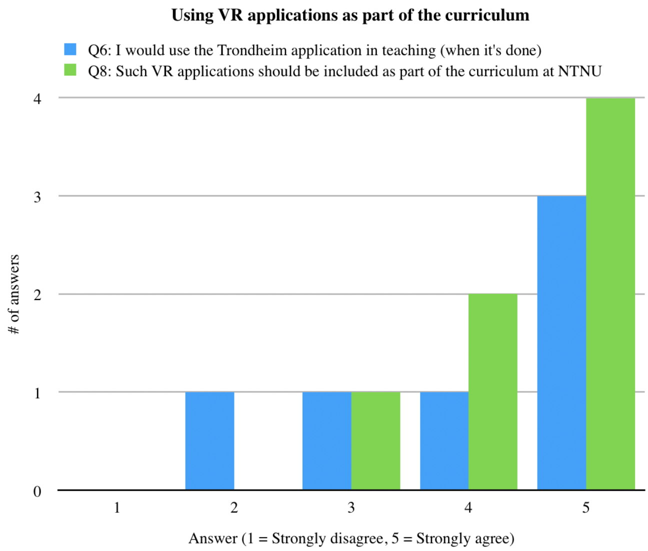

Figure 4.8: Using VR applications as part of the curriculum. 2 respondents did not answer Q6, one respondent did not answer Q8.

This is probably due to this taking additional cognitive effort, compared to circling boxes [11, p. 438]. Two respondents wanted to see a visualization of historical development, and one wanted a visualization of quick clay deposits.

4.4.3 Discussion

With this being the first iteration, it was just as much a test of me as the application.

Observations

User interaction and feedback is one of the best things about developing a VR application. Because of the very visual medium, the users are soon discussing possibilities, and how ”cool” it is - even in a very early stage of development. The challenge is getting past these initial comments, to get more helpful feedback.

During observation, finding the floating menu and understanding how to use it, was one of the main problems the users had. This was not a huge surprise, as it was just implemented as a fast way to enable interaction, without too much thought put into it.

The trigger button would (as default) be used both to teleport around, and to select from the menu. This is not ideal, as completely different actions should use different inputs. While the default way to teleport in SteamVR applications is with the trackpad on the front of the controller, here the trigger button was used, as the versatility of the trackpad was needed for other interactions. While the choice of button was a non-issue, the choice to have teleport be on button release rather than button down was hard for users to grasp. This should be changed for the next iteration. The menu should also be built up from the ground to be easy to find (and extend with more functionality), with a tutorial to introduce users to the interactions.

Even with no virtual representation of the self (except for floating controllers), participants reported that scaling up and down felt like becoming larger or smaller. Users preferred a larger-than-life height, and said it was a helpful way to get a better overview of the world. This fits in accordance with previous research. Another reported reason for liking the larger than life size was the low fidelity of the city model, with the elevated view keeping you further away from the details.

In addition to changing their height, users would also use time on changing the sea level. This was a surreal experience according to several testers. Because the project was just using a simple plane to represent the water, the reported sea level would not be 100 % accurate. A solution to this, as well as a higher fidelity water surface (reflections, refractions, waves) should be focused on for further development. Another problem with this version was that users could increase the water level with no limit. When the water was above eye height, it would become invisible. A limit to the height would have to be introduced, or some sort of underwater landscape created.

Users were mostly bothered with the automatic time of day adjustment, as everything was harder to see during night-time. Especially because it was just a visual change, there seemed like there was no reason to keep the automatic day-/night-cycle.

Questionnaire

Going into the questionnaire, the results were positive. Most participants believed that climate change was an important societal problem, and that VR applications should be a part of the curriculum. There was some mixed reactions on using this specific application as a teaching tool, but as it was still in early development, that's easy to understand. As most people agreed that seeing something on a local level is more effective than not, this sort of application is useful.

There are several potential problems with respondents having to answer questions on a Likert scale. When answering questions that have a ”socially correct” answer, some people might answer in a way that portrays themselves in a good light. In this case, the questions regarding climate change. Respondents may also avoid using extremes, agree with statements that are presented, and pick the options first given (in this case the negative ones). It's still a good way of gathering quantitative data, if using the results more as a guidance than set in stone.

The results from the feature options should also be taken with a grain of salt. The possible choices were way to vague, with several respondents not answering the question, and some adding question marks on the side of the page. Because of this, I would mostly focus on what the users said during the testing, what was observed, and the open ended question, for future development.

Conclusion

In the end, the first iteration was very useful, with several lessons being learned both about future development, and improving the process. Three requirements were completed (R1-R3), and 7 more were added (table 4.2). For the next iteration, the focus would be on improving the user interactions, as well as start the work on visualization of GIS data to actually be able to answer the research questions.

4.5 Continued iteration

This section will discuss the main part of the application development, including five user tests with following questionnaires. This represent the continued iterative process that was performed. In the end, the main findings are summarized.

ID	Requirement	Priority
R9	Interaction should be introduced by some sort of tutorial.	High
R10	Users should be able to access information about sea level and other data layers.	High
R11	The application should visualize historical data.	Medium
R12	The application should include vegetation to make it more realistic.	Medium
R13	Users should easily be able to get to landmarks in the city.	Medium
R14	Realistic underwater graphics.	Low
R15	Auditory feedback and ambience sounds should be included to increase immersion and emotional response.	High

Table 4.2: Additional requirements specified after the first iteration. The original requirements can be seen in table 3.1

4.5.1 Implementation

As discussed in the previous section, the requirements list was now extended with 7 additional requirements, for a total of 15. This section will go through the completion of some of these.

User interface

Section 2.1.3 discussed the three main methods of showing menus in VR. After the initial prototype, the implementation was changed from a menu floating in front of the user, to a menu pinned to the left controller. A virtual phone was created to be used to interact with the environment, to create a user experience that is close to what most people are used to in their daily lives - the smartphone. This sort of *interaction metaphor* takes the users knowledge from other domains to use [11, p. 278]. The right controller would still be used to change the sea level and avatar height, with the addition of using the grip button on the side of the controller to toggle between the different interactions. This new menu system was also extendable, making it easy to create buttons and sub-menus.

To select buttons and items on the menu, the user would tap the item on the screen with the right controller. This was again a design choice to make the experience close to what people do daily when they use their mobile phones.

Figure 4.9: The second iteration of the user interface, with the tutorial showing how to move around.

Tutorial

To complete requirement R9, and making the specific interaction patterns of this application clear to the user, a tutorial was created. The initial version of the tutorial was implemented before the third user test. The user would read and click through each step. Before the fifth user test, this was changed to having to actually perform each of the actions to continue the tutorial. ”Tutorials that cannot be completed until the user has indicated a clear understanding and effective interaction are a great method of inducing mental models into the minds of users” [11, p. 278].

Geographic modeling

To be able to answer the research questions, and complete several of the requirements, some way to display real map information in the city model was required. As all geographic information is available as GIS data, this meant converting 2D information to 3D geometry to be displayed by Unity. This was a process that took a lot of time, with steps detailed below:

1. **Creation of calibration points:** To be able to convert coordinates between different coordinate systems, at least two coordinates needs to be selected, where the coordinates in both systems are known. Two points in the city centre was selected, with some distance in both the latitudinal and longitudinal direction. This created a 'good enough' match between the systems, but getting a higher accuracy was something that would be a problem for the rest of the project.
2. **Methods for convertion between systems:** Next, methods to convert between the two coordinate systems had to be implemented. One method took in latitiude and longitude as parameters, and another took in x and z in the Unity coordinate system. Convenience methods that directly converted Unity's Vector2 and Vector3 to latitude/longitude was also created.
3. **Finding GIS layers:** There exists many different sources to get map information from. Some layers were downloaded from *The Norwegian Water Resources and Energy Directorate*, while others were created by one of the project supervisors.
4. **Parsing GeoJSON:** To parse the information, the third party parser *SimpleJSON* was used, as the native parser did not support the structure of the GeoJSON files. The library is fast, but the parsing still takes time because of the large files.
5. **Ray casting:** Because most GIS layers only use latitude and longitude pairs (and not height), the best solution for displaying the points right above the ground was the use of *Ray casting*. This meant moving the (x, y) point some height over the ground, and shooting a ray directly down until some surface was hit. This point was then set as the y coordinate of the point, thus having the completed (x, y, z). Some GIS layers also include height, but this was thrown away, as it did not accurately match with the city model height. Ray casting is not a very expensive operation, but with thousands of points, it still takes some time.
6. **Delaunay triangulations:** While parsing point and line data layers was simple, the format of polygon data made it hard to convert to Unity objects. While the GIS layers just included points at the outline of the areas, meshes require points in the middle to create triangles. After a long time of experimentation, the method of

Delaunay triangulation was discovered. Using the C# library Triangle.NET [30], points in the middle of areas were calculated, making it possible to create meshes, and fill sections. This was another slow process, and performance would have to be weighed against high details.

7. **Customizing layers:** To make it easier for the user to separate between the different layers and make the impact of different climate effects as big as possible, it was important to have the different layers look and feel different. Initially, the only difference was the color of the layers, to be improved later. All information about the layers, like name, description, and materials, would be stored in custom *ScriptableObject* assets.
8. **Optimizing:** During this entire process, it was important to think about how to go about optimizing the import and display of information. With huge text files to parse and display, this was a constant struggle. In the end, a solution was found to reduce the loading time to a few seconds, by creating custom methods to cache the results and meshes. The first time a new layer was loaded, or when any changes were done, the full loading time was required, often of 30 minutes.
9. **Chunking:** With huge data layers, containing thousands of thousands of objects and points, rendering these can be a problem unless the user has a powerful computer. To minimize the system requirements, a technique called *chunking* was implemented. By dividing the world up into squares, only the map features closest to the user would be loaded. Meshes in the same chunk were then combined into a single big mesh.

After completing these steps, requirement R4 was finally completed. R5 was almost fulfilled, but a few small changes to the file structure had to be done to work with the SimpleJSON parser. Some work was done on requirement R8, but the layers were still quite similar in appearance. See figure 4.10 for an illustration.

To show and hide layers, the user would select a button on the menu interface (figure 4.11). At the same time, she could read information about the specific layer, including what it represented, and why it was important. Very basic information about sea level rise was also implemented, to satisfy requirement R10.

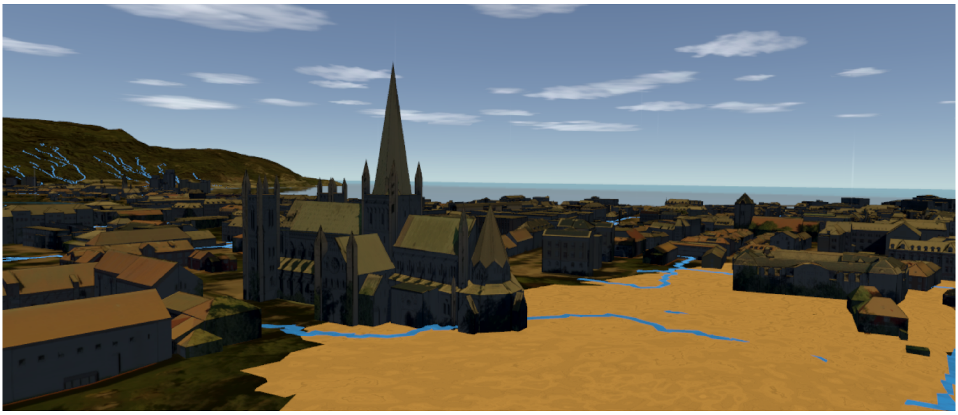

Figure 4.10: Quick clay and running water around the Nidaros Cathedral.

Figure 4.11: Loading the quick clay layer, and reading relevant information

Address search and interest points

To finish requirements R7 and R13, two new ways of getting around was implemented. First, some important landmarks in Trondheim were identified, including The Old Town Bridge, Studentersamfundet, and the Nidaros Cathedral. The user was able to select any of these on the menu, and teleport instantly. In a later iteration, a virtual keyboard and address search was implemented. By typing in any address, the user could teleport there. This could potentially help the emotional pull of the application, by the user seeing his or her house affected by climate change.

The address search use the Geocoding Service of the Google Maps API. By sending an address to the service, matches are returned with a corresponding latitude and longitude. Because the process should be easy for the user, the application appends ”Trondheim” to any search query.

Sensory feedback

To give an increased emotional impact and immersion (discussed in section 2.1.2), sound effects and haptic feedback was implemented for both ambience and user interactions (requirement R15). For a long time, traffic simulations based on CO_2 emission levels were planned added to see if it improved immersion. Because of time constraints, this had to be skipped. Instead, sounds of cars and city life was included, with the volume increased when the user was close to ground level. Rain effects would play, with increased intensity when the rain was most intense.

To get the user to better notice the controllers, sound sources were added to each controller. These would play when the user selected items, and when a part of the tutorial was completed. A gentle haptic feedback was used when selecting items, with stronger haptics when the user changed the sea level or changed his height.

Localization

The application was originally only in Norwegian, but it was soon realized that it should at least support English, as one of the supervisors, as well as several potential testers, didn’t speak Norwegian. A list of keys representing each text in the application was created. For each translation, the only thing needed to do was to copy the list of keys, one key per line, followed by the translation.

4.5.2 Evaluation: User tests

In this section, some of the main finding from observing the user tests and the questionnaire results are discussed. In total, five rounds of user tests were performed, but as the application was similar during some, some questions will be combined.

The first test was, as in the previous iteration, done with students and a few teachers, at the teacher education line at NTNU. A total of 12 people tested the application, and answered a short questionnaire afterwards. As this was before the tutorial was implemented, the participants got a short introduction to how to use the controllers. Because of the new way of interacting with the application, the focus of the questions was on the user experience. All three questions, except for the open ”general feedback” question, was to be rated on a five point Likert scale from ”Completely disagree” (1) to ”Completely agree” (5). The questions ”I had no problems understanding how to use the application” and ”I liked how navigation in the application worked” both had a mean of 4. Q3, ”An application like this can give a better understanding on how climate change affects the local community” had a mean of 5. In addition to this, there was a lot of general feedback, including a simpler way to get around (2 respondents), information about actual sea level rise predictions, and a need for more informational layers. In this version, only one test layer (quick clay) was implemented, and as the Delaunay triangulation was implemented later, it just displayed the outline of areas.

The second demo was performed at a conference for members of the Department of Computer Science at NTNU. Changes from the previous version included the initial version of the tutorial, and virtual keyboard and address search. As this was done at a remote location instead of the VR lab, the alternative equipment discussed in section 4.3 was used. This was a great way to test that the application would perform well with other equipment than the HTC Vive. The System Usability Scale (SUS) was selected as an evaluation form. By doing an analysis of the results, a SUS score of 73 was calculated (out of 100).

The next three demos would happen in a short span of time. The questionnaires were

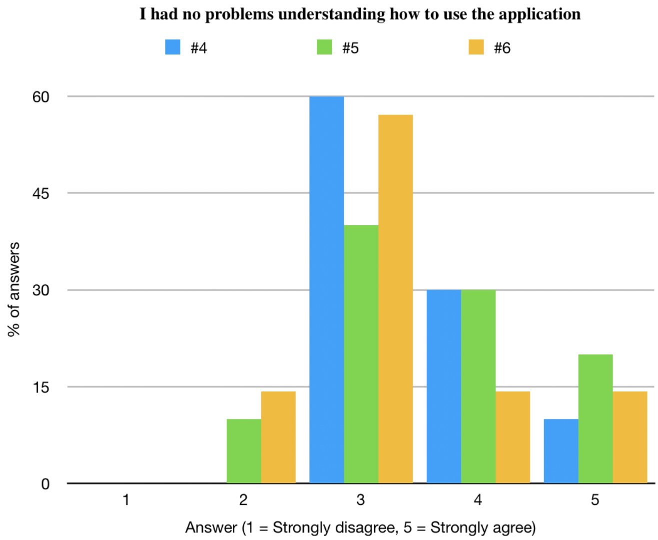

Figure 4.12: Users responses to question regarding application understanding from three user tests. As the number of respondents were different between tests, the values are represented as percentages.

similar, with a focus on the user interaction, and how to improve the application. Because of the problems of getting realistic visualizations into the application, it was still hard to gauge the emotional response from users. The application was identical between the first two demos (#4 and #5). On demo #6, the tutorial would be completed by performing the specified action, instead of clicking through. This was also the first time the map layers were actually filled in, instead of just showing outlines. On the question ”I had no problems understanding how to use the application”, the most frequent answer from all three evaluations was 3 (on a scale from 1-5). After user test #4, a question regarding liking the menu interactions had a most frequent answer of 4.

From demos #4-#6, additional feedback through observations and written feedback was gathered. Selecting menu options and changing the interaction mode was still difficult to understand (observed and received through written feedback). One respondent wanted audible explanations in addition to the text. Most respondents agreed that more work should be done on improving the visual of the layers, and give more relevant information.

4.5.3 Discussion

Implementation

Arguably the most important part of the project was being able to show GIS information augmented on the city model. This process, as discussed in the implementation section, took longer than planned, and created several problems. The first problem was finding the correct formulas for converting between two coordinate systems. Several formulas were tried, but all had a problem with accuracy. Warning users about this inaccuracy was the best solution found.

The method of Delaunay triangulation to calculate points inside areas was found quite late, and also required some time to implement. Until very late in the development, the layers displaying areas (such as quick clay), just displayed the outline of the areas. As this was difficult for users to understand, it also made it hard to answer the first research question until quite late in the process.

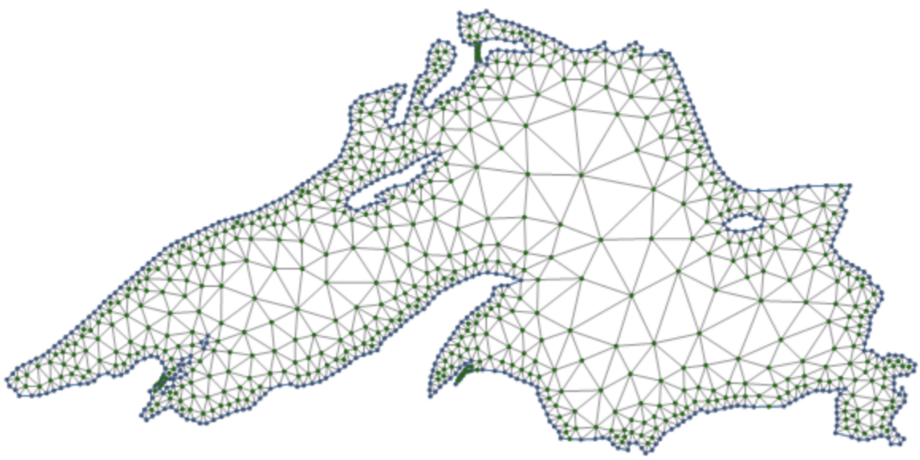

Figure 4.13: A delaunay triangulation of Lake Superior. By providing points along the edge, the algorithm calculates triangles and points in the middle. Source: [30]

When the Delaunay triangulation method was discovered, the long time to import layers was still an issue. When a solution to cache the import was finally implemented, not much time was left to create more advanced animations. Better interaction between the different layers would also have been preferable, but was again hard to accomplish in time. Another problem with the triangulation, was the distance between points created problems when ray casting. In some places the quick clay would be displayed above house roofs, as the resolution of the layers would have to be quite low for the sake of performance.

The very long import time made the requirement of users importing and displaying their own data sets less relevant, especially since it the import was error prone due to the difference in file structures between GeoJSON files.

Evaluations

The main takeaway from the evaluations, was that users liked the application and menu interactions, but had some initial difficulty understanding some of the interactions. Both changing interaction modes, and selecting menu options by ”tapping”, seemed to be less intuitive than ideal. Others understood it right away. The most positive results regarding understanding was actually from the first user test, when the tutorial was yet to be implemented. This was probably due to the explanation outside of VR before the demo took place.

The second user test, evaluated by the SUS scale was also positive in regards to the user experience, with a score of 73. This is regarded as ”Good”. With the participants having a computer science background, they were probably more comfortable with the headset and controllers, and had to a higher degree already experienced VR. In most of the other tests, few of the participants had ever tried VR before.

Because of the inability to see their hands in VR, some users didn’t know the location of the grip button in relation to their hands. Some users changed their grip, even if their finger was already on top of the button. Some participants tried pressing the trigger (teleport) button. Others pressed the System button, leading to a break in immersion, as they paused the application. Either the basic interactions had to be changed, or a better tutorial would have to be created. Ideas from users included highlighting the specific button, and having the text spoken instead of read. The last suggestion would also decrease arm fatigue from holding the controller up to the face.

As there was not much time left for development, improving the tutorial would have to do. As the users had understood the interactions when guided outside of VR (before the tutorial was implemented), it was also interesting to see if it was possible to make a tutorial in VR that was equally effective.

One thing I realized was that the menu was too advanced, because of several planned features that never panned out. I also received a proposal from one of my supervisors on a new menu that seemed logical. Implementing this would hopefully make the goal of the application more clear.

Conclusion

This iteration saw the completion of several requirements (R4, R7, R9, R10, R13), in addition to a few where development was started (R5, R6, R8). One additional requirement was added.

ID	Requirement	Priority
R16	Information should be read aloud, to better understanding and decrease arm fatigue.	High

Table 4.3: One additional requirement before the last iteration.

4.6 Final iteration

In this section, the implementation and evaluation of the final evaluation will be discussed. Compared to previous iterations, three different evaluation methods were performed, including demo sessions, a group interview, and an expert evaluation.

4.6.1 Implementation

This section reviews the features improved and developed during the final iteration, most notably simplified menus, a voice interface, and an improved tutorial. Most of the requirements were completed, with a few exceptions. The requirements will be discussed in the next chapter.

Simplified menus

Because of the way the menu system was implemented, creating new sub-menus was easy. The new menu strips away options that are not longer relevant or important. Instead, it only has three options: *Teleport* lets users teleport to a specific address. Instead of using the in-application keyboard, a person outside VR has to type in the specified address. *Sea Level* shows additional information about the current sea level, and how realistic it is. It also lets the user fast toggle between 0 meters, and 7 (the approximate rise if all of the Greenland ice sheet melts [13]). Instead of having realistic underwater graphics (R14), the maximum sea level is adjusted, with the user seldom being below the water surface. *Layers* lets users activate and deactivate additional information layers, and get information about the layers. The old way of using the application still exist, while this is more of a ”demo mode”. The final version of the menu can be seen in figure 4.14.

Figure 4.14: The three pages of the final menu. The main menu (left). Layers menu (middle). Sea level menu (right).

Voice interface

Instead of the user having to hold up their hand for an extended amount of time to read information on the menu screen, most text was removed, instead to be spoken to the user via a voice interface. This reduces arm fatigue, and the need to squint at text. There were two options for this implementation; either having a real person recording the voices, or using a text-to-speach synthesizer. The choice fell to the second option because of several reasons, but most notably to easily be able to change the text, or add new languages.

The application already took in use the Google Maps API (section 4.5.1), and it was an easy choice to also use Google's Cloud Text-to-Speech, which supports over 20 languages, including Norwegian. The voices sound natural, and the free tier of the service offers 1 million characters sent to the service. More than enough. The first time a text is to be spoken, a request is sent to the service. This returns the synthesized text as a base64-encoded string. The application saves the string to disk, to be retrieved and converted for subsequent uses. Any changes to the text will send a new request to Google.

Figure 4.15: Pointer tutorial

Tutorial improvements

One important aspect that had to be improved, was the tutorial at the start of the application. As the two-dimensional image of the controller did not work, it was changed to a three-dimensional model of the controller. This made it possible to do animations and highlight buttons through code. To make it even clearer what the user has to do, a red line is drawn between the actual controller and the miniaturized model. To be completely certain that users understand menu selection, they now have to select three small buttons to continue (see figure 4.15).

In the final iteration, the tutorial steps are as follows:

1. Short introduction to what the contents of the application is. The page will automatically change when the spoken text has finished.
2. A tutorial on how to use the pointer to select items on the screen. An animation that shows how to do the interaction is played. The user has to click on all three buttons to continue.
3. Information on movement by teleportation. The user has to teleport three times to continue.
4. Information on use of the trackpad. The user has to change the sea level to +1 meter.
5. Information on how to change what the trackpad adjusts. The user has to press the side button to change the interaction type to avatar height.
6. The user has to adjust his height to 100 meters to get a better overview.

Conclusion

With those features, the development had to be wrapped up. The last iteration was mostly changes to existing features.

4.6.2 Evaluation: User tests

In the final user test, 9 students from the geography line at NTNU tested the final iteration of the application. In addition to questionnaires and observations, application logs were recorded. The logs include the actions performed and the exact timestamps, and make it possible to to quantitative data analysis, including time to complete tasks. These logs are not identifiable to the testers. One of the recorded logs are included in Appendix B as an example.

Observations

Before each user started the test, they got a short introduction about the application. They were told it would show climate information relevant to Trondheim, that it wasn't 100 percent accurate, and that the sea level prediction followed RCP8.5. Because the test subjects studied at the geography line, most of them knew what this meant. If not, they got a short introduction to RCP (section 2.3). They were then showed how to hold the controller correctly to be able to reach all buttons without changing the hand position.

Task	Time (mean)	Time (median)
Step 2	12.22 sec	8 sec
Step 5	7.44 sec	7 sec
Total	1:51 min	1:43 min

Table 4.4: Time to complete the steps of the tutorial that previously was difficult, as well as the total time.

Both selecting menu items, and changing the trackpad mode seemed to be performed significantly faster than previously. Two of the test subjects asked what they were supposed to do in the selection part of the tutorial, but no answer was provided. They shortly figured it out by themselves. Table 4.4 lists the time to complete certain parts of the tutorial.

Questionnaire

Compared to previously, the final evaluation had a pre- and post-test questionnaire. This method, and some of the questions were based on [31]. The user was asked four questions before, and 11 questions after trying the application. Two questions were asked both before and after the experience, to establish a baseline of environmental behavior to. All questions used the Likert scale, this time with a six point scale (1-6) to avoid respondents picking the neutral options.

To make discussing the questionnaire easier, all the questions asked is presented in table 4.5. Answers are translated from Norwegian, with the original formulations found in appendix A.7.

Table 4.16 displays the environmental conscious behavior of users before and after the experience. While the questions before the experience had been answered with both 1 and two, the lowest score after the experience was 3. In general, the environmental behavior was more positive after the experience.

When it comes to the questions regarding worriedness (figure 4.17), the results were somewhat weighed to the high end of the scale, but there did not seem to be a higher worriedness for a specific neighborhood than Trondheim in general.

ID	Question
Q1	How experienced are you with Virtual Reality?
Q2	If possible, I use the bike/public transport over the car
Q3	I try not to take to long/hot showers
Q4	I have a good understanding of climate change
Q5	I felt worried when I observed Trondheim with an increased sea level
Q6	I felt worried when I observed my neighborhood with an increased sea level
Q7	I felt worried when I observed areas in Trondheim with quick clay and/or stormwater
Q8	I felt worried when I observed areas in my neighborhood with quick clay and/or stormwater
Q9	I felt present in the virtual environment
Q10	It was easy to understand how to interact with the application
Q11	After using the application my understanding on climate change has improved
Q12	I think this experience can motivate to a change in environmental behavior
Q13	If possible, I use the bike/public transport over the car in the future
Q14	I try not to take to long/hot showers in the future
Q15	At times I felt nauseous/dizzy during the experience

Table 4.5: The questions asked on the final questionnaire (translated from Norwegian). Questions Q1-Q4 were asked before the demo, while the rest were asked afterwards.

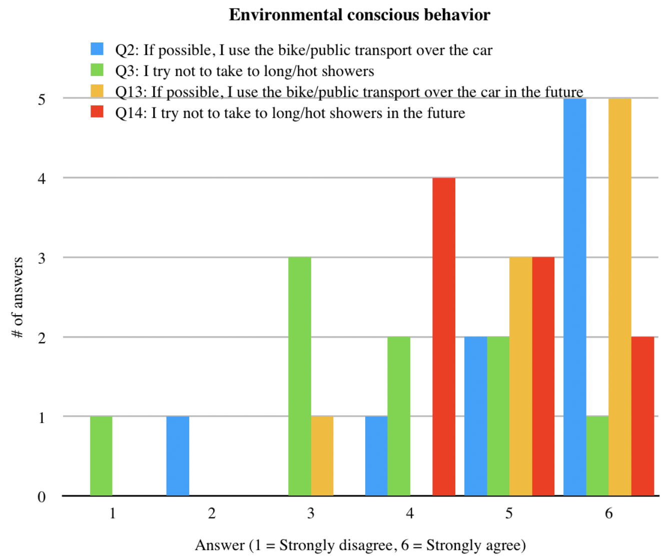

Figure 4.16: Environmental conscious behavior before and after.

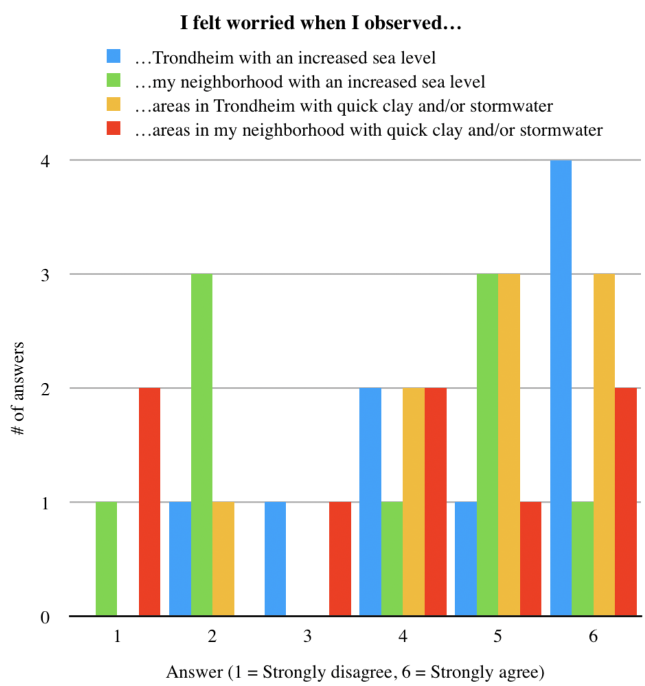

Figure 4.17: Users response regarding worriedness after using the application.

On the question regarding motivation to behavior change, most people responded with a 6, while the question regarding understanding was mostly answered with 3 and 4. This result, displayed in figure 4.18, will be discussed in the next section.

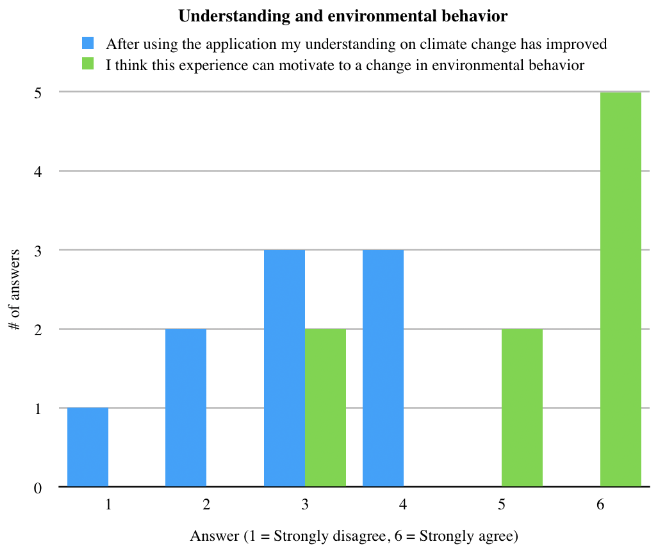

Figure 4.18: Understanding of climate change, compared to motivated environmental behavior change

With the improved tutorial, it was interesting to see how users understood the interaction. Four respondents answered with 4, and two with both 5 and 6, for a mean of 4.44. On the question ”I felt present in the virtual environment”, the mean response was 4.11.

4.6.3 Evaluation: Group interview

The last version of the application was tested by four representatives (three men M1-M3 and one woman F1) from Trondheim Municipality, with a following semi-structured group interview. Performing a group interview makes it easier for participants to share details about their common experiences, with a smaller group size enabling participants to share more anecdotes and find common ground. [22]

The interview lasted for 30 minutes, with participants especially eager to talk about possibilities with the technology. When talk got off-topic, the participants was guided back on track, either with a new question, or a follow-up question. The focus of the interview guide was on the emotional experience of the users, including positive and negative reactions, especially if they felt worried when seeing Trondheim below water or quick clay. They were asked how interacting with the application felt, including the tutorial and sounds. Lastly, a question regarding future development was included in the guide. After getting written permission, the interview was recorded, and the audio transcribed. In this section, the results are summarized by topic.

Emotional response

Asked how the emotional impact of the application was, M1 said that the sea level change over time was a good way for users to get a ”wake-up call”; being more aware of the changes that will happen to Trondheim, and what effects they will have. F1 said she saw her house beside quick clay, but as she already knew about this, it wasn’t a surprise. The emotional impact would be bigger if she had less knowledge.

F1 mentioned that emotions was another pathway to understanding, compared to the intellectual. By exposing politicians to the application, they would see information in a much more personal way than looking at a map, and use their heart to a larger degree. As politicians are normal people with different degrees of knowledge, this would be a good way for them to expand their knowledge, and understand the decisions they made (M1). Both M1 and F1 agreed that looking at a map would not create the same emotions.

Regarding the sounds, M2 said that the ambience of the rain increased the immersion. The city sounds were also positive, and he saw no problem in that the sounds were playing without any actual sources (cars or people). F1 agreed that the inclusion of background noise was important for the emotional response. The missing people could perhaps be included in the next version of the application. M2 liked the spoken voice during the tutorial.

Geographic information

M2 especially liked looking at the city from a bird’s-eye view, as it allowed him to understand relationships better, for example between quick clay areas. Being able to change the perspective allowed him to explore from different angles, going closer and further away. Looking from above gave more of a ”map feeling”, while still feeling like being part of the world. Compared to a 2D map, this 3D model displayed the information in the world, and M1 liked how it was easy to see the grade of the terrain. With the buildings on top, this made it possible to internally visualize what would happen if a landslide was to occur, and also think of the consequences. While ordinary maps can show dangerous spots as yellow or red, that’s much more abstract.

As the layers are displayed above the ground, F1 had a question about why. She felt that the display of quick clay was especially odd, since it in reality is below ground. When the technical reasoning was explained, she understood it, but said that this should be explained to users in some way, as it could cause some confusion.

Tutorial and user interface

When first trying the application with no explanation, there was some confusion about how to hold the controllers, and they had to change their grips. Everyone agreed that some sort of explanation should be done before taking on the headset, as this is technology most people haven’t tried. M2 believed that using two controllers with different actions was a bit difficult, and F1 agreed. M2 wanted to be able to teleport further. M1 proposed a solution to be able to teleport directly by selecting areas on a map. He also mentioned that he got lost when he was looking at street-level, and wanted some sort of indicator for were he was, for example the street address. Other than this, the interviewees liked the tutorial and user interface.

Continued development

While the developed application was a good step 1, several ideas were posed for both continued development, and similar applications that was outside the realm of climate. As the application uses standard GIS layers as a base, several other layers were suggested, such as noise levels and air pollution. An idea by F1 was displaying environmental toxins as skulls, and displaying scenarios when landslides or floods would carry them around. Another idea by F1 was a simulation of dam breaches.

The interviewees were enthusiastic about the use of the application as a planning tool. If politicians was to look at some areas of Trondheim, they would never dare to build in a traditional way (F1). They mentioned it would be interesting to compare the use of the application during planning meetings, with using traditional maps. In general, using such an application for planning the city going forward would be very useful.

4.6.4 Evaluation: Expert

In the end of the project, the application was evaluated by an expert in game design, human-computer interaction, VR, and AR. Before starting, the motivation for the application was introduced. The expert tried the application without interruption, before a short conversation took place. The key points of the conversation were written down.

In general, he was impressed with the application. The tutorial was well made, and easy to follow. The rising sea level was the most emotional part of the application, with the other layers being more abstract. The information about future sea level rise was a bit too buried, and should be more front and center.

With a few small changes, the experience would have been much more educational. Firstly, some sort of heads-up display with the current temperature or CO_2 emission status would have helped. The geographic layers could have been modeled and animated in a more exciting way. It would also have been interesting to get notified when key buildings and areas was affected, for example when the water rose above the main city square.

Chapter 5

Discussion

5.1 Final evalutions

Testers of the application had somewhat worried responses when seeing Trondheim under water, or covered by quick clay, and as the animations were quite tame, it seems like even basic simulations of climate effects gives emotional responses when displayed in VR. It would be interesting to see the responses to more advanced simulations.

Several of the answers to the last questionnaire seemed inconsistent. One of the most glaring examples of this was the answers to the questions Q11 vs Q12. As figure 4.18 shows, most users somewhat disagreed that the application improved understanding on climate change, while at the same time, most users thought the experience could motivate to changes in environmental behavior. One reason for this could be that the users already had understanding of the topic, and believed that users with less knowledge could be motivated to change. It might also be the different wording (climate change vs environmental), but this seems unlikely. In the end, it's hard to draw any definite conclusions.

It's also hard to draw any conclusions from the questions regarding worriedness, as users used the entire scale to respond. This might signify that the sea level and layers were too abstract and static for users to have any meaningful reactions.

Regarding changes in behavior, the results from the post-questionnaire was more positive than the pre-questionnaire. Means are calculated to (Q2: 5.11 vs Q13: 5.33 and Q3: 3.78 vs Q14: 4.77). As this is ordinal data, some would argue that calculating a mean is meaningless, but it still gives the result of positive change. The problem with this sort of question is still that users might answer in a way they think is preferable.

During the group interview, the emotional potential for such an application was more apparent: ”VR is an important tool to connect more to the emotional. Nobody gets very upset by seeing something on a map”. This difference between a 2D map and 3D representation would be interesting to directly compare, and see the difference in both emotional response and understanding.

As discussed in section 4.6.2, the time to complete the tutorial in the last version seemed to be reduced from previously, and users seemed more confident afterwards. With the more extended tutorial on menu selection (having to select three buttons), the users did not perform the action by accident. It would have been interesting to compare the results directly to the previous version, but the idea of generating application logs was unfortunately not thought about earlier.

One limitation by how the tutorial was implemented, was that the users were not incentivized to complete the tutorial as fast as possible. After unlocking the possibility to move around and manipulate the sea level, some users started trying to find their neighborhood or other landmarks. To get more correct timings, some way to motivate the user to complete the tutorial as fast as possible could have been implemented.

Another limitation of this result is that, as discussed above, the testers were shown how to use the controller. The grip button wasn't mentioned specifically, but they were told that they should hold the controller a specific way to be able to reach all the buttons at the same time. This introduction step should not have been performed, to more easily be able to compare the results to previous tests.

In the end, this method for user selection is not recommended, even if people grasped it quite quickly in the end. The tutorial had to be very detailed for users to understand the interaction. The same can be said for using the grip button for an important interaction, as people not used to the controller are unaware of its position. A simpler way of using the application, maybe using both controllers in the same way would probably have been more effective. In general, having the time to test more types of user interaction and menus would have been interesting, for example by A/B testing.

5.2 Project limitations

The main limitation of the thesis was time, and being just one person. Planning, creating a project from scratch, demonstrations and several iterations of a project, developed by a single person, while also writing an accompanying thesis, takes time. With a life on the side, and other obligations, this means some corners had to be cut, and desired functionality had to be left out, maybe to be developed at a later stage.

This limitation of being alone is especially apparent when it comes to VR, as it is both a new and cross-disciplinary field, and a lot of experimentation is needed to figure out what to do, and what directions to follow. Being two people working together would be very beneficial, especially with somewhat different fields of expertise.

Some of the limitations regarding the questionnaires are already discussed. When answering questions on a Likert scale, some users might select options that are ”socially correct” or agree with statements presented. Arithmetic means have been calculated from some questions, which some people argue is meaningless. Not having had any statistics courses was a limiting factor, with little previous practice in data analysis and gathering. Also, some of the questions could probably have been formulated better, or removed in favor of questions better for answering the research questions.

Little control was had over the timing of the user evaluations, and the number of participants that showed up. Especially after the last iteration, it would have been favorable with a larger sample size to get more definitive answers.

In general, it was difficult to measure empathy and behavioral change. Instead of asking direct questions, using an indirect measure like the amount of hot water used [2] or some other behavior could have given more accurate results. As some key parts of the application was slower to develop than planned, this also meant that questions focusing on empathy were useless in large parts of the study.

5.3 Not implemented features

As is the case with most other projects, the amount of features that was planned to be implemented in the start, was far greater than what was implemented in the end. Falling for the planning fallacy meant that the development of each feature took much longer time than expected. One feature that was never started because of time constraints, was visualizing historical data (R11).

The development of several features were started, but because of difficulties never implemented fully. One feature some time was put into, was a traffic system, with cars driving, and people walking around. The amount of motor traffic would reflect climate data. This was suggested as feature during the second user test, and would potentially improve the immersion in the virtual world. Unfortunately, because of time constraints, this could not be completed in time. Instead, ambient sounds were added to simulate a busy city.

To get a higher level of immersion, the development of a virtual avatar was started. By using additional trackers on your feet, and inverse kinematics, you would be able to see both your arms, hands, and feet in the virtual world, and the movement being reflected from your real body. A selfie camera was developed, where you could see your virtual body.

5.4 Reflections on the work

To round off, and look back at the work done in this thesis, I think narrowing the scope of the project would have been beneficial. Stating what not to do can be just as important as stating what to do [11, p. 393]. Some time was spent on developing features that was either never implemented. Being more focused on the core features would likely have made the application even better suited to answering the posed research questions. It would also have left more time to work more on the questionnaires, user tests, and the report.

Chapter 6

Conclusion

To conclude the thesis, this section discusses the application compared to the state of the art, before summing up the specific contributions. A section on future work is included.

6.1 Comparison

Table 6.1 summarizes some of the features of the applications discussed in section 2.5, with special focus on features related to the research questions. X* signifies that the application has the feature to a limited degree. As an example, walking around in The Stanford Ocean Acidification Experience is possible in certain parts of the application.

	Local (Trondheim)	**Data visualization**	**Story**	**Free walk**	**User interaction**
Stanford OAE	-	-	X	X*	X
Greenland Melting	-	-	X	-	-
Look Ahead - SF	-	-	X*	-	X
This is Climate Change	-	-	X	-	-
My app	X	X	-	X	X

Table 6.1: State of the art experiences in climate change and VR

6.2 Contributions

While results are discussed after each iteration, this section summarizes some of the contributions made, based on the research questions.

RQ1 To what extent can VR exposure to local climate change provoke empathetic response to modify environmental behavior?

With the societal importance of climate change, and the emergence of VR as a tool for increasing empathy, this question felt both important and interesting. While previous experiences has mostly focused on global topics, such as the Greenland ice or coral reefs, a local approach could lead to interesting results.

Based on this thesis, it's not easy to give a definitive answer to the question, but the key findings are summarized below:

- Even with basic visualizations, some people show an empathetic response to climate change. This might be those novel to VR.
- Participants self-reported environmental behavior are better after VR exposure
- Seeing effects on a local scale makes people more aware of the changes that are relevant to them
- When looking at something in VR instead of on a map, a more personal and emotional connection is created

RQ2 How can you implement and visualize two-dimensional climate data in VR to increase understanding of climate change?

There has been some work done on data visualizations in VR, with much less found on climate data. This is an interesting area to do more research on. A few key points are summarized:

- By being able to see the data from different perspectives, relationships are better understood
- Having information in three dimensions, it's easier to see how the data is affected by the terrain.
- During implementation, a focus on optimization need to be had from the start, especially with large data sources.
- Only using animations is not enough for good visualizations. Either more animations or sounds should be implemented.

RQ3 What is an efficient way to interact with menus in VR when visualizing climate change?

As there are still questions regarding VR and user interface, it was interesting to try a few less used techniques, even if getting negative results.

- If the experience is used by people new to VR, a tutorial outside VR is most likely needed

- Having to select menu items by physically tapping with the controller is most likely a bad idea, at least if the affordances are not apparent.

6.3 Summary

With climate change being an important societal problem, this thesis set out to investigate how a VR experience can help affect understanding of the topic. By focusing on local climate effects and inhabitants of Trondheim, a stronger emotional response was believed to be possible. Learning from previous work, it was discovered that not much exists when it comes to visualizing local climate data in VR, and the application would have to be developed through experimentation and a user-centered design approach. Arriving at the final application, it is hard to draw any definite conclusions regarding emotional impact, as . But it seems like VR is a good way to visualize climate data, with the ability to easily look at information from different perspectives. The results are also positive towards VR in general to visualize and make users empathize with climate change.

6.4 Future work

As discussed in section 5.2, the main limitation of this thesis was time, and that it was developed by a single person. With this, there are several features and enhancements that had to be cut before delivery. Some specific features are discussed in section 5.3, while this section discuss a few more general ideas.

When working on the project, it was clear that the sort of application developed was not just interesting around the city of Trondheim, but on a national scale. One of the focus areas during development was thus to create a generic base, with Trondheim-specific layers on top.

To start of, most of the application code has no mention of Trondheim, but uses generic names for classes, methods, and class members. By changing out the city model, creating new calibration points, and using new map layers, the project will work with any location in the world. A higher fidelity model of Trondheim can also easily be used. Some work can still be done with separating out the generic application logic to a separate module. This was unfortunately not completed due to time restrictions.

Some further development will be performed before The Big Challenge festival in June 2019, where the application will be demoed. With the results from the last iteration, and a larger sample size, hopefully some of the questions can be answered more definitive.

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Appendices

Appendix A
Questionnaires

Below is a presentation of the questionnaires in their original language. All questionnaires started with the respondents filling in their age and gender, to be sure to have the information if it would be needed in any analysis. Except for the third questionnaire, they were all printed and delivered to the test subjects.

A.1 First

Except for the 7th question, all questions were filled out on a scale from 1-5 (”Disagree completely” - ”Agree completely”). In question 7, the user should tick either ”Not important”, ”No opinion”, or ”Important” (”Ikke viktig”, ”Ingen formening”, ”Viktig”) for each item.

1. Jeg mener at klimaendring er et viktig samfunnsproblem
2. Jeg har god kunnskap om klimaendring
3. Jeg likte å bruke Stanford-appen
4. Etter gjennomføring fikk jeg en bedre forståelse av havforsuring
5. Jeg får bedre forståelse for klimaendring når jeg får se det på et lokalt nivå
6. Jeg ville brukt Trondheims-appen i undervisning (når den blir ferdig)
7. Hvilken funksjonalitet burde inkluderes i Trondheims-appen? (Havstigning, Vegetasjon og trær, Integrasjon med klimadata, Navigasjon, Spillelementer (quiz e.l.), Infobokser, Visualisering av historiske data)

8. Slike VR-apper bør inngå som en del av fagtilbudet ved NTNU
9. Har du andre forslag til innhold/funksjonalitet som kan være interessant i Trondheims-appen?

A.2 Second

The respondents was to answer on a scale between 1 and 5 for all questions except the last one, which was free form.

1. Jeg hadde ingen problemer med å forstå hvordan man brukte applikasjonen
2. Jeg likte hvordan navigering i applikasjonen fungerte (menyer, bevegelse, endring av havnivå etc)
3. En slik applikasjon kan gi en bedre forståelse for hvordan klimaendring påvirker lokalsamfunnet
4. Har du noen andre kommentarer/utdypninger (noen spesifikke problemer de hadde, hva mangler, hva kan bli bedre, annet)

A.3 Third

The form should be filled like a normal System Usibility Scale form.

1. I found the system unnecessarily complex
2. I thought the system was easy to use
3. I think that I would need the support of a technical person to be able to use this system
4. I found the various functions in this system were well integrated
5. I thought there was too much inconsistency in this system
6. I would imagine that most peoplewould learn to use this system very quickly
7. I found the system very cumbersome to use
8. I felt very confident using the system
9. I needed to learn a lot of things before I could get going with this system
10. Do you have any additional comments?

A.4 Fourth

Again, questions were answered on a scale between 1-5, except for the last free form question.

1. Jeg hadde ingen problemer med å forstå hvordan man brukte applikasjonen
2. Jeg likte hvordan navigering i applikasjonen fungerte (menyer, bevegelse, endring av havnivå etc.)
3. En slik applikasjon kan gi en bedre forsåelse for hvordan klimaendringer påvirker lokalsamfunnet
4. Har du noen andre kommentarer/utdypninger? (noen spesifikke problemer du hadde, hva mangler, hva kan bli bedre, annet)

A.5 Fifth

The last two questions were free form, while the rest were answered on a scale from 1-5.

1. Klimaendring er et viktig samfunnsproblem
2. Denne typen applikasjon (når ferdig) kan være et nyttig verktøy i undervisning
3. Jeg hadde ingen problemer med å forstå hvordan man brukte applikasjonen
4. Har du noen ideer til hvordan forskjellige kartdata (flomsoner, kvikkleire, utsatte områder etc) kan visualiseres effektivt for brukere av applikasjonen?
5. Har du noen andre kommentarer/utdypninger? (noen spesifikke problemer du hadde, hva mangler, hva kan bli bedre, annet)

A.6 Sixth

The questions were the same as in the fifth questionnaire.

A.7 Seventh

In addition to age and gender, the final questionnaire had a total of 15 questions. Questions 1-4 were asked before the demo, and the rest afterwards. This time, a six point Likert scale was used. Question one had a scale from ”Ikke erfaren”/”Not experienced” to ”Veldig erfaren”/”Very experienced”. All other questions had a the scale from ”Helt enig”/”Completely agree” to ”Helt uenig”/”Completely disagree”.

1. Hvor erfaren er du med Virtual Reality?
2. Om mulig bruker jeg heller sykkel/kollektivtransport over bil
3. Jeg prøver å ikke ta for lange/varme dusjer
4. Jeg har god forståelse for klimaendring
5. Jeg følte meg bekymret da jeg observerte Trondheim med et økt havnivå
6. Jeg følte meg bekymret da jeg observerte nabolaget mitt med et økt havnivå
7. Jeg følte meg bekymret da jeg observerte områder i Trondheim med kvikkleire og/eller overvann
8. Jeg følte meg bekymret da jeg observerte områder i mitt nabolag med kvikkleire og/eller overvann
9. Jeg følte meg til stede i det virtuelle miljøet
10. Det var enkelt å forstå hvordan man skulle interagere med applikasjonen
11. Etter å ha brukt applikasjonen har min forståelse for klimaendring blitt bedre
12. Jeg tror denne opplevelsen kan motivere til endring i miljøadferd
13. Om mulig bruker jeg heller sykkel/kollektivtransport over bil i fremtiden
14. Jeg prøver å ikke ta for lange/varme dusjer i fremtiden
15. Til tider følte jeg meg kvalm/svimmel i løpet av opplevelsen

Appendix B

Example log file

Below is an example of a log file generated from the last user test. Each action was appended to an array, then saved to disk either when the application was terminated, or when the scene was reloaded for a new person.

```
[11:16:04] Moved to new chunk (Chunk(6,8)) with 8 neighbors
[11:16:05] Player height adjusted to 5.0m
[11:17:47] Finished step 0 of the tutorial.
[11:17:54] Selected button with name: Tutorial_Button2
[11:18:23] Selected button with name: Tutorial_Button1
[11:18:29] Selected button with name: Tutorial_Button3
[11:18:29] Finished step 1 of the tutorial.
[11:18:42] Teleported to (2566.3, 14.5, 3720.9) with laser
[11:18:53] Teleported to (2560.4, 14.5, 3735.2) with laser
[11:18:55] Teleported to (2556.4, 14.5, 3753.2) with laser
[11:18:55] Finished step 2 of the tutorial.
[11:19:24] Teleported to (2570.4, 14.6, 3747.9) with laser
[11:19:26] Sea level adjusted to +0.2m
[11:19:28] Sea level adjusted to +0.0m
[11:19:32] Teleported to (2585.1, 13.4, 3737.5) with laser
[11:19:35] Sea level adjusted to +0.1m
[11:19:37] Finished step 3 of the tutorial.
[11:19:41] Sea level adjusted to +4.5m
[11:19:45] Finished step 4 of the tutorial.
[11:19:45] Changed to interaction AvatarHeight
[11:19:57] Player height adjusted to 55.0m
[11:20:00] Player height adjusted to 67.6m
[11:20:05] Teleported to (2628.2, 14.8, 3903.7) with laser
[11:20:06] Finished step 5 of the tutorial.
[11:20:07] Player height adjusted to 130.9m
[11:20:09] Player height adjusted to 155.9m
[11:20:17] Player height adjusted to 147.6m
[11:20:18] Changed to interaction TimeOfDay
[11:20:44] Teleported to (3056.1, 7.1, 4050.9) with laser
[11:20:53] Teleported to (3356.5, 10.3, 4484.5) with laser
[11:20:53] Moved to new chunk (Chunk(7,8)) with 8 neighbors
[11:21:04] Teleported to (3602.7, 8.0, 4716.6) with laser
[11:21:09] Teleported to (3838.8, 8.0, 4956.1) with laser
[11:21:09] Moved to new chunk (Chunk(7,9)) with 8 neighbors
[11:21:11] Teleported to (4183.9, 11.7, 5034.0) with laser
[11:21:14] Changed to interaction WaterLevel
[11:21:19] Sea level adjusted to +7.4m
[11:21:28] Sea level adjusted to +5.6m
[11:21:37] Selected button with name: LayerButton
[11:21:42] Loading layer Layer_name_waterway
[11:21:42] Selected button with name: ActivateWaterWays
[11:21:52] Loading layer Layer_name_quickclay
[11:21:52] Selected button with name: ActivateQuickClay
[11:21:52] Layer_name_quickclay layer already loaded
[11:21:55] Deactivated layer Layer_name_waterway
[11:21:55] Selected button with name: ActivateWaterWays
[11:22:10] Sea level adjusted to +4.3m
```

```
[11:22:11] Selected button with name: ActivateQuickClay
[11:22:11] Selected button with name: QuickClaySpeak
[11:22:14] Teleported to (3759.6, 9.2, 4770.3) with laser
[11:22:14] Moved to new chunk (Chunk(7,8)) with 8 neighbors
[11:22:20] Loading layer Layer_name_stormwater
[11:22:20] Selected button with name: ActivateStormWater
[11:22:20] Layer_name_stormwater layer already loaded
[11:22:35] Sea level adjusted to +2.8m
[11:22:42] Deactivated layer Layer_name_quickclay
[11:22:42] Selected button with name: ActivateQuickClay
[11:22:44] Deactivated layer Layer_name_stormwater
[11:22:44] Selected button with name: ActivateStormWater
[11:22:51] Changed to interaction WaterLevel
[11:22:51] Selected button with name: SeaLevel
[11:23:13] Sea level adjusted to +7.9m
[11:23:15] Sea level adjusted to +8.4m
[11:23:16] Sea level adjusted to +8.5m
[11:23:23] Sea level adjusted to +8.4m
[11:23:24] Selected button with name: 7m
[11:23:24] Sea level adjusted to +7.0m
[11:23:36] Selected button with name: 7m
[11:23:36] Selected button with name: 0m
[11:23:37] Sea level adjusted to +0.0m
[11:23:55] Teleported to (4130.2, 11.0, 5015.2) with laser
[11:23:55] Moved to new chunk (Chunk(7,9)) with 8 neighbors
[11:24:18] Teleported to (4510.5, 19.4, 4999.8) with laser
[11:24:23] Teleported to (4577.5, 22.0, 5005.2) with laser
[11:24:27] Sea level adjusted to +1.9m
[11:24:35] Sea level adjusted to +8.0m
[11:24:42] Sea level adjusted to +3.3m
```

Appendix C

Risk and vulnerability analysis

Klimaendringer - utredningstema			Sannsynlighet		Klimasårbarhet - konsekvens og risiko		
Hovedårsak	**Klima-relatert hendelse**	**Detaljer**	**Grad**	**Faktor**	**Liv og helse**	**Ytre miljø**	**Materielle verdier**
Økt nedbør	**Ekstrem-nedbør**	Flom	Meget sannsynlig	4	2	2	4
			Risiko		**8**	**8**	**16**
	Flom	Regnflom	Meget sannsynlig	4	2	2	4
			Risiko		**8**	**8**	**16**
		Snøsmelteflom	Mindre sannsynlig	2	2	2	3
			Risiko		**4**	**4**	**6**
		Isgang	Mindre sannsynlig	2	1	1	2
			Risiko		**2**	**2**	**4**
	Skred fra fjell	Steinskred, -sprang	Meget sannsynlig	2	2	2	2
			Risiko		**4**	**4**	**4**
		Fjellskred	Usannsynlig	1	1	1	1
			Risiko		**1**	**1**	**1**
	Skred i løsmasser	Jordskred	Meget sannsynlig	4	3	3	4
			Risiko		**12**	**12**	**16**
		Kvikkleire-skred	Sannsynlig	2	4	4	4
			Risiko		**8**	**8**	**8**
	Skred i snø	Løssnø/ flak	Mindre sannsynlig	2	1	1	1
			Risiko		**2**	**2**	**2**
		Sørpe	Mindre sannsynlig	2	1	2	2
			Risiko		**2**	**4**	**4**
Økt vind	**Sterke vinder**		Meget sannsynlig	3	2	4	3
			Risiko		**6**	**12**	**9**
	Stormflo		Meget sannsynlig	4	2	3	3
			Risiko		**8**	**12**	**12**
Varmere klima	**Økt lokal temperatur**		Meget sannsynlig	4	1	2	1
			Risiko		**4**	**8**	**4**
	Tørke		Sannsynlig	3	1	2	1
			Risiko		**3**	**6**	**3**
	Havstigning		Sannsynlig	4	1	3	3
			Risiko		**4**	**12**	**12**

Table C1: A Risk and vulnerability analysis developed by Trondheim Municipality. As some of the specific terms are hard to translate correctly, all terms are left in Norwegian.

NTNU
Norwegian University of
Science and Technology