Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Information Technology and Electrical Engineering
Department of Electronic Systems

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Master's thesis in Electronics Systems Design and Innovation
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# Abstract

Over the past decades, the data quantity and complexity has increased rapidly. Without the right tools to present and analyse the large quantity of data, the data might become incomprehensible. To utilise the data in the best possible way, we need to explore new methods and tools for data analysis and how they impact the Quality of Experience (QoE) of the end-users. The QoE is important to investigate in order to gain knowledge about new analysing methods and tools because it measures the end-to-end performance and the users' overall experience of the service.

In this research, we investigate new methods of exploring data through Immersive Analytics (IA) by using immersive multimedia technologies such as Virtual Reality (VR) as an analytical tool. IA can be used to analyse and visualise data when the standard desktop setup is insufficient. It allows the user to be immersed in the data and can provide a new perspective. However, understanding to what extent IA and the use of VR as an analytical tool impact the users' QoE and level of understanding compared to the standard desktop for 3-Dimensional (3D) data visualisations remains unclear. The primary purpose of this study is to determine to what extent does a Virtual Reality Environment (VRE) affect the users' QoE, and to what extent does a VRE affect the users' understanding of the data?

In this thesis, we design, develop, and compare an interactive prototype for 3D weather data analytics in two analysis environments: a Desktop Environment (DE) and a VRE. 12 participants (6 for each environment) were presented with 4 tasks to explore and analyse the displayed weather data. The participants interacted with the prototype to analyse the presented data in order to find the correct answers. The number of incorrect answers for each task provided objective measures regarding the users' level of understanding. Subjective measures, including qualitative data, of the experience, were provided through a post-hoc survey.

The results report that participants felt that the visual aspect of the VRE was more involving than the DE, and they were less conscious of being in the real world. This show a minimal increase in QoE for the VRE. For the users' level of understanding, the subjective measures report that the DE led to a higher level of understanding. In contrast, the objective measures report less incorrect answers for the VRE. However, the results fail to report any significant difference confirming a difference in the users' level of understanding between the analysis environments.

We conclude that VRE provides the user with a comparable level of understanding to the DE when analysing data, but it does not necessarily increase the users' level of understanding. However, we conclude that IA and VR increase the users' immersion when analysing weather data, resulting in a minimal impact and improvement in QoE.

# Contents

# Chapter 1

# Introduction

We are living in the era of "Big Data". Every day the data volume increases and so does the complexity of the datasets. At the same time, people are regularly exposed to all kinds of data and utilises this information to draw conclusions and make decisions. Therefore it is necessary to find new tools to present and analyse the data before it becomes too complicated. The emerging research field, named Immersive Analytics (IA), addresses this problem and investigates new possibilities for presenting data in an intuitive and meaningful manner. It is possible to say that humans are visual creatures and that the brain is excellent at recognising patterns and shapes, and consequently more responsive to visual data. IA utilises this by combining data visualisation and immersive technologies to imitate the perceptions and interactions of the real world, thus acting as a bridge between the data and human intuition.

Today, the most common setup for analysing data is a desktop screen, a mouse, and a keyboard. However, new technologies create new opportunities for presenting and analysing data. Over the last decade, there have been significant advancements in the field of immersive technologies such as extended reality, tangible surfaces, and large displays. An example is Mechdyne's room-sized Cave Automatic Virtual Environment (CAVE) that combines high-resolution, stereoscopic projections, and 3-Dimensional (3D) visualisations to create an immersive analysis environment [1]. Nowadays, many companies are developing immersive technologies such as Head-Mounted Displays (HMDs), this includes Microsoft's HoloLens [1] and HTC Vive [2]. The development of HMDs results in products being offered to a fraction of the price and size compared to Mechdyne's CAVE and making HMDs more available to the consumer market. Similarly, we see extensive development in sensor technology and artificial intelligence. Immersive technologies can take advantage of this to develop better applications and software with f. ex: better speech recognition and hand gestures.

[1]https://www.microsoft.com/en-us/hololens
[2]https://www.vive.com/us/

This research looks at the difference in weather data analysis for two different analysis environments: Desktop Environment (DE) versus Virtual Reality Environment (VRE). Every day people are making decisions based on the weather, f. ex. airports can determine flight schedules, taxi companies can plan how many taxis should be available, and a person can decide what to wear. In other words, the weather affects everyone, the general public, industries, and businesses. Consequently, being able to interpret and draw conclusions from weather data is essential when planning and making decisions. A prototype displaying 3D weather data is implemented to address the difference for weather data analysis between the VRE and the DE. The prototype allows for user interactions to manipulate and analyse the presented data. The VRE presents 3D weather data within an HMD, while the DE presents 3D weather data visualisations on a 2-Dimensional (2D) screen. In each environment, the user is presented with 4 tasks they must answer by using interactions to explore and analyse the weather data. The number of incorrect answers is collected to measure the difference objectively. A post-hoc survey subjectively and qualitatively measures the experience.

This study investigates how the analysis environment impacts the users' Quality of Experience (QoE) and level of understanding when analysing weather data in an HMD VRE compared to a 3D DE. More precisely, we ask (i) to what extent does a virtual reality environment affect the users' Quality of Experience when analysing data? (RQ1), and (ii) to what extent does a virtual reality environment affect the users' level of understanding when analysing data? (RQ2).

This research contributes to the field of IA and will contribute to the utility of Virtual Reality (VR) as an immersive analytical tool. This study also contributes to the World of Wild Waters: Gamification of Natural Hazards project at the Norwegian University of Science and Technology (NTNU) by exploring a technology stack that allows for visualising data on a map.

In this thesis, we present the findings of our research from a case study comparing two analysis environments for interactive 3D weather data analysis. First, we present relevant concepts and related work. Next, we present the design and implementation of the prototype used in the experiment, followed by a presentation of the experimental design and setups. In the end, we present the results, along with discussion and limitations. Finally, we deliver a conclusion and suggestions for further work.

# Chapter 2

# Background

## 2.1 Immersive Analytics

First, we present the emerging research field of immersive analytics by looking at previous research. Previous studies investigate how novel interfaces and devices can be utilised to present the data in a new and meaningful manner. Since immersive analytics benefits from technologies such as VR, natural user interface devices, and sensors, it can further immerse the user into the data [2], allowing the user to interact and perceive the data from an inside-out-view.

Chandler et al. [2] introduce immersive analytics through several examples. The examples look at how one can exploit the opportunities provided by immersive technologies to create better analysis tools for better reasoning and decision making. They explain that immersive analytics share many goals with visual analytics, but focuses more on immersive technologies, not only data visualisation. They also suggest that the term "immersive" does not only include 3D VR displays, but also tangible surfaces since they allow for more direct and natural interaction compared to a desktop.

## 2.2 Related Work

### Comparing Analysis Environments

Bach et al. [3] researches how effective it is to explore and interact with 3D visualisation by comparing three different analysis environments: an immersive Augmented Reality (AR) HMD (Microsoft HoloLens) environment, a handheld tablet AR environment, and a desktop environment. The environments exploited the natural human perception in different ways and are evaluated by conducting an experiment consisting of 4 tasks. The results reveal that each environment had its strengths, and the AR HMD environment was equally as precise as the desktop environment. However, the AR HMD environment outperformed the two other environments for tasks that required high manipulation.

Millais et al. [4] looks at the difference of exploring data in VR compared to 2D data visualisation on a desktop. They report on how VR affects the users' experience and understanding of data by asking the participants to report any insight they gain during the data exploration. The results show no significant difference in the overall data exploration between the two environments. However, the results revealed that the performance workload was lower for the VR. This result corresponds to the participants in VR feeling more successful when the doing tasks and satisfied with their performance, which resulted in fewer inaccurate insights reported for the VR environment.

Furthermore, Wagner et al. [5] compare three approaches for analysing multidimensional data: desktop-based 2D, desktop-based 3D, and immersive HMD. The results were conducted through user tasks, followed by a subjective questionnaire. The results indicated an advantage for classification accuracy, distance perception, and outlier identification. From the subjective measurements, the immersive setup was rated more accurate and engaging for the tasks.

### Visualising Weather Data

Very recent work from Li et al. [6] presents a preliminary report using Oculus Rift S to visualise meteorological events. In collaboration with Earth Science experts, they developed an interactive VR system to visualise spatiotemporal atmospheric weather named *MeteoVis*. They demonstrate MeteoVis through a pilot case study with meteorologists [7], [8]. The preliminary report does not present any results from using MeteoVis as an analysing tool.

Andersen et al. [9] explores weather data visualisation by using three different interfaces: a desktop display with input via Xbox One controller, VR with input via Xbox One controller, and VR with input via *Leap Motion* and they collected the results through questionnaires and user tasks. The results report no statistically significant differences in the visualisation tasks. However, the VR display with the controller was overall rated significantly higher than the desktop display, including significantly higher for data comprehension.

## 2.3 Quality of Experience

The QUALINET white paper on definitions of Quality of Experience [10] defines QoE as:

> *"The degree of delight or annoyance of the user of an application or service. It results from the fulfilment of his or her expectations with respect to the utility and / or enjoyment of the application or service in the light of the user's personality and current state."*

QoE does consider not only the system but also the content and the user as a factor. Numerous influencing factors (IFs) such as human (HIF), system (SIF), and context (CIF) factors can impact the QoE. HIFs are very complex and can influence the user on two levels: a low-level (f. ex. age, physical, emotional, and mental constitution) or a high-level (f. ex. previous experience, prior knowledge, understanding, interpretation). SIFs are content-, media-, network-, and device-related (f. ex. bandwidth, screen size, audio, frame rate). While CIFs embrace the situational properties to describe the users' environment f. ex. physical-, social-, task-, temporal-, and technical (f. ex. task type, inter-personal relations, location) [10, 11].

# Chapter 3

# Method

## 3.1 System Design

### 3.1.1 HTC Vive

In this research, the VRE was deployed on an HTC Vive, which an HMD is developed by HTC and Vive. It consists of an HMD, two base stations, and two 360-degree controllers [12]. HTC Vive displays the content on two high definition screens (1080 $\times$ 1200 pixels per eye) with a refresh rate of $90Hz$, 110 degrees field of view [13], and it weights $470g$ [12]. According to Vives website, HTC Vive can provide the user with haptic feedback, directional audio, and headset tracking.

The base stations, also known as a lighthouse tracking system, consists of two boxes. When placed in opposite corners of the room and facing diagonally towards each other, they create a 360-degree play area [14]. The base stations are continuously tracking the position and movements of the HMD and controllers within the play area.

The user can interact and teleport within the VRE by using one of the two handheld controllers. The controllers have five interactable buttons: trackpad, grip buttons, trigger button, system button, and a menu button [13].

### 3.1.2 Unity

The cross-platform game engine Unity was used to develop the prototype for this research. Unity allows developers to create immersive and interactive experiences. Unity is developed by Unity Technologies [15], and is a world's leading platform for developing interactive and real-time content in 2D and 3D [16].

### 3.1.3 SteamVR

SteamVR is a Unity plugin developed by Valve Corporations. It allows developers to easily create VR applications that can run on popular HMDs, such as HTC Vive. According to Valve Corporations, SteamVR manages three things for developers: *"loading 3d models for VR controllers, handling input from those controllers, and estimating what your hand looks like while using those controllers"* [17].

### 3.1.4 Mapbox

Mapbox is a developer platform used to create applications in need of maps, data, and spatial analysis [18]. Through Application Programming Interfaces (APIs) and Software Developer Kits (SDKs) Mapbox delivers maps (in 2D and 3D) and locations. One of the core features of Mapbox is Mapbox Studio which allows developers to customise the map design [19]. To implement the map used in this prototype, we used the Mapbox SDK for Unity. It lets the developer build Unity applications with real map data. Developers can interact with Mapbox APIs and create GameObjects by using C#-based API and Graphical User Interface (GUI) [20]. The SDK also allows the developer to insert a longitude and latitude to create a GameObject at the desired location.

### 3.1.5 Dark Sky

Dark Sky API was used to provide weather data. The API can return either a forecast or historical weather data for anywhere in the world. A forecast request returns the current weather conditions and a forecast up to a week. While a historical weather request can return weather conditions going back decades. However, both requests will return data in a JSON format. The Dark Sky API takes in longitude and latitude and outputs weather data for the location. The API offers an extensive collection of meteorological conditions including, temperature, precipitation rate, and wind speed [21].

### 3.1.6 OpenCage Geocoder

OpenCage Geocoder was used to convert city names to their respective longitude and latitude via a RESTful API [22].


Figure 3.1: Overview of the prototype.

## 3.2 Data Visualisations

The prototype and its visualisations were implemented by using Unity, SteamVR, Mapbox, Dark Sky, and OpenCage Geocoder. Figure 3.1 show an overview of the prototype. The prototype presents the user with a map of Norway provided by Mapbox. The map is presented in a virtual outdoor environment with an encapsulating skydome. The outdoor environment was chosen due to the possibility to visualise weather data as a part of the users' surrounding. However, the majority of the data is presented on the map.

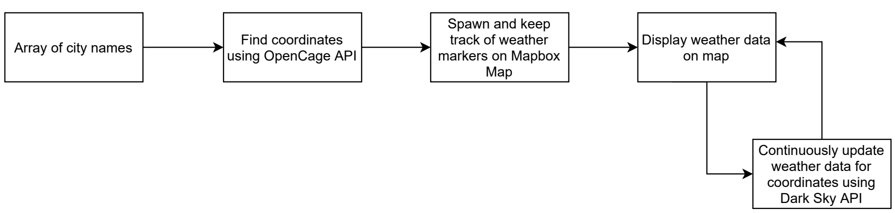



Figure 3.2: Flow chart of how weather data (GameObjects) are being created at the correct geographical location on the map.

### 3.2.1 Spawning Weather Data on the Map

To present weather data (GameObjects) on the map, we used Mapbox, Dark Sky, and OpenCage Geocoder. Figure 3.2 show a flow chart on how the GameObject was created at the correct geographical location on the map. First, we presented an array of strings to the user, where one could add the desired city names. For each of the entries in the city name array, the OpenCage Geocoder API converted each city name to a GPS coordinate (longitude, latitude). A map was created through the Mapbox SDK. The created map from the Mapbox SDK contained a function that transformed the GPS coordinates to a position in the Unity scene, making the GameObject appear at the correct geographical location on the map. Each GameObject sent a request to the Dark Sky API for weather at its GPS coordinate. The Dark Sky response was on a JSON format containing weather data for the particular city. The GameObject extracted the desired data points and rendered the GameObject (weather data) at the correct geographical position. New weather data was fetched at a given interval.

### 3.2.2 Weather Data Visualisations


(a) Weather icons, 3D bars, and wind arrow.

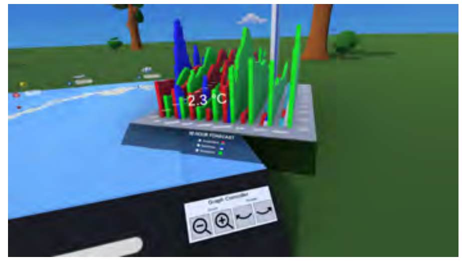
(b) Changing weather conditions in the outdoor environment.

Figure 3.3: Two example of visualised weather data on the map.

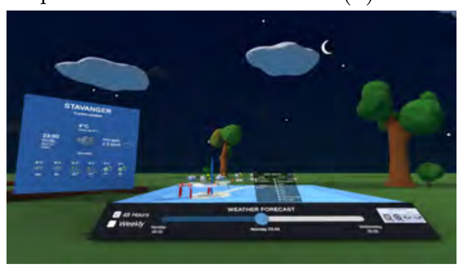
The weather data for each city on the map displayed the current weather, temperature, precipitation type and intensity, wind speed, and wind bearing. A 3D weather icon visualised the current weather (see Figure 3.3a). If the current weather were "rain" or "snow", the weather icon would display an animation of the precipitation type as seen in Figure 3.3a and Figure 3.3b. Also, if the current weather were "rain" or "wind", the weather icon would play either rain or wind sounds. 3D bars were used to visualise temperature, precipitation type, and intensity. Where the red 3D bar represented temperature, and the blue 3D bar represented precipitation type and intensity, as seen in Figure 3.3a. The 3D bars changed height depending on the temperature and precipitation intensity, where taller bars indicated higher temperature/more intensity. The 3D bars changed colour according to temperature or precipitation type. Furthermore, wind speed and wind bearing were rendered as 3D arrows. The wind speed determined the length of the arrows, and the bearing determined the direction of the arrows (see Figure 3.3a).

In addition to the visualised data on the map, a side panel was created (see Figure 3.4a). The side panel displayed additional information about the weather in the selected city for the selected time instance. In addition to the current weather, the side panel also provided the user with the apparent temperature, time, date, and a six-hour forecast.


(a) The side panel.




(b) The 3D bar chart.




(c) The appearance of the skydome change.

Figure 3.4: Visualised weather data in the prototype.

We implemented a 3D bar chart visualising wind speed, temperature, precipitation type and intensity, as shown in Figure 3.4b. The bar chart displayed the 48 hour-by-hour forecasts for each city. This feature allowed the user to compare the data for each city for the next 48 hours.

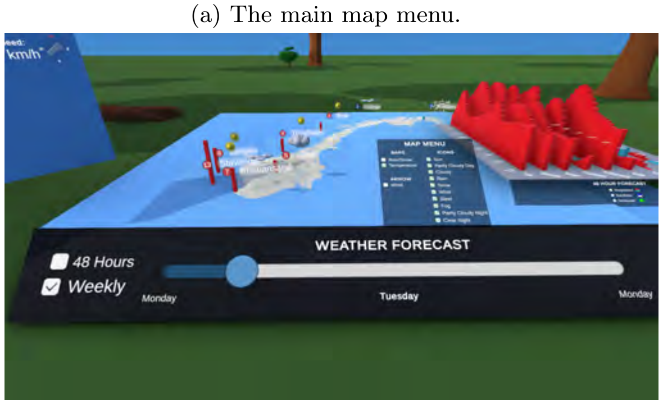
Furthermore, we implemented a feature that could change the weather condition in the outdoor environment. Thus the weather surrounding the user changed to the current weather in a selected city. Figure 3.3b shows an example of this feature, exposing the user to the current weather in Tromsø, in this case, snow, in the surrounding environment. Furthermore, the appearance of the encapsulating skydome changed light settings with respect to the current time. The light settings changed to imitate day or night and display either a sun or a moon and stars on the sky. Figure 3.4c shows how the environment would look like when the user was looking at weather data for night time.

## 3.3 User Interaction

The prototype allows the user to interact and manipulate the data in several ways, see Figure 3.5 for examples. To reduce the learning curve, the user could interact with the prototype through various control panels. First, we implemented the main map menu (see Figure 3.5a), allowing the user to manipulate the presented data on the map by toggling on/off the 3D bars, wind arrows, and weather icons. Next, a 48 hour forecast menu, see Figure 3.4b, was implemented. Letting the user alter the data in the bar chart by toggling on/off the data types. The user could also zoom in/out and rotate the bar chart. Further, a weather forecast menu consisting of a slider and buttons was implemented, as shown in Figure 3.5b. The interactive buttons let the user change the forecast type on the map and in the side panel. The buttons allow the user to switch between an hour-by-hour forecast for the next 48 hours or a day-by-day forecast for the next week. In addition to the buttons, the slider allows the user to perceive the data for different times. To interact with the slider, the user could click on the knob and drag it to the desired time. This feature allowed the user to perceive and analyse the data in its natural form, as the presented weather data would change over time.

The user could also interact with the visualisations on the map. Clicking on a city name would toggle on/off the side panel in Figure 3.4a, showing more/less information about the selected city. Additionally, the user could hover over the 3D bars and wind arrows on the map to look at the value (see Figure 3.3a).


(a) The main map menu.




(b) The weather forecast menu.

Figure 3.5: Example of user interaction opportunities.

## 3.4 Data Collection

This prototype visualises weather forecasts, provided by Dark Sky, for different cities in Norway. The prototype requested and retrieved data for eight Norwegian cities. The cities were selected based on population size [23] (Oslo, Bergen, Stavanger, Trondheim) and geographical location (Bodø, Tromsø, Kirkenes) to get a geographical spread. In this experiment, we extracted the weather forecast for 20.04.2020 - 28.04.2020 for each city and used this as the dataset. For each dataset, we retrieved data point objects (see Table 3.1) for the current weather condition, 48-hour forecast, and the day-by-day forecast for the next week. The training session used the real-time API requests as datasets.

| **Data Point Object** | **Description** |
|---|---|
| apparentTemperature | The apparent temperature in degrees Fahrenheit |
| apparentTemperatureHigh | Daytime high apparent temperature in degrees Fahrenheit |
| apparentTemperatureLow | Overnight low apparent temperature in degrees Fahrenheit |
| icon | Machine-readable text summary of the data point |
| precipIntensity | Intensity (inches/hour) of precipitation occurring at the given time |
| precipType | Precipitation type occurring at the given time |
| summary | Human-readable text summary of the data point |
| temperature | Air temperature in degrees Fahrenheit |
| temperatureHigh | Daytime high temperature in degrees Fahrenheit |
| temperatureLow | Overnight low temperature in degrees Fahrenheit |
| windBearing | Direction of where the wind is coming from in degrees, with true north at 0° |
| windSpeed | Wind speed (miles per hour) |

Table 3.1: Retrieved data point objects from each dataset with additional description [21].

(a) The VRE setup.　　(b) The DE setup.

Figure 3.6: The different environment setups.

## 3.5 Experimental Design

### 3.5.1 Setups

The prototype explored in this research is the same for the VRE and the DE. Both environment setups support the same exploration, interaction, and navigation options. However, the environments setups differ.

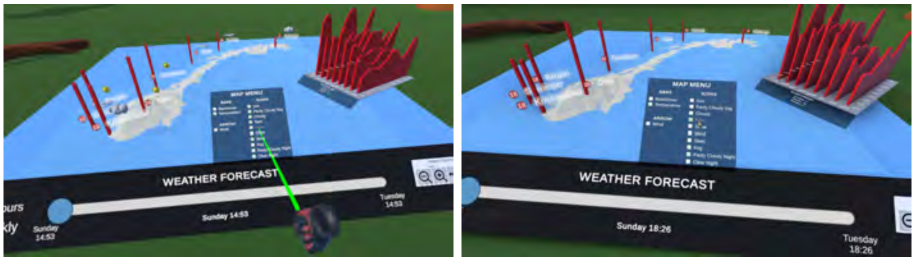
**Virtual Reality Environment (VRE):**

This environment consisted of a HTC Vive setup (see Section 3.1.1). Participants wore a Sony MDR-1000X wireless and noise reducing headset [24] to experience the audio aspect of the prototype. Figure 3.6a shows the VRE setup. For communication purposes, the headset was set to "ambient sound", allowing voices to pass through. The experiment was conducted in a quiet and spacious room, with enough space for the participant to move freely.

In the VRE, the participant used an HTC Vive controller for interactions and navigations. The HTC Vive controllers' trigger button was used to interact with the environment through a laser pointer (see Figure 3.7a) and worked equally to a left mouse click in the DE. The participant was able to move freely in the environment by either walking or teleporting to the desired position by using the trackpad button on the controller.

**Desktop Environment (DE):**

In the DE, the participant used a traditional desktop setup consisting of a screen, keyboard, and mouse (see Figure 3.6b) for interactions and navigation. The prototype is visualised and interacted with on a 2D screen. The arrows on the keyboard provided visual movements in the prototype and allowed the user to move back/forward/right/left. The right mouse button was used to rotate, while the left mouse button was to interact with the prototype by clicking (see Figure 3.7b).




(a) VRE interactions. (b) DE interactions.

Figure 3.7: Interactions within the different environments.

Due to the COVID-19 situation, the participant was using their private desktop in their homes. We asked them to have sound on, so they could hear sounds from the prototype. When the prototype runs on the desktop, it displayed in full screen. The experiment was carried out through videoconferencing software (Facebook Messenger[1] and Zoom[2]). The participants downloaded the prototype from a Google Drive folder before the experiment.

### 3.5.2 Procedure

We conducted the experiments over five days, between 12:00 PM and 5:00 PM. During this experiment, we tested the prototype for two different environments. However, the procedure was the same for both environments.

First, the participant was given a web-based demographic questionnaire regarding demographic data and previous experience with VR, gaming, and analysing data. Afterwards, the participant conducted a training session to familiarise themselves with the particular environment, equipment, prototype, and controls. During the training session, the participant was able to see all the interaction opportunities for the prototype. In the training session, all participants were presented with real-time data, resulting in different datasets during the training session. The training session was followed by the main session when the participant felt comfortable using the prototype. In the DE, the experimenter instructed the participant on how to change the dataset, from the real-time API request to the fixed dataset, before the main session started. In the VRE, the experimenter changed the dataset.

During the main session, the participant was asked to answer 4 tasks. The experimenter explained the tasks to the participant through verbal communication. The tasks were in the same fixed order in both environments. The participant was encouraged to explore the presented data and use the features of the prototype to find the answers. They were told there was no time limit for solving the tasks. When they thought they had the correct answer, they would

[1] https://en.wikipedia.org/wiki/Facebook_Messenger
[2] https://en.wikipedia.org/wiki/Zoom_(software)

tell the experimenter. If the participant answered incorrectly, the experimenter asked them to continue searching for the correct answer. The participant was allowed to continue to the next task when they had found the correct answer.

After the main session, we asked the participant to fill out a web-based survey to assess their subjective experience of the prototype. The survey included questions about their QoE, level of understanding, and overall experience.

### 3.5.3 Tasks

The participant was asked to do 4 tasks during the experiment. The purpose of the tasks was to collect objective measurements on the participants' level of understanding for the two environments. The same dataset was used for all tasks, for all participants during the main session. In the following, we describe the tasks in the order they were presented in the experiment.

1. By exploring the weather data presented, can you tell what season it is?
2. You want to go on a sailing trip. You want to go on a day with nice weather (sun), temperature (over 10°C) and wind speed between 10 km/h - 20 km/h. What day and in what city would be the best?
3. You want to take a weekend trip (Friday - Sunday) to either Oslo or Kristiansand, but you want to go to the city with the highest mean temperature in the weekend. What city do you choose?
4. You want to go skiing in Tromsø today (Monday), and you want to go after it has been snowing for at least 3 hours. When can you go skiing at the earliest?

### 3.5.4 Measures

#### Task

The participants level of understanding was measured objectively by tracking the task error (*error*) for all tasks. If the participant answered a task incorrectly, the experimenter noted one error (incorrect answer). The experimenter kept track of the number of errors (incorrect answers) for all tasks, and the errors were reported individually for each task.

#### Demographic Questionnaire

Before the participant started the training session, they were presented with a web-based demographic questionnaire. The demographic questionnaire was used to map the participants' background, such as age, gender, and occupation following questions regarding the participants' previous experience with VR, gaming, and analysing data.

**Survey**

After the participant had finished all 4 tasks, we asked them to fill out a web-based survey. The survey gathered subjective measures of the participants' experience of the prototype. The survey was divided into three sections measuring the QoE, level of understanding, and overall experience.

The QoE aimed to measure *emotions*, *usability* and, *immersion*. The questions regarding *emotions* were presented as a 9-point Self-Assessment Manikin (SAM) scale [25] measuring the level of *pleasure*, *arousal*, and *dominance* when using the prototype. Further, *immersion* was measured through adaption of questionnaires assessing immersion in gaming [26] and the core elements of a gaming experience [27]. The purpose of this was to evaluate the participants' immersion f. ex. presence (the "feeling of being there") and engagement. *Usability* was measured based on the System Usability Scale (SUS) [28] to provide a subjective measurement of the prototypes usability.

The subjective evaluation of the participants' level of understanding was adapted from a study developing a questionnaire to measure immersion in video media [29] and the questionnaire considers comprehension of the themes and concepts of the video as a factor.

Lastly, the participant was asked to evaluate their overall experience. After this section, the participant was able to add comments, allowing for qualitative feedback. All questions in the survey, except for the SAM scale regarding *emotions*, used a 5-point Likert scale, where 1="Strongly disagree", 2="Disagree", 3="Neutral", 4="Agree", 5="Strongly agree".

### 3.5.5 Hypothesis

Null-hypotheses for $H_{QoE}$ is that there will be no difference between the user's QoE. While the null-hypothesis for $H_{understanding}$ is that DE participants will have a higher level of understanding.

- $H_{QoE}$: For Quality of Experience, we expect the VRE to score higher. The VRE allows the user to be surrounded by the environment, use of natural body movements to move, and natural interaction with the data.
- $H_{understanding}$: For the level of understanding, we expect the VRE users to experience a higher level of understanding due to the egocentric and stereoscopic view of the data.

### 3.5.6 Participants

We asked 12 participants to partake in this study. Figure 3.8 and Figure 3.9 show the gender and age distribution among the participants, respectively.

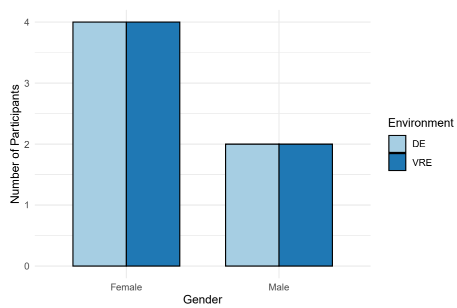



Figure 3.8: Gender distribution of the participants for each environment.

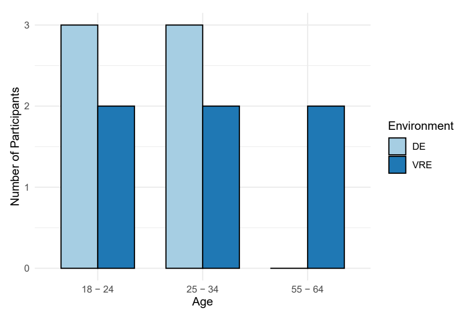



Figure 3.9: Age distribution of the participants for each environment.

We observe that the average age was lower for the DE compared to the VRE and the majority in both environments were female. The participants in the DE were mainly students or had a computer science background. In the VRE, the participants came from diverse backgrounds, but the minority were students. Except for one participant in the VRE, all participants had no or little experience with VR. While in the DE, all of the participants had experience with gaming, and the majority did it irregularly or regularly. In the VRE, the majority of the participants had no or little experience with gaming, but two participants did it regularly. All of the participants in the DE stated they were familiar with analysing data. Whereas for the VRE, the participants reported different prior experience, but the majority was stating they had little or no experience.

# Chapter 4

# Results

In this chapter, we present the results of our user study with respect to *error*, subjective measures, and user feedback for the two environments. All analysis in this research was conducted in RStudio IDE (Integrated Development Environment) [1]. The results are presented as Mean Opinion Score (MOS) bar charts, which is the arithmetic mean overall participants' [30]. All bar charts are plotted with an error bar representing a 95% Confidence Interval (CI).

We found that the results from neither the objective measures nor the subjective measures were normally distributed. Thus an UNPAIRED TWO-SAMPLE WILCOXON test was applied to the results to determine a significant difference between the two environments. To investigate $H_{understanding}$, a one-sided UNPAIRED TWO-SAMPLE WILCOXON test was used to examine if the level of understanding was higher for the VRE. Significant values are reported for $p < 0.1$ (*) and $p < 0.05$ (**), respectively, represented by the number of stars in parenthesis.

First, we present the objective measures from the tasks addressing the user's level of understanding, followed by the subjective measures from the survey. In the end, we present quantitative data in the form of user feedback.

## 4.1 Objective Measures

In the following, we present the results from the objective measures. Figure 4.1 shows the results for *error* with a upper error bar indicating 95% CI. Figure 4.1 show that the DE have a higher average *error* than the VRE. Both environments have the same score for task number 1 and 3, while the average *error* for the VRE is lower for task number 2 and 4. Table 4.1 show a notable difference for task 2, where VRE (M=0.17, SD=0.4) score lower than DE (M=0.67, SD=1.2).

[1] https://rstudio.com/

However, the results from the one-sided UNPAIRED TWO-SAMPLE WILCOXON test presented in Table 4.1 show no significant difference in the level of understanding between two environments. Thus, the objective measures do not support $H_{understanding}$, even though VRE had fewer *errors* on average.

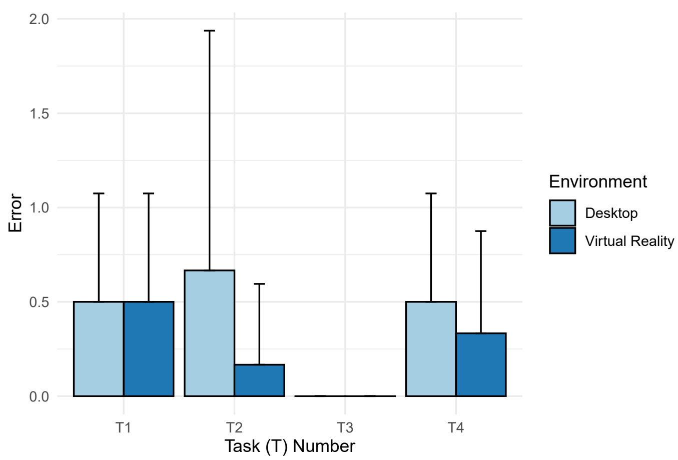



Figure 4.1: Average task error with upper error bars showing a 95% CI.

| | **Task 1** | **Task 2** | **Task 3** | **Task 4** |
|---|---|---|---|---|
| **VRE Mean** | 0.50 | 0.17 | 0.00 | 0.33 |
| **DE Mean** | 0.50 | 0.67 | 0.00 | 0.50 |
| **Delta** | 0.00 | -0.50 | 0.00 | -0.17 |
| **p-value** | 0.54 | 0.80 | 1 | 0.74 |

Table 4.1: The mean average score for VRE and DE. Delta is the difference between the means. The p-value shows the p-value from the one-sided UNPAIRED TWO-SAMPLE WILCOXON test for the tasks.

## 4.2 Subjective Measures

In this section, we present the results gathered from the subjective post-hoc survey consisting of 23 questions. The questions are divided into three sections, and the results are shown in their natural manner. Note that the prototype is referred to as "application" in the questions.

Figure 4.2 present the results from the 9-point SAM scale concerning the users' emotions while using the prototype. The questions (Q) for this section were: **Q1:** How happy or unhappy did you feel while using the application? (Very unhappy (1) - Very happy (9)), **Q2:** How calm or excited did you feel while using the application? (Very calm (1) - Very excited (9)), **Q3:** How much or little control did you feel you had while using the application? (Being controlled (1) - In control (9)). Where **Q1** measures *pleasure*, **Q2** measures *arousal*, and **Q3** measures *dominance*.

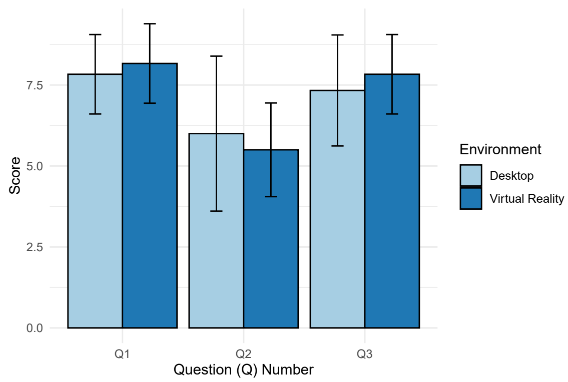



Figure 4.2: Average score for question regarding *emotions*.

| | Q1 | Q2 | Q3 |
|---|---|---|---|
| **VRE Mean** | 8.17 | 5.50 | 7.83 |
| **DE Mean** | 7.83 | 6 | 7.33 |
| **Delta** | 0.34 | -0.5 | 0.5 |
| **p-value** | 0.61 | 0.74 | 0.68 |

Table 4.2: Mean average for all subjects for each environment for questions regarding *emotions*. Delta is the difference between the VRE and DE mean. P-value shows the p-value from the UNPAIRED TWO-SAMPLE WILCOXON test.

Figure 4.2 and Table 4.2 shows that the VRE score slightly higher than DE for *pleasure* and *dominance*, whereas DE score slightly higher on *arousal*. In other words, the participants in the VRE felt happier, calmer, and more in control than the DE participants. However, the results from the UNPAIRED TWO-SAMPLE WILCOXON test show no significant difference.

Figure 4.3 presents the result from question 4, 5, and 6 asking about the *usability*. Note that the following results used a 5-point Likert scale. The questions in this section were: **Q4:** I thought the application was easy to use, **Q5:** I thought there was too much inconsistency in the application, **Q6:** I felt very confident using the application.

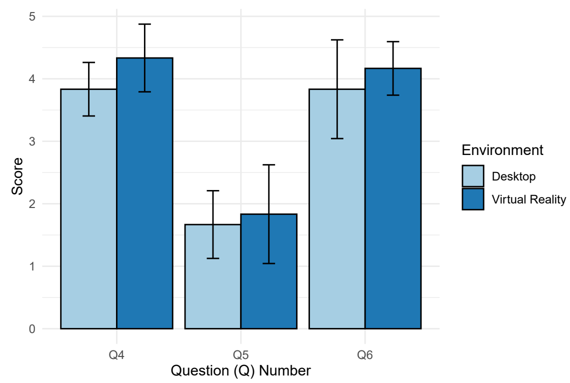



Figure 4.3: Average score for questions regarding usability.

| | **Q4** | **Q5** | **Q6** |
|---|---|---|---|
| **VRE Mean** | 4.33 | 1.83 | 4.17 |
| **DE Mean** | 3.83 | 1.67 | 3.83 |
| **Delta** | 0.5 | 0.17 | 0.33 |
| **p-value** | 0.11 | 0.78 | 0.39 |

Table 4.3: Mean average for all subjects for each environment for questions regarding *usability*. Delta is the difference between the VRE and DE mean. P-value shows the p-value from the UNPAIRED TWO-SAMPLE WILCOXON test.

Figure 4.3 show that the VRE had a higher average score than the DE for all questions. **Q4** gave the most considerable difference between the two environments, reporting that the VRE was easier to use compared to the DE. The UNPAIRED TWO-SAMPLE WILCOXON test shows no significant difference between the two environments, but we can see a trend towards ($p = 0.11$) the VRE being easier to use than the DE.

Figure 4.4 show the results concerning *immersion*. The questions in this section were: **Q7:** I was immersed into the environment, **Q8:** I felt separated from the real-world environment, **Q9:** The visual aspect of the environment involved me, **Q10:** The auditory aspect of the environment involved me, **Q11:** My senses were completely engaged, **Q12:** I was aware of my display and control devices, **Q13:** I enjoyed using the application, **Q14:** I felt that the data and application was something I was experiencing, rather than watching, **Q15:** I was consciously aware of being in the real world while using the application.

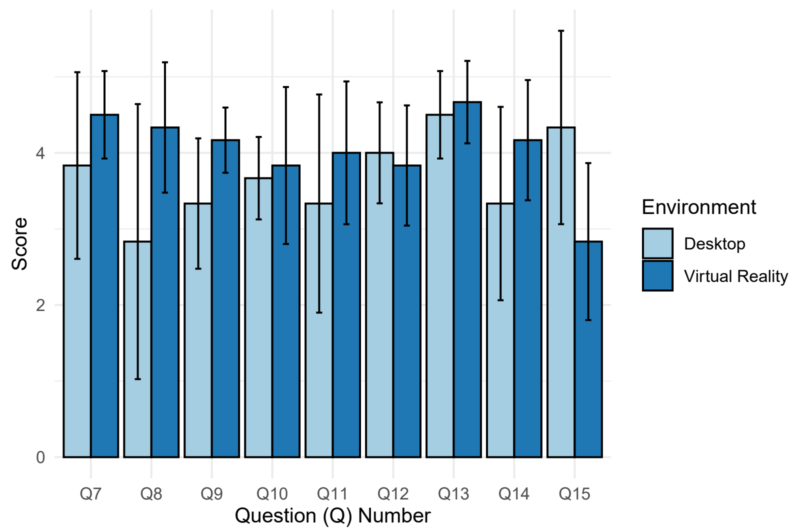



Figure 4.4: Average score for questions regarding immersion.

| | Q7 | Q8 | Q9 | Q10 | Q11 | Q12 | Q13 | Q14 | Q15 |
|---|---|---|---|---|---|---|---|---|---|
| **VRE Mean** | 4.50 | 4.33 | 4.17 | 3.83 | 4.00 | 3.83 | 4.67 | 4.17 | 2.83 |
| **DE Mean** | 3.83 | 2.83 | 3.33 | 3.67 | 3.33 | 4.00 | 4.50 | 3.33 | 4.33 |
| **Delta** | 0.67 | 1.50 | 0.83 | 0.17 | 0.67 | -0.17 | 0.17 | 0.83 | -1.50 |
| **p-value** | 0.34 | 0.13 | 0.056* | 0.50 | 0.36 | 0.72 | 0.64 | 0.24 | 0.045** |

Table 4.4: Mean average for all subjects for each environment for questions regarding *immersion*. Delta is the difference between the VRE and DE mean. P-value shows the p-value from the UNPAIRED TWO-SAMPLE WILCOXON test.

Figure 4.4 show a notable difference for **Q8** and **Q15**. Table 4.4 reports the same absolute difference ($Delta = \pm 1.50$) between the means of **Q8** and **Q15**, which both addresses the participants' sense of being in the real world. Since a VR environment surrounds the participant, these results were expected. Figure 4.4 also show a notable differences between the environments for **Q7**, **Q9**, **Q11**, and **Q14**, but reports minimal difference for **Q10** and **Q13**. The DE received a higher average score for **Q12** and **Q15**. However, **Q12** and **Q15** reports how aware the participant was of their presence in the real world and the devices. Even though there is notable difference for several questions, Table 4.4 reports only significant difference (*) for **Q9** and (**) for **Q15**. Overall, the results favour the VRE and indicate that the participants felt more immersion in the VRE, and are consistent with our expectations ($H_{QoE}$).

Figure 4.5 provides subjective measures regarding the users' level of understanding. The questions in this section were: **Q16:** I felt I was a part of the data, **Q17:** The data was easy to understand, **Q18:** The data was challenging to analyse, **Q19:** I think I understood the data well, **Q20:** It was difficult to find the answers to the tasks.

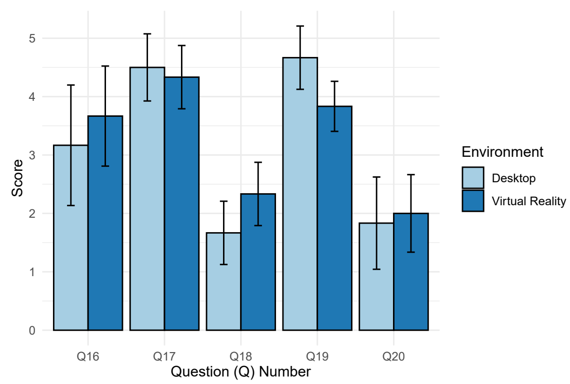



Figure 4.5: Average score for questions regarding the users' level of understanding.

| | **Q16** | **Q17** | **Q18** | **Q19** | **Q20** |
|---|---|---|---|---|---|
| **VRE Mean** | 3.67 | 4.33 | 2.33 | 3.83 | 2.00 |
| **DE Mean** | 3.17 | 4.50 | 1.67 | 4.67 | 1.89 |
| **Delta** | 0.50 | -0.17 | 0.67 | -0.83 | 0.11 |
| **p-value** | 0.17 | 0.75 | 0.98 | 0.99 | 0.36 |

Table 4.5: Mean average for all subjects for each environment for questions regarding level of understanding. Delta is the difference between the VRE and DE mean. P-value shows the p-value from the one-sided UNPAIRED TWO-SAMPLE WILCOXON test.

Figure 4.5 shows that the results favour the DE, but **Q16** has higher average for the VRE. This result was not unexpected since we suspected higher *immersion* for the VRE. However, the results indicate that the data was more challenging to analyse (**Q18**) in the VRE, and the participants in the DE felt they understood the data (**Q19**) better.

Figure 4.6 reports the overall experience. The questions in this section were: **Q21:** I enjoyed the overall experience with the application, **Q22:** I felt the tasks were interesting in the environment, **Q23:** I would like to analyse data in this environment again.

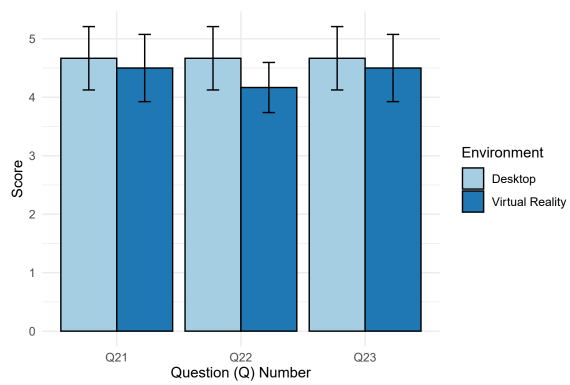



Figure 4.6: Average score for questions regarding the overall experience.

| | **Q21** | **Q22** | **Q23** |
|---|---|---|---|
| **VRE Mean** | 4.50 | 4.17 | 4.50 |
| **DE Mean** | 4.67 | 4.67 | 4.67 |
| **Delta** | -0.17 | -0.50 | -0.17 |
| **p-value** | 0.64 | 0.11 | 0.64 |

Table 4.6: Mean average for all subjects for each environment for questions regarding the overall experience. Delta is the difference between the VRE and DE mean. P-value shows the p-value from the UNPAIRED TWO-SAMPLE WILCOXON test.

The results in Figure 4.6 indicates that the DE participants had a better experience using the prototype, and they especially found the tasks more enjoyable. However, the UNPAIRED TWO-SAMPLE WILCOXON test shows no significant difference between the two environments.

## 4.3 Qualitative Data

At the end of the survey, the participant had the opportunity to give feedback. They reported feedback regarding their experience, but also informal feedback to improve the prototype.

For DE, the participants reported the prototype to be a fun experience (*"It [the prototype] was fun to try!"*). They also reported that it was an intuitive way to experience and analyse data ("*[...] an enjoyable and intuitive way to experience a weather forecast.*"), ("*I thought it was easy to find data, and it was fun to answer the questions. I liked that you got so much information.*"). However, one participant commented that he/she did not feel fully immersed due to pixelated graphics ("*The only reason I did not feel I was 100% a part of the game was because the game was a little pixelated [...]*"). One participant described problems with using a VR prototype on a desktop ("*The movement felt unnatural at times*"). They reported the prototype to be little complicated to understand at first, especially the slider ("*I thought the slider [...] was most difficult to use. It was not easy to understand at first what day I was looking at, but when I first understood it, it worked very well*"). Regarding further work, they reported that it would be nice if the bar graph could be updated in time ("*[I] Wish that the bar graph also would update to the average over the week*") and that the camera movements could "*have followed the mouse directly*".

In the VRE, the participants reported that they liked the layout, and it was a pleasant experience ("*Nice graphics, aesthetic layout, nice experience!*"). Regarding further work, they reported that it would be easier if one could use the bar graph more ("*It would be easier if one could use the histogram for several of the task*"). They also reported that "*It would have been nice to turn to one weather type faster*".

# Chapter 5

# Discussion

The purpose of this study was to determine "*to what extent do a virtual reality environment affect the users' Quality of Experience when analysing data?*" and "*to what extent do a virtual reality environment affect the users' understanding of the data?*". The short answer would be that *a virtual reality environment increases the users' immersion, and slightly affecting the QoE, but it does not necessarily improve and affect the users' level of understanding.*

For the questions regarding QoE (*emotions*, *usability*, and *immersion*), the VRE scored overall higher on average than the DE. The largest difference between the two environments was measured for *immersion*. In particular, significant difference was reported for **Q9** "*The visual aspect of the environment involved me*" ($p = 0.056$) and **Q15** "*I was consciously aware of being in the real world while using the application*" ($p = 0.045$). The difference in *immersion* is most likely due to the VRE surrounding the user. This result was expected and corresponded to our assumptions in $H_{QoE}$.

However, no significant difference was reported for *usability* and *emotions*, even though **Q4** show a trend towards ($p = 0.11$) the prototype being easier to use in the VRE. This result is interesting, come in mind that the participants in the VRE had overall less experience with VR and gaming, hence less experience from perceiving and interacting with display environments such as an HMD or a desktop. Having that said, the qualitative data for the DE reported that "*The movements felt unnatural at times*". Thus, an explanation for the result in **Q4** is that the VRE allowed for more natural movements such as body movements in space and natural interactions with the prototype. While the movements in the DE was more unnatural, as a result, the VRE was easier to use.

The participants report design issues for both of the analysis environments in the qualitative data. In the VRE, participants report that changing to one weather type took to long and that the bar chart could have been used more to analyse the data. In the DE, participants report difficulties in understanding how to interpret the slider. These design issues could have impacted the prototypes *usability* and the users' overall experience, hence impacted the QoE negatively. The qualitative data for the DE also suggest that the graphics of the prototype was pixelated, which could have impacted the *immersion* negatively for the DE.

For $H_{understanding}$, the VRE was at least as good as the DE across all objective measures. The VRE even scored overall lower on average for *error*, thus indicating that the VRE participants interpreted and understood the data better. In contrast, the subjective measurements for the level of understanding reported that the DE scored higher on average than the VRE for all questions, except one.

These results are both interesting and surprising, and not what we expected in $H_{understanding}$. One explanation for the conflicting results can be the difference in familiarity and prior knowledge to the environment and analysing data. The DE participants might have felt more confident due to the familiarity of the situation when conducting the tasks. As a result, the survey reflects this and suggest a higher level of understanding in the DE. While the participants in the VRE might have felt more insecure conducting the tasks due to less experience with the environment and situation. The familiarity and prior knowledge can explain why the data was more challenging to understand and analyse in the VRE, as suggested in **Q17**, **Q18**, **Q19**, and **Q20**, hence impacting the users' level of understanding negatively. An explanation for the objective measures and the low *error* average for the VRE participants can be seen in the context of the subjective measures and prior knowledge. Due to less familiarity with the situation and the data being more challenging to analyse, the participants could have used additional time to analyse the data and checking their answers more carefully before answering, resulting in lower *error* average.

However, VRE scored higher for **Q16** ("*I felt I was a part of the data*"). This is in line with the results regarding *immersion*. In the VRE condition, the participants were experiencing the data rather than watching it. The result from **Q14** support this assumption. Although there are some notable differences regarding the users' level of understanding, the subjective and objective measures fail to report any significant difference between the two environments. Thus we have to reject $H_{understanding}$.

The results for the users' overall experience indicates that the participants in the DE had a better experience. The subjective measures regarding the level of understanding suggest that the data was easier to understand and analyse in the DE. At the same time, the DE group was more familiar with the technology and situation. These factors combined can explain why the DE scored higher on average for this section. However, no significant difference was reported for the overall experience, although **Q22** show a trend toward significance ($p = 0.11$). A reason for this can be that the VRE participants' might have found the tasks less appealing due to less experience and the data being more challenging to interpret and analyse, which could have affected the average score and QoE.

## 5.1 Limitations

The results of this study are limited due to the small sample size. Additionally, the demographic background and previous experience for the two user groups were very different. The participants in the DE was younger and mainly students with more experience with VR, gaming, and analysing data. For future research, the sample size can advantageously be larger and cover a larger demographic group. Additionally, we encouraged to assess the two environments for two user groups with more similar previous experience.

Familiarity with the DE might have a positive impact on the reported results. Since VRE participants had to use a novel technology, this might have influenced the results negatively. However, the result indicated that the VRE was easier to use, even without previous knowledge. This can be because of the nature of the implementation of the prototype. As mentioned earlier, can HIFs such as previous experiences and prior knowledge, influence the QoE and need to be considered.

The DE for each of the participants conducting the DE condition was different. The participants conducted experiments using different desktop setups and in different environments. Consequently, the experimental environment, such as screen size, audio, and the location was not consistent during the experiment. One can consider the experimental conditions as SIFs and CIFs, and thus factors influencing the QoE. For future research, a definite advantage would be to have the same desktop setup for all DE participants.

The tasks could have been designed to require more analysis in spatial space and utilising the opportunities offered by VR such as stereoscopic view, natural interactions, and movements. The weather data could have been visualised and presented to take advantage of the benefits of VR. This could have led to better analysis and more insight regarding the difference and impact of the environments. The tasks could have been integrated into the prototype. For example, presenting the tasks within the environment by using text and allowing the user to select the object they thought was the correct answer. At the same time, the prototype could track the number of errors. By doing this, the participant could have conducted the entire experiment without any distractions from outside the environment. Since interruptions can be considered as a CIF, this could have influenced the results for the QoE. Also, the participant could have been presented with a training task during the training session. The training task would allow the participant to get more familiar with the prototype in terms of user area as an analytical tool before the main session.

# Chapter 6

# Conclusion

In this thesis, we have presented a study comparing two analysis environments for interactive exploration of tasks in 3D visualisation. In particular, we compared a VRE and a DE for analysing 3D weather data. This research aimed to determine to what extent IA and the use of VR as an analytical tool affected the users' QoE, and level of understanding compared to a desktop setup. This was done by designing, implementing, and comparing a prototype for 3D weather analysis. The prototype was evaluated by using subjective and qualitative measures conducted through a post-hoc survey and objective measures by tracking the number of incorrect answers for 4 tasks.

The subjective results report a higher average score for QoE in the VRE. More specifically, participants in the VRE felt that the visual aspect of the VRE was more involving than the DE, and they were less conscious of being in the real world. The results show a significant difference in *immersion*. Thus, a minimal increase in QoE for the VRE compared to the DE. The qualitative data report design issues for both environments that could be improved to raise the QoE. Although the results indicate a minimal increase in QoE for the VRE, we can not fully accept $H_{QoE}$ due to the lack of significance in *usability* and *emotions*. However, we conclude that *analysing weather data in a VR environment with HTC Vive improves the users' immersion compared to a desktop environment.*

The subjective measures report a higher level of understanding in the DE, but the objective measures report lower task error for the VRE. The subjective and objective results measuring the users' level of understanding fail to report any significant difference between the two analysing environments. To conclude, the VRE does not necessarily affect and improve the users' level of understanding compared to the DE. Thus we reject $H_{understanding}$.

Our results suggest that IA and VR provide the user with a comparable level of understanding of data compared to the more familiar desktop setup, but it does not necessarily improve the level of understanding. However, the most important finding in this research is that IA and the use of VR as an analytical tool increases the users' immersion, resulting in a small increase and impact in the users' QoE. It demonstrates that IA and VR have a positive impact on the users' overall experience when conducting weather data analysis.

This research investigated the environments impacts on the users' QoE and level of understanding for weather data analysis. This research clearly shows an increase in immersion for VRE, but it would be interesting to investigate how much immersion affects the users' level of understanding. To better understand how weather data can utilise IA, one could investigate which type of weather data analysis would benefit from IA. It would also be interesting to compare weather data analysis in an immersive environment to a traditional 2D desktop analysis approach.

Regarding further development of the prototype; The qualitative feedback reported that features allowing quicker analysis could be implemented to improve the interaction and analysis opportunities. Obvious developments include expanding the prototype by adding more analysis opportunities and data. It also is possible to implement a novel VR menu design that uses a different approach than a traditional 2D menu.

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# Appendix A

# Research Protocol

# Research Protocol

Mia Berge

March 2020

## 1 Synopsis

Today, we are being exposed to large amounts of data. Without the right tools to present and analyse it, the large amounts might become incomprehensible. New technologies are creating new opportunities for presenting and analysing data. It is now possible to immerse the user into the data by using technologies such as head-mounted displays (HMDs), large screens and sensor technology. Presenting data using these new technologies, rather than the standard desktop setup, can possibly build a bridge between complex data and human intuition. By using immersion as a data analysing tool, it might lead to better analysis and understanding of the data. The purpose of this study is to observe how effective it is to present data in a virtual reality environment compared to on a desktop environment and if the virtual reality environment will affect the Quality of Experience. This will be done by testing an application displaying weather data, using both a head-mounted display and a desktop setup. The HMD will place the user inside a virtual environment where the user is exposed to the data, while the desktop will preset the same data on a computer screen located in front of the user. A group of people will participate in the experiment and give feedback by doing a survey after the experiment.

## 2 Introduction

During the last decade there has been a huge increase in the data available. This means that people and businesses are being exposed to large amount of data everyday. Today, one of the most common tools to analyse data is a desktop setup, this includes a computer screen, keyboard and a mouse. But when the amount of data keeps growing, so does the complexity, and that is why we need to explore new methods to present the data in an intuitive and meaningful way.

At the same time we are also seeing an increasing interest and huge developments in the field of extended reality. The combination of new technologies is known as an emerging research field called Immersive Analytics. Immersive Analytics opens up for new possibilities for presenting and analysing data, but since it is an emerging research field, it has many unanswered questions, such as; how effective is the use of virtual reality versus a desktop when analysing data? Do the user feel more immersed into the data in a virtual reality environment? Do the user understand the data better?

# 3 Hypothesis

*Research Question (RQ):*
**RQ1:** To what extent do a virtual reality environment affect the users Quality of Experience when analysing data?

**RQ2:** To what extent do a virtual reality environment affect the users understanding of the data?

*Hypothesis (H):*
**H1:** The virtual reality environment will affect the users Quality of Experiment when analysing data.

**H2:** Participants analysing data in a virtual reality environment (experimental condition 1) will experience a higher level of understanding of the data than participants in a desktop environment (experimental condition 2).

# 4 Methodology and Design

The experiment will test the hypothesis by interacting and analysing the same data in the same application, using two different setups; one virtual reality (VR) setup and one desktop setup. The application will present the user with a scene displaying a map of Norway with additional weather data. The user will be able to interact with the application to manipulate and change the data, and the presented data will depend on the users input. The applications is made with Unity version 2019.3.0f6 and the Unity plugin SteamVR.

Due to the Covid-19 situation this experiment will have less participants than recommended earlier (30-35 participants). It is expected to be 12-16 participants in this experiment, divided into two groups. The group that will be using the VR setup are family and close friends. The participants in this group are chosen in regards to the governments recommendations for gathering people due to the situation. For the desktop setup it is expected that most of the participants are students. It is expected that both groups will have good experience with a desktop setup, but none of them will be so familiar with VR. The recruitment of participants will happen through a social network.

## 4.1 Experimental Conditions

*Experimental condition 1: VR setup*
The VR setup experiment will take place at Skaun folkebibliotek. In this setup the participants will test the application using HTC Vive. The HTC Vive setup consists of one HMD, two controllers and two lighthouses (base stations). The

lighthouses will be mounted diagonally across from each other in the room, and they are used to track the users movements inside selected area. The participant will wear the HMD and be placed inside the virtual environment. The participant can use the controllers to interact with the scene inside the virtual reality environment. The application will be run on a Acer Predator PH317-51 gaming laptop, with 16GB RAM, NVIDIA GeForce GTX 1060 and a Intel Core i7-7700HQ CPU @ 2.8 GHz (8 CPUs) processer, from the game engine Unity and the Unity plugin SteamVR.

*Experimental condition 2: Desktop setup*
The desktop setup experiment will take place where the participant is located. The non-VR version of the application will be embedded into a website by using WebGL. The participant will receive a link to website. In this setup the user will use a desktop to explore and view the application. The user is able to interact and move its position in the application by using the mouse and the keyboard.

Before the experiment is executed the participant is presented with an information sheet about the experiment. The information sheet will contain an explanation of the experiment, including the questionnaire and survey and. It will also contain information about the technology that is being used, the purpose of the experiment and potential discomforts, such as motion sickness for the VR setup. After reading the information sheet, the participant will be presented with a consent form. In the consent form the participant approve that they are participating in the study and the data obtained from the questionnaire and survey will be used in the study.

After signing the consent form, and consenting that they will participate in the research, the participants will be handed a demographic questionnaire they have to answer before the experiment starts. The participants in the VR setup will be executing the experiment one by one. It is expected that the whole experiment will take 45 minutes for each participants, for both experimental conditions. After the participant is finished testing the application, the participants will be given the survey. In the end the participant will be rewarded with a cinema ticket.

## 4.2 Questionnaire

The demographic questionnaire will be used to gather background information about the participant. While the survey following the experiment will be used to measure the participants subjective experience. The questionnaire and the survey will be on a point scale form, except for the demographic measures (gender, age, occupation) in the demographic questionnaire. The participant will need to rate their experience to a point on the scale. Example of how a question can look like:

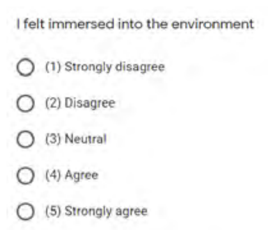



Figure 1: Example of a question on point scale form.

The demographic questionnaire and the survey will be presented to the participant in the form of two Google Forms. Google Forms allows the answers to be collected instantly when the participant is submitting the Google Form. The experiment is finished when the participant has submitted the last Google Form (the survey).

- **Demographic questionnaire:** The demographic questionnaire will be used to map the participants background. This includes demographic measures (age, gender, occupation). The demographic questionnaire will also contain questions to map the participants previous experience with virtual reality, gaming and data analysis.

The survey conducted after the experience to measure the participants experience are divided into three section:

- **Quality of Experience**
  - **Emotions:** To measure the users emotions the questions will be based on the Self-Assessment Manikin (SAM) scale. The goal of this part is to measure how the participants emotions when using the application.
  - **Immersion:** The questions for the immersion will be based on questionnaires for game experience. The aim of this part is to evaluate how immersed (f.ex. presence and engagement) the user feels into the application.
  - **Usability:** The usability of the application will be measured based on the System Usability Scale (SUS). The aim of this part is to determine how easy or difficult the application was to use.
- **Understanding of data:** These questions will give a subjective measure of the participants understanding of the data. The questions will f.ex. be if the data was easy to understand, if it was easy analyse and compare data.
- **Overall experience:** In the overall experience section, the participant will rate the whole experience. This section will be at the end of the

survey. After this section the participant will be able to add comments and feedback.

### 4.3 Tasks

To evaluate **R2** and **H2** more objectively, the participants will be asked to do 4 tasks while using the application. The purpose of the tasks is to collect objective measurements of understanding and analysing data when using two different environments.

Before doing the tasks, the participant will be able to do a training session. The purpose of this is to get the participants accustomed to the setup. In the training session the participant will be familiarized with the application and its controls. The presented data will change between the training session and the main session.

When the participant is feeling ready and comfortable with the application, the main session will start. The participant will be asked to explore the application to find answers to 4 questions.

1. Find the city with the highest precipitation at a specified time instance X.
2. Find the time instance where the temperature difference is the highest between city A and city B.
3. Find the city with the highest mean temperature.
4. Find the city where the weather is most stable over time.

When the participant think they have found the answer to the task, they will tell the experimenter, who will approve the answer. The participant is allowed to continue to the next task when they have found the correct answer. The experimenter will keep track of potential incorrect answers. There will be no time limit on how long the participant can explore the application to find answers to the tasks.

## 5 Results

The demographic questionnaire and the survey will be collected by using two Google Forms, one for each part. To measure the participants experience of the application, the survey will be given to the participant after the experiment, in both groups. The results from the surveys will be analysed and compared when all participants have submitted the surveys. The programming language R and the RStudio IDE (Integrated Development Environment), will be used to analyse the data. To determine if there are any significant difference between the two experimental conditions, it is possible to use a t-test. The t-test can determine if the hypothesis can be validated or thrown.

## 6 Timetable

20.04.2020: Approval of research protocol
21.04.2020 - 23.04.2020: Recruitment period
27.04.2020 - 03.05.2020: Test period
04.05.2020 - 10.05.2020: Analysing results
11.05.2020 - 12.06.2020: Writing paper

## Information Sheet

**Evaluation of the Environment's Impact on QoE and Understanding of Data - Comparison Between a Virtual Reality Environment and a Desktop Environment**

Dear participant,

You have been invited to partake in this research. Before you decide if you want to participate in this study it is important that you understand why this research is being done and what it involves. Please take time to read the following information carefully.

The purpose of this research is to observe how effective it is to present data in a virtual reality environment (VRE) compared to a desktop environment (DE) and if the VRE will affect the users Quality of Experience (QoE), which is defined as:

> *The degree of delight or annoyance of the user of an application or service. It results from the fulfillment of his or her expectations with respect to the utility and / or enjoyment of the application or service in the light of the user's personality and current state.*

In this experiment you will be exploring an application using a HTC Vive setup (VRE) or your own personal computer (DE). The application will present you with a map of Norway and additional weather data. It is possible to interact with the application to change the data, and the presented data will depend on your input. Regardless of what environment you are using, the experiment will take approximately 45 minutes. After participating in the experiment you will be given a cinema ticket for your time and effort.

*For VRE participants:*
In this experiment you will be using a HTC Vive setup. The HTC Vive setup includes a head-mounted display (HMD), two controllers and lighthouses (base stations). The application will be running on a Acer Predator PH317-51 gaming laptop and the application will be displayed inside the HMD. You will be wearing the HMD on your head and use the two controllers to interact with the application when wearing the HMD. The lighthouses will track your position and movements when you are inside the virtual environment.

If you decide to participate in this research you will be participating in a 3 part experiment:

1. **Demographic questionnaire:** After signing the consent form you will be asked to fill out a web-based demographic questionnaire. The purpose of the demographic questionnaire is to collect statistical data.
2. **Exploring the application:** You will explore the application and the presented data to answer 4 questions.

(a) Training session: You will first be able to do a training session to get familiar with the application and the controls.

(b) Main session: In this session you will explore and analyse the data to answer 4 questions.

NB! When doing the tasks you are not being evaluated, the application is!

3. **Survey:** After exploring the application you will answer a web-based survey. The purpose of the survey is to measure your subjective experience.

The potential discomfort for the VRE participants is motion sickness. The DE is not anticipated to cause any disadvantage or discomfort for the participants.

All information collected during this research will be strictly confidential and will be anonymised. There will be no personal identification in the data. The collected data and the identification will be stored separately and can not be linked. All information conducted will be used for research purposes only.

It is completely voluntary to participate in this research. If you decide to participate, you can withdraw your participation at any time without any questions asked. If you withdraw your participation there will be no consequences of any kind.

If you have any questions during or after the experiment, please feel free to ask Mia Berge.

Contact information for Mia Berge:<br>
**Phone:** +47 40 45 30 35<br>
**E-mail:** miapb@stud.ntnu.no

# Consent Form

I have read the information and agree to participate in the research *Evaluation of the Environment's Impact on QoE and Understanding of Data - Comparison Between a Virtual Reality Environment and a Desktop Environment*. I have been informed that this research is conducted by Mia Berge, who is conducting this research as a part of a Master Thesis, under the supervision of Andrew Perkis in the Department of Electronic Systems at Norwegian University of Science and Technology (NTNU).

I understand that the data will be collected through a demographic questionnaire and a survey, in the form of two Google Forms. I understand that all the data I provide will be confidential, and there will be no personal identification in the data. I approve that the data will be stored and anonymised, e.g. the data collected and the identification data will be stored separately and can not be linked. I understand that the collected data will be used in the study and only for research purposes.

I understand that my participation in this experiment is voluntary. I am free to withdraw my participation at any point. If I decide to withdraw my participation there will be no consequences. I have been informed about potential risks, this includes motion sickness for the virtual reality experimental condition. I have had the opportunity to ask Mia Berge about any questions I have regarding the experiment and my participation.

If I have any enquires about the study I can contact Mia Berge (see contact information below). By signing this consent form I am giving my consent to participate in the research.

______________________________
Name of the participant

____________________
Date

______________________________
Signature of the participant

Contact information for Mia Berge:
**Phone:** +47 40 45 30 35
**E-mail:** miapb@stud.ntnu.no

# Appendix B

# Subjective Measures

## B.1 Demographic Questionnaire

# Demographic Questionnaire

*Må fylles ut

1. What environment are you going to use for the experiment? *

   *Markér bare én oval.*

   - Virtual reality environment
   - Desktop environment

2. What's your participant number? You will get the number from the experimenter *

3. Age *

   *Markér bare én oval.*

   - Under 18
   - 18 - 24
   - 25 - 34
   - 35 - 44
   - 45 - 54
   - 55 - 64
   - 65+

4. Gender *

   *Markér bare én oval.*

   - Male
   - Female
   - Prefer not to say

5. Please state your occupation. If you're a student, please state your study programme *

6. Do you have previous exerience with virtual reality? *

*Markér bare én oval.*

- No experience
- I've tried it (once or twice)
- I use it irregulary (here and there)
- I use it regularly

7. Do you have previous experience with gaming? *

*Markér bare én oval.*

- No experience
- I've tried it (once or twice)
- I do it irregulary (here and there)
- I do it regularly

8. What is your experience with analysing data? *

*Markér bare én oval.*

- No experience
- Little experience
- Ok experience
- Good experience
- Expert

## B.2 Survey

# Survey

The purpose of this survey is to measure your subjective experience.
*Må fylles ut

1. What environment did you use during the experiment? *

   *Markér bare én oval.*

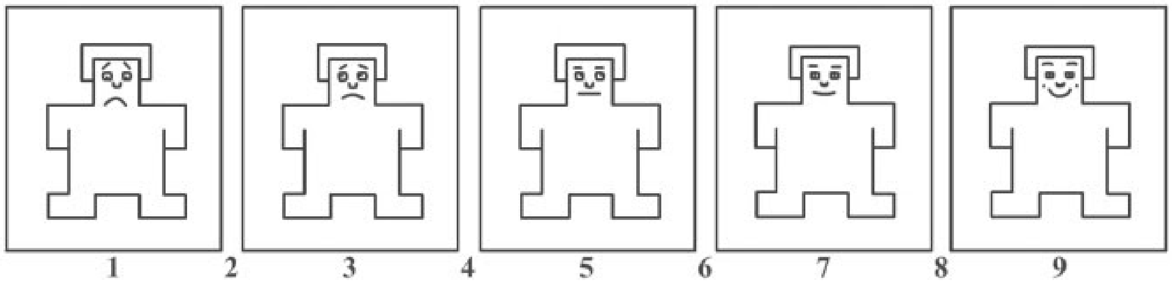
   - Virtual reality environment
   - Desktop environment

2. What's your participant number? You will get the number from the experimenter

## Section 1

In section 1 you should look at the picture and chose the point on the scale (the scale is going from 1 - 9) you feel most related to.

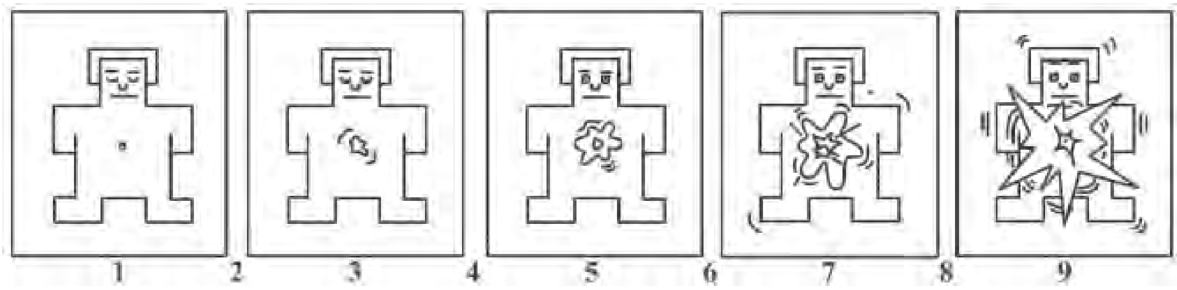
3. How unhappy or happy did you feel while using the application? (1: very unhappy/sad - 9: very happy) *




*Markér bare én oval.*

- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9

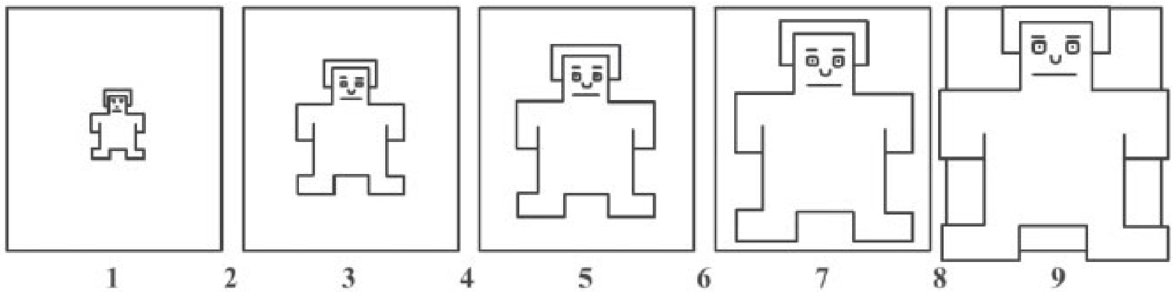
4. How calm or excited did you feel while using the application? (1: very calm - 9: very excited) *




*Markér bare én oval.*

- ( ) 1
- ( ) 2
- ( ) 3
- ( ) 4
- ( ) 5
- ( ) 6
- ( ) 7
- ( ) 8
- ( ) 9

5. How little or much control did you feel you had while using the application? (1: being controlled - 9: in control) *




*Markér bare én oval.*

- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9

Section 2

The questions in section 2 have a rating system with a scale ranging from 1 - 5. Where the points on the scale represents:

1 - Strongly disagree
2 - Disagree
3 - Neutral
4 - Agree
5 - Strongly agree

6. I thought the application was easy to use *

*Markér bare én oval.*

- Strongly disagree
- Disagree
- Neutral
- Agree
- Strongly Agree

7. I thought there was too much inconsistency in the application *

*Markér bare én oval.*

- Strongly disagree
- Disagree
- Neutral
- Agree
- Strongly Agree

8. I felt very confident using the application *

*Markér bare én oval.*

- Strongly disagree
- Disagree
- Neutral
- Agree
- Strongly Agree

9. I was immersed into the environment *

*Markér bare én oval.*

- Strongly disagree
- Disagree
- Neutral
- Agree
- Strongly Agree

10. I felt separated from the real-world environment *

*Markér bare én oval.*

- Strongly disagree
- Disagree
- Neutral
- Agree
- Strongly Agree

11. The visual aspect of the environment involved me *

*Markér bare én oval.*

- Strongly disagree
- Disagree
- Neutral
- Agree
- Strongly Agree

12. The auditory aspect of the environment involved me *

*Markér bare én oval.*

- Strongly disagree
- Disagree
- Neutral
- Agree
- Strongly Agree

13. My senses were completely engaged *

*Markér bare én oval.*

- Strongly disagree
- Disagree
- Neutral
- Agree
- Strongly Agree

14. I was aware of the display and control devices *

*Markér bare én oval.*

- Strongly disagree
- Disagree
- Neutral
- Agree
- Strongly Agree

15. I enjoyed using the application *

*Markér bare én oval.*

- Strongly disagree
- Disagree
- Neutral
- Agree
- Strongly Agree

16. I felt that the data and application was something I was experiencing, rather than watching *

*Markér bare én oval.*

- Strongly disagree
- Disagree
- Neutral
- Agree
- Strongly Agree

17. I was consciouosly aware of being in the real-world while using the application *

*Markér bare én oval.*

- Strongly disagree
- Disagree
- Neutral
- Agree
- Strongly Agree

18. I felt I was a part of the data *

*Markér bare én oval.*

- Strongly disagree
- Disagree
- Neutral
- Agree
- Strongly Agree

19. The data was easy to understand *

*Markér bare én oval.*

- Strongly disagree
- Disagree
- Neutral
- Agree
- Strongly Agree

20. The data was challenging to analyse *

*Markér bare én oval.*

- Strongly disagree
- Disagree
- Neutral
- Agree
- Strongly Agree

21. I think I understood the data well *

*Markér bare én oval.*

- Strongly disagree
- Disagree
- Neutral
- Agree
- Strongly Agree

22. It was difficult to find the answers to the tasks *

*Markér bare én oval.*

- Strongly disagree
- Disagree
- Neutral
- Agree
- Strongly Agree

23. I enjoyed the overall experience with the application *

*Markér bare én oval.*

- Strongly disagree
- Disagree
- Neutral
- Agree
- Strongly Agree

24. I felt the tasks were interesting in the environment *

*Markér bare én oval.*

- Strongly disagree
- Disagree
- Neutral
- Agree
- Strongly Agree

25. I would like to analyse data in this environment again *

*Markér bare én oval.*

- Strongly disagree
- Disagree
- Neutral
- Agree
- Strongly Agree

26. Comments

## B.3 Demographic Questionnaire Answers

| environment | age | gender | occupation | previous_experience_with_vr | previous_experience_with_gaming | experience_analysing_data |
|---|---|---|---|---|---|---|
| DE | 18 - 24 | Female | Bsc nursing | I've tried it (once or twice) | I've tried it (once or twice) | Little experience |
| DE | 18 - 24 | Female | Lektor i fremmedspråk | No experience | I do it irregulary (here and there) | Little experience |
| DE | 18 - 24 | Female | Student: Cybernetics and Robotics | I've tried it (once or twice) | I do it irregulary (here and there) | Ok experience |
| DE | 25 - 34 | Male | MTELSYS | I've tried it (once or twice) | I do it irregulary (here and there) | Good experience |
| DE | 25 - 34 | Female | Digital Forretningsutvikling | I've tried it (once or twice) | I do it irregulary (here and there) | Ok experience |
| DE | 25 - 34 | Male | Software engineer | I've tried it (once or twice) | I do it regularly | Ok experience |
| VRE | 25 - 34 | Female | Student | No experience | I've tried it (once or twice) | Good experience |
| VRE | 55 - 64 | Female | Biblioteksjef | I've tried it (once or twice) | No experience | Little experience |
| VRE | 18 - 24 | Female | Studerer rettsvitenskap | No experience | No experience | No experience |
| VRE | 25 - 34 | Male | Software Engineer | I use it regularly | I do it regularly | Expert |
| VRE | 18 - 24 | Female | Arbeidsøker | I've tried it (once or twice) | I do it regularly | No experience |
| VRE | 55 - 64 | Male | Økonom | No experience | No experience | Ok experience |

## B.4 Survey Answers

| | DE | DE | DE | DE | DE | DE | VRE | VRE | VRE | VRE | VRE | VRE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Q1** | 9 | 9 | 7 | 6 | 8 | 8 | 8 | 9 | 9 | 8 | 9 | 6 |
| **Q2** | 4 | 8 | 6 | 6 | 9 | 3 | 3 | 5 | 6 | 6 | 7 | 6 |
| **Q3** | 9 | 7 | 5 | 8 | 9 | 6 | 7 | 8 | 9 | 8 | 9 | 6 |
| **Q4** | 3 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 5 | 4 | 4 | 5 |
| **Q5** | 2 | 1 | 1 | 2 | 2 | 2 | 1 | 2 | 1 | 2 | 3 | 2 |
| **Q6** | 4 | 4 | 3 | 4 | 5 | 3 | 4 | 4 | 4 | 5 | 4 | 4 |
| **Q7** | 3 | 4 | 2 | 4 | 5 | 5 | 5 | 4 | 5 | 4 | 4 | 5 |
| **Q8** | 1 | 5 | 2 | 1 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 3 |
| **Q9** | 3 | 4 | 2 | 3 | 4 | 4 | 4 | 4 | 5 | 4 | 4 | 4 |
| **Q10** | 3 | 4 | 3 | 4 | 4 | 4 | 2 | 4 | 5 | 4 | 4 | 4 |
| **Q11** | 2 | 5 | 2 | 3 | 5 | 3 | 3 | 4 | 4 | 3 | 5 | 5 |
| **Q12** | 4 | 4 | 4 | 4 | 5 | 3 | 4 | 3 | 5 | 3 | 4 | 4 |
| **Q13** | 5 | 5 | 4 | 4 | 5 | 4 | 5 | 4 | 5 | 4 | 5 | 5 |
| **Q14** | 4 | 2 | 2 | 3 | 5 | 4 | 4 | 4 | 5 | 4 | 5 | 3 |
| **Q15** | 5 | 5 | 5 | 5 | 4 | 2 | 2 | 2 | 4 | 2 | 3 | 4 |
| **Q16** | 3 | 2 | 2 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 2 |
| **Q17** | 5 | 5 | 4 | 4 | 4 | 5 | 4 | 4 | 5 | 5 | 4 | 4 |
| **Q18** | 1 | 1 | 2 | 2 | 2 | 2 | 3 | 2 | 2 | 2 | 3 | 2 |
| **Q19** | 5 | 5 | 4 | 4 | 5 | 5 | 4 | 4 | 4 | 4 | 3 | 4 |
| **Q20** | 2 | 3 | 1 | 2 | 2 | 1 | 2 | 2 | 3 | 1 | 2 | 2 |
| **Q21** | 5 | 5 | 4 | 4 | 5 | 5 | 5 | 5 | 5 | 4 | 4 | 4 |
| **Q22** | 5 | 4 | 4 | 5 | 5 | 5 | 4 | 4 | 5 | 4 | 4 | 4 |
| **Q23** | 5 | 4 | 5 | 4 | 5 | 5 | 4 | 4 | 5 | 4 | 5 | 5 |

## B.5 Qualitative Data: Desktop Environment

"Jeg synes det var veldig gøy å bruke programmet. Det jeg synes var mest vanskelig var den baren da man kunne rulle igjennom uken. Var ikke helt lett å forstå med en gang hvilken dag jeg var i, men da jeg skjønte hvordan det funket var det veldig bra. Eneste grunnen til at jeg ikke følte med 100% som en del av spillet er fordi spillet er jo litt pikslete, men det var som forventet. Jeg synes det var lett å finne data og det var gøy å svare på spørmsål. Likte at du fikk såpass mye informasjon. Alle boksene som man kunne tippe av var lett tilgjengelig (de kunne sikkerg var lagt i en drop-down boks så de ikke tok så mye plass). Skulle ønske at graph baren gså oppdaterte seg til gjennomsnitt over uken, men var lett å forstå og lett å burke. Dette var gøy å prøve!! :D"

"Using an application tailored for a VR setup on a desktop had some issues. The movement felt unnatural at times, and would have benefited from a grounding in the environment and your control devices: - A character you moved, so you have one less axis to handle - The camera could have followed the mouse directly without negatively impacting the experience. Otherwise an enjoyable and intuitive way to experience a weather forecast."

"Next time in VR ;)"

"Veldig pent :))"

## B.6 Qualitative Data: Virtual Reality Environment

"Fin grafikk, estetisk layout, - fin opplevelse!"

"Det hadde vært enda enklere om man kunne brukt histogrammet til flere av oppgavene. Det hadde også vært fint å kunne skru til kun en værtype raskere."

# Appendix C

# Objective Measures

| | DE | DE | DE | DE | DE | DE | VRE | VRE | VRE | VRE | VRE | VRE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Task 1** | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 0 |
| **Task 2** | 3 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 |
| **Task 3** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Task 4** | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 |

# Appendix D

# Prototype

## D.1 GitHub Repository

The following link contains the Unity project used to create the prototype in this experiment: `https://github.com/miapb/Master-Thesis`

## D.2 Prototype

The following link contains the final build of the prototype used in this experiment. The Drive folder contains two versions of the prototype. WeatherApp_API.zip fetches the datasets from the Dark Sky API, while WeatherApp_dataset.zip uses the datasets used in the main session of the experiment. `https://drive.google.com/drive/u/0/folders/1sEgYzRB0yqnnlx9efp3-o1ZFSwyBCyZu`

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