Bjørn Rude Jacobsen

Raising Awareness of Individual Contributions to Climate Change with Virtual Reality

Master's thesis in Computer Science
Supervisor: Ekaterina Prasolova-Førland and Monica Divitini
August 2021

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Acknowledgement

This project would not have been possible without the support and assistance I received. I would like to sincerely thank my supervisor Ekaterina Prasolova-Førland for facilitating user testing, reading my revisions, suggesting improvements and changes, and altogether guiding me through the project. I also want to thank Monica Divitini for the opportunity to write this thesis, and to Tone Lise Dahl and Mikhail Fominykh for providing helpful feedback. Thanks to Lina Furuseth for audio recording. Thanks to Irina Rogozhina, Ghazal Moghaddam and Luna Marina Luoto at REACT for their collaboration and to all unnamed participants for providing me with feedback.

Finally, I'd like to thank my parents, whose patience, support and unconditional love I am endlessly grateful for.

Abstract

Despite decades of warnings from scientists, global carbon emissions are still on the rise, propagating climate change. When attributing the emissions from consumer goods and services to the total household emissions, 72% of all greenhouse gas emissions are related to individual households [Hertwich and Peters 2009], but many people are unwilling to make the necessary lifestyle changes required to mitigate climate change [Herrmann et al. 2017] [Moberg et al. 2019].

Virtual Reality (VR) has shown promising results as a learning tool and driving behavioural change, and studies indicate that VR may be well suited for environmental causes. VR has a unique capability to induce a feeling of presence through immersion, creating active and engaging experiences.

The objective of this thesis is to examine the potential of VR to increase awareness of personal contributions towards climate change. For this purpose, I developed a VR application in the Unity game engine to visualize and personalize the individuals emissions and emission cuts of carbon dioxide, the greenhouse gas largely responsible for driving climate change.

The application was developed in three iterations over the course of a semester, with user testing at the end of each iteration. The feedback of the first and second user tests guided the direction of the subsequent development iterations, and the final results were generated though final prototype testing, concluding expert interviews and a stakeholder interview.

Although more work is needed, the findings suggest that the solutions used in the application are suitable for the task at hand, and that application may increase awareness of individual climate contributions for young people.

This project is considered a proof-of-concept for a larger project, and as the results are promising, it may serve as a basis for continued development.

Abbreviations

VR	-	virtual reality
RQ	-	research question
CFV	-	carbon footprint visualization
CE	-	carbon emission
CAV	-	collective action visualization
HMD	-	head-mounted display
VVCT	-	Visualizing Climate Change in Trondheim
RSLT	-	Rising Sea Levels in Trondheim
SOAE	-	Stanford Ocean Acidification Experience
GL	-	Greenland Melting

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1 Introduction

Climate change is arguably one of our time's most pressing issues. The comprehensive and significant impacts it brings will increasingly affect humanity in the coming decades and threaten global peace and stability. Mitigating the worst consequences requires drastic changes to everyday life, but in Europe, the necessary changes are undermined by several factors [Dubois et al. 2019] [Moberg et al. 2019] [Lujala et al. 2015] [Lorenzoni and Hulme 2009] [Stoknes 2014]. These relate to people's confusion around which environmental actions are effective, the perceived pointlessness of individual actions, ignorance of the substantial contribution that individual consumption has on climate change, and the perceived remoteness of environmental impacts.

Virtual Reality (VR) may help address these issues. VR is a computer-generated environment that can be sensed and interacted with similarly to reality. One of the unique strengths of the technology is its ability to induce a feeling of presence in the virtual environment [Slater and Wilbur 1997] and consequently a feeling of embodiment [Slater et al. 2010]. This technology also enables users to experience different situations from any perspective, and perspective-taking, empowerment and visualizations are indicated to be unique uses for VR in environmental education [Fauville et al. 2021]. These properties enable VR to be used as a tool to provoke empathy and pro-social behavioural change [Hamilton-Giachritsis et al. 2018] [Herrera et al. 2018] [Ahn et al. 2013].

This master thesis will examine the possibility of using VR to help users become more aware of their personal carbon footprint, feel more personally responsible for their own emissions and present environmentally effective and individually executable actions.

1.1 Background

Ever since the start of the Industrial Revolution, carbon dioxide levels in the atmosphere has been increasing [Solomon et al. 2007]. Carbon dioxide, or CO_2, is one of the most important gases causing climate change.

Climate change poses a significant threat to human life and welfare as well as global peace and stability. This is because it will disrupt both local and global systems that affect humans, such as rising sea level, ocean acidification, ecosystems destabilization, reduction in global biodiversity, changing global temperature, changing weather dynamics and an increasing frequency of floods, droughts, wildfires and extreme weather. There is great concern that food shortages and mass migrations will result in humanitarian crises across the world.

The REACT Project was formed to contribute to climate change mitigation. REACT, short for "*from resistance to action*" (https://www.react-project.com/), is a interdisciplinary and multinational pilot project that works for a greener and more sustainable society. By utilizing a combination of scientific, societal and academic fields, the project aims to involve the general public in reducing carbon emissions by mitigating individual overconsumption [Rogozhina 2019]. The project is based in Trondheim and coordinated by the Norwegian University of Science and Technology. The research from the project should serve as a proof of concept for environmental action plans both nationally and internationally. This master thesis is a collaboration with REACT, and should contribute to the pilot study by developing a prototype for a tool to be used in this regard (Appendix A).

1.2 Objective

The main objective of this masters project is to develop a VR prototype to be used as a tool for pro-environmental action, and to evaluate its potential.

A considerable obstacle to mitigating climate change is that separately, individual contributions may appear vanishingly small, and that people's own actions to mitigate their environmental emissions may seem pointless. When carbon emissions from individuals are added up, however, they make up a substantial portion of global emissions. The application should raise awareness about these individual contribution by utilizing the unique properties of VR.

REACT aims for the finalized tool to be used by local, young people. One of the intentions is to provide a resource for teachers to use in environmental education at High Schools. The target demographic are therefore young people in Trondheim, from High School students to young adults. Furthermore, a desired feature of the application from REACT, substantiated by findings from a preparatory project, was to visualize individual environmental actions.

The main Research Question (RQ) of this masters thesis is as follows:
How can VR help young people become more aware of their individual contributions to climate change?

This RQ is answered in part through two supplementary RQs:

1. How can VR increase knowledge of climate change that is difficult to achieve through traditional means?

2. How can a VR application be developed that visualizes environmental actions with a high level of user-friendliness?

Because this is an initial prototype, the objective is not to create an optimal solution, but to provide a possible approach to address the aforementioned issues. The application will focus on the fundamental mechanisms and visualizations and should guide future development.

1.3 Research method

This project follows a mixed-method Design-and-creation strategy [Oates 2005] generating both qualitative and quantitative data. This strategy is used to develop IT artifacts intended to create new knowledge through research, and the strategy was chosen for this reason.

The development process was conducted over three iterations. Each iteration concluded with user testing and subsequent questionnaires. The users were observed during testing, with notable observations and oral feedback being recorded by hand, and the questionnaires provided quantitative data. After the final prototype was finished, qualitative data were generated through two semi-structured expert interviews, and a stakeholder interview with REACT. The interviews were recorded and transcribed, and the expert interviews were analyzed thematically.

1.4 Results

The outcome of this application is a VR application that visualizes environmental actions. The experience utilizes a 3D-model of Trondheim, and is centered around a house by Gamle Bybro. The house represents the user's home, in which environmental upgrades and installments can be made. The user can replace poorly insulated windows with high-performance ones, install a solar panel, and replace energy-inefficient lights with LEDs. Users are able to travel between the present and a visualized future in the year 2050 at will.

The application is twofold, with an explanatory introduction to be played before the main content. When launching the application, the user can choose between starting the introduction or the main content.

The introduction is divided into multiple segments accompanied by audio instructions. In the first segments, the user is taught how to interact with objects and how to time travel. Afterwards, there are two visualization segments. The carbon footprint visualization (CFV) visualizes carbon emissions (CEs) from some emission sources, which produces black "molecules" that represents the user's personal CEs from now until year 2050. Then, the user is briefly shown the CE reduction animation, which is triggered when environmental actions are performed. The second visualization is the collective action visualization (CAV), in which humanoid figures mirror the user's movements. The user is explained that the actions taken in this app represent a large population in order to visualize the outcomes of the environmental actions. Finally, the user is explained what to do in the main part of the app, how the locomotion works, and how to reset the application.

A video summary of the final application can be found at the following link:

https://www.youtube.com/watch?v=mmjY-LE5TO8

2 Theory

This section presents relevant theory and literature, as well as general information about contemporary VR technology and state-of-the-art VR applications.

2.1 Climate change

In the years since 1850, human activities have raised the concentration of CO_2 in the atmosphere by 48% [NOAA 2021a], which is a major factor driving climate change. Climate change increases global temperature and affects ecosystems and modifies habitats, acidifies the ocean, threatens agriculture and food production and increases the frequency and intensity of droughts, floods and extreme weather, among other impacts. According to NOAA (https://www.noaa.gov/), the global temperature has increased at an average rate of 0.08°C every decade since 1880, but has increased to 0.18°C since 1981 [NOAA 2021b]. 2020 was the next warmest year ever recorded. Figure 1 shows global temperature anomalies since 1880.

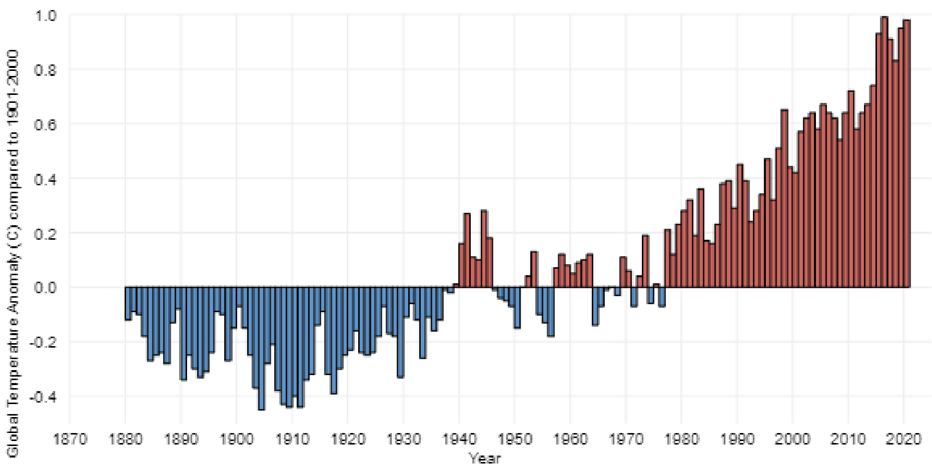

Figure 1: Global temperature compared to long-term average.
Source: NOAA 2021b

2.1.1 Greenhouse gases

Greenhouse gases is the term used for the gases responsible for our current climate change event [Mann 2019]. The term is used because of its association to the greenhouse effect, which is the process that enables infrared radiance to be absorbed as heat in the atmosphere. Specifically, the rays of the sun generate infrared radiance on the surface of the earth, and when this radiates out towards space, it hits gas particles in the atmosphere which increases the temperature of the atmosphere.

Carbon dioxide is a significant greenhouse gas that is involved in many natural processes, but the increase in atmospheric concentration is due to human activities such as burning fossil fuels and forests [Mann 2019].

2.1.2 Solutions

In order to mitigate climate change, carbon dioxide emissions must be reduced. Hertwich and Peters (2009) found that individual households' total carbon emission account for 72% of all global emissions when emissions from consumer goods and services are attributed to individual consumers.

Project Drawdown (https://drawdown.org/) is a climate change mitigation project presenting viable solutions to reduce emissions. Each solution has an estimate of how much CO_2 the solution can reduce or sequester through 2050. Most of the solutions require substantial resources, such as installing large-scale wind turbines, but a number of the solutions are fairly easy to execute by individuals. Table 1 presents some of these solutions.

Table 1: Individually actionable solutions from Project Drawdown.

Solution	Emission cuts			Description
	Min	Average	Max	
Plant-rich diets	65.01	78.37	91.72	Shifting from a meat centric diet to a diet rich in plants.
Distributed solar photovoltaics	27.98	48.31	68.64	Installing solar panels for households.
Insulation	16.97	17.99	19.01	Reducing households' energy-demanding temperature management by decreasing heat exchange.
LED lighting	16.07	16.80	17.53	Replacing energy inefficient lighting fixtures with LEDs.
High-performance glass	10.04	11.34	12.63	Reduce buildings' energy load for lighting, heating and cooling by improving windows' efficiency.
Smart thermostats	6.99	7.20	7.40	Increasing energy-effectiveness of residences by utilizing sensors, algorithms and analyzations to control temperature.
Recycling	5.50	5.76	6.02	Avoiding emissions by substituting virgin feedstock with recycled materials, and avoiding emissions related to landfilling.
Composting	2.14	2.64	3.13	Avoiding methane emissions by converting organic material to stable soil carbon.
Bioplastics	0.96	2.38	3.80	Reducing emission from plastic production by substituting petro-plastics with bioplastics.
Recycled paper	1.10	1.53	1.95	Decrease methane emissions from paper decomposition and reduce carbon emissions from harvesting and processing.
Low-flow fixtures	0.91	1.24	1.56	Decreasing energy related to cleaning, transportation and heating water in homes by using more efficient fixtures and appliances.
Green and cool roofs	0.60	0.85	1.10	Using soil and vegetation as living insulation on rooftops to decrease heat exchange and thus energy usage.
Dynamic glass	0.29	0.38	0.47	Use "smart glass" that changes the reflective properties in response to sunlight and weather.

2.1.3 Challenges

There are many obstacles in the way of reducing carbon emissions, one of which is people's personal attitudes and perceptions. Spence et al. (2012) refers to four different kinds of psychological distances towards climate change; temporal, social, spatial and uncertainty. The study suggest that people are more concerned when they believe (low uncertainty) that environmental impacts of climate change may occur (low temporal distance) in their local area (low spatial distance) and affect themselves or people around them (low social distance). Furthermore, people's attitude and perception towards climate change are influenced by direct experiences with environmental impacts related to climate change [Lujala et al. 2015].

2.2 Virtual Reality

In the broadest terms, VR is a computer-generated simulation of an environment that can be sensed and interacted with, where the nature of the environment, the interactions, and the mode of sensing may vary. VR is generally divided into two categories; non-immersive and immersive.

Non-immersive VR may be based on a standard computer setup [Freina and Ott 2015], such as traditional computer games. Another example of VR is using a smartphone to view 360°-videos. 360°-video is video recorded in all directions, and the viewing direction during playback on a phone can be changed according to the user's rotational movement of the phone.

Immersive VR is more extensive, enabling the virtual environment to be sensed and interacted with in a convincingly similar way to reality [Slater and Wilbur 1997]. Users perceive themselves to be physically present in the virtual environment, giving rise to a feeling of presence.

Slater and Wilbur (1997) defines immersion as the extent to which the computer displays are capable of delivering an illusion of reality, while the sense of presence is a subjective state of consciousness where the user has a sense of being "in a place" instead of looking at screens. Immersion may be considered the objective description of the system and is a prerequisite to experiencing a sense of presence, but does not necessarily give rise to it.

Embodying a virtual body for the user to self-identify with is indicated to be an important contributor to the sense of presence [Slater et al. 2010]. The sense of embodiment is related to the sense of self-location [Kilteni et al. 2012]. Whereas presence is concerned with the relationship between one's self and the environment, self-location refers to the relationship between one's self and one's body. Using their virtual body, the user can perceive and interact with the virtual environment.

The illusion of "stepping into" a virtual environment is a key component in what makes VR fun and engaging. The immersive nature of the technology opens up a number of interesting uses, some of which are presented in Section 2.4.

For the remainder of this thesis, the use of the word "VR" means the immersive kind.

2.2.1 Head-mounted displays

There are different ways to experience VR. CAVE-systems are room-scale solutions where the images are rendered on multiple walls. The images changes according to the movement of the user's head, and is perceived stereoscopically through LCD stereo shutter glasses [Creagh 2003].

Another way to experience VR is using a head-mounted display (HMD). In the last few years, commercial HMDs have become more available as the result of technological advance-

Figure 2: The world's first head-mounted display (1968). Source: https://www.informit.com/articles/article.aspx?p=2516729&seqNum=2

ments. These HMDs blocks user's vision of their real surroundings and replaces it with digital surroundings. Head movement is reflected digitally, creating the illusion of moving in the virtual environment. Additionally, stereoscopic displays in the HMDs ensures that the user experience depth vision, mimicking real-life perception.

The launch of the Oculus Rift and HTC Vive in 2016 marked an important step for commercial VR. By connecting the HMD to a capable PC and to external sensors, consumers are able to experience high-fidelity VR at home. The HMDs and their controllers are both positionally and rotationally tracked. VR of this type is often called "PC-VR"; although there are PC-VR solutions that do not require physical cables or external sensors, they still need a capable PC in proximity.

A "standalone" HMD does not require an external PC, but uses internal components for computing and internal sensors for tracking. This provide greater convenience and usability, as they can be used anywhere. In 2019, Oculus released their first standalone HMD, Oculus Quest (Figure 3).

2.2.2 Cybersickness

Users can develop a temporary malady called "VR sickness", "cybersickness" or "VIMS" (visually induced motion sickness) through VR experiences, which is a collection of symptoms that are induced by optical flow [Somrak et al. 2019] [Rebenitsch and Owen 2016]. The user may feel

Figure 3: Oculus Quest. Source: Amazon.com

nauseousness, dizziness, vertigo, eyestrain, disorientation or drowsiness, among other symptoms. To assess the levels of discomfort, the Simulator Sickness Questionnaires (SSQ) can be used. A study using this questionnaire found that cybersickness is negatively correlated with user experience [Somrak et al. 2019], and it is therefore important to take measures to reduce the likelihood of users developing these symptoms.

Although cybersickness can be related to resolution, refresh rate, and other parts of the hardware, the actual content can also affect the experience significantly [Saredakis et al. 2020]. Reducing the horizontal field of view, increasing tactile feedback and avoiding locomotion with high speeds are some solutions that appear to decrease symptoms [Rebenitsch and Owen 2016].

2.3 Technologies

This section presents the technologies used in the project.

2.3.1 Unity

Unity is a widely used game engine developed by Unity Technologies. The software receives continuous updates. The engine can run on mobile platforms (iOS, Android), desktop platforms (Windows, Mac, Linux), the web (WebGL), consoles (Playstation, Xbox, Nintendo), and VR platforms (Oculus, SteamVR and more).

Unity has a primary scripting API in C#, which is an object-oriented programming language. Object-oriented programming is a programming paradigm relying on class-based objects containing data and code, and enables easy code re-use. The base class for all entities in Unity scenes is the GameObject class. Components are scripts that can be attached to GameObjects, which describe the behaviour of the GameObject. For instance, every GameObject has a Transform component defining the GameObject's position, rotation and scale in the scene.

2.3.2 XR Interaction Toolkit

XR Interaction Toolkit is a component-based interaction system created by Unity's XR team to streamline XR development. "XR" is a term that encompasses the entire spectrum of immersive technologies. The toolkit is a "preview package" for Unity, meaning that it has not been officially released yet and is considered an unfinished product, but is still high-quality.

The toolkit is mainly centered around the use of Interactor and Interactable components, which can be attached to GameObjects for interactive properties. As an example, adding an Interactor to a hand object and an Interactable to a ball object makes interactions between the two possible. The ball can be hovered over, selected, grabbed, rotated and thrown by the hand.

There are basic UI interactions available, and the toolkit supports both continuous locomotion and teleport-based locomotion.

The toolkit is platform-agnostic, meaning that the developer does not need to develop for specific devices. It is basically an interface for all XR devices, enabling the developer to easily build an application to different devices with little extra effort.

2.4 Educational virtual reality

VR is uniquely suited to enable experiential learning through direct experiences by utilizing tactile and locomotive interactivity and presence, resulting in increased learning outcome over traditional, indirect learning [Kwon 2019]. Beheiry et al. (2019) argues that VR encourages exploration and curiosity-driven action, and motivates the user to absorb new knowledge. Weisberg and Newcombe (2017) states that embodied learning approaches that use gestures and spatial movement helps offload taxing cognitive resources and contribute to learning and internalizing context-relevant information. Markowitz et al. (2018), exploring the learning effect of using VR in environmental education, suggested that gained knowledge was positively correlated with the amount of exploration of virtual environments.

There is great educational potential for VR to be used for representing multi-dimensional datasets and visualize patterns of interest [Tamayo et al. 2018] [Donalek et al. 2014]. Due to the complexity of the data, it is challenging to visualize and understand these patterns with traditional tools, and it is suggested that using immersive and interactive technologies for this purpose should increase the available data bandwidth to our brains. The technology enables effective data visualization and interactions that improves perception of datascape geometry, increases intuitive data understanding and improves retention of the perceived relationships in the data, while collaborative data visualization and exploration can transform the way we communicate and interact with our peers.

VR enables users to experience different situations from any point of view, and there are promising studies indicating that VR can be used for perspective-taking scenarios, increasing empathy and promoting pro-social behaviour. While traditional perspective taking methods are cognitively demanding [Zaki 2014], perspective-taking in VR is less so, as the situation is simulated virtually and does not necessitate imagination. One study compared the effects of using VR for perspective-taking by embodying a homeless person compared to traditional perspective-taking methods [Herrera et al. 2018]. The participants using VR achieved a significantly higher degree of positive attitudes and empathy towards homeless people, and the effect lasted longer than the participants that did not use VR. Hamilton-Giachritsis et al. (2018) found that mothers who took the perspective of a four-year old child in VR reported increased empathy for the embodied child, and Ahn et al. (2016) found that taking the perspective of animals in VR made the participants report greater involvement and interconnection with nature, albeit short-term.

Fauville et al. (2021) found that perspective-taking, empowerment and visualizations are three unique ways in which VR can contribute to traditional environmental education. By utilizing perspective-taking, users can embody someone affected by the environmental consequences through their work, diet or economy. This makes the subject relatable and relevant to the users, increasing comprehension of the issues and creating a personal connection to it. This is supported by Ahn et al. (2013), which found that VR was an effective tool for promoting behaviour change and promoting pro-social behaviour through perspective-taking.

Regarding empowerment, Fauville et al. (2021) states that by showing the users the environmental consequences of their everyday choices, VR should empower the users to realize that they can make a difference, which should inform better real-life judgements and positive contributions and participation in society.

Lastly, VR enables objects to be observed from any perspective, and a literature review on uses of VR in education concluded that the main motivation for using VR in education was visualizing and simulating events that are not perceivable or practically feasible in real life [Freina and Ott 2015]. Atoms and molecules can be visualized in immersive virtual environments, and has been shown to make chemistry education more accessible [Ferrell et al. 2019]. Visualizing carbon dioxide molecules may help the public better understand the micro and macro aspects of climate change [Fauville et al. 2021]. The study suggests that visualizing future trajectories of the environment, based on the user's CO_2 emissions, can be a useful way to make the user perceive environmental phenomenons over temporal distances that are normally hard to perceive. It is generally hard for individuals to envision themselves more than 20 years into the future [Lorenzoni and Hulme 2009], but VR may extend this timescale.

2.5 Related work

This section presents state-of-the-art VR applications, ending in a summarizing comparison with this project. Two of the projects were developed at IMTEL's VR lab at Dragvoll in Trondheim. IMTEL researches immersive technologies for learning under the Department of Education and Lifelong Learning. The research group is headed by Ekaterina Prasolova-Førland, who is also supervisor of this project.

2.5.1 Visualizing Climate Change in Trondheim

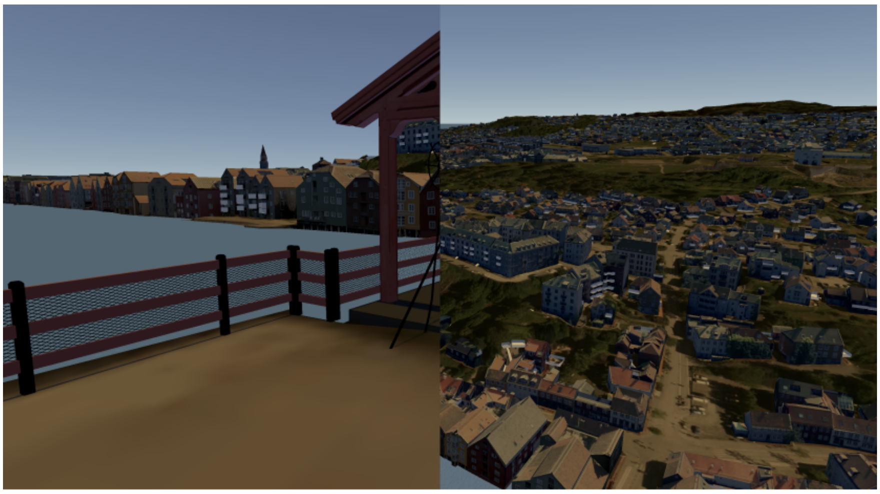

Figure 4: Screenshot from Visualizing Climate Change in Trondheim. Source: Warvik 2019

For his master thesis, Warvik (2019) developed an environmental VR application (Figure 4) at IMTEL. The application lets the user set the height of sea level and move around the city of Trondheim to see how different sites are affected. The user is able to view projected water flow and collection of water in cases of extreme rainfall, as well as quick clay deposits. It is also possible to change the scale of the model, so that the user may gain a bird's eye perspective of the city.

2.5.2 Rising Sea Levels in Trondheim

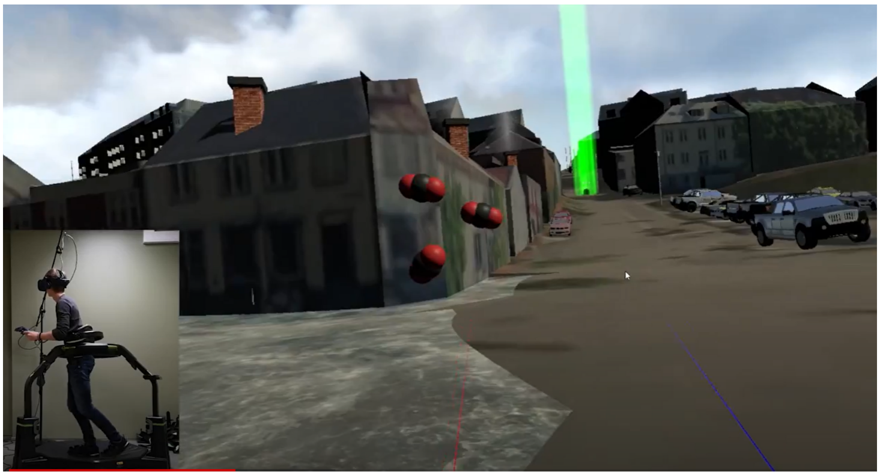

Figure 5: Screenshot from Rising Sea Levels in Trondheim. Source: Barak et al. 2019

Figure 6: Screenshot from Rising Sea Levels in Trondheim. Source: Barak et al. 2019

Figure 7: Screenshot from Rising Sea Levels in Trondheim. Source: Barak et al. 2019

Rising Sea Levels in Trondheim (Figure 5) is an environmental VR game developed by a group of students at IMTEL. In the game, the player must run through heavy rain across Gamle Bybro in Trondheim towards the goal at Bakklandet. The sea level starts low but rises rapidly, and if the user is submerged for too long, the game is lost. To delay the rise, the user has to "shoot" three different types of targets. Shooting chimneys, cars and carbon molecules turns them into solar panels, bicycles and trees respectively. The aim is to hit all the targets and get to the goal before the water rises too high.

The player's progress is tracked on the gun. The leftmost parameter shows the gradually increasing sea level, and the rightmost parameter indicates well the climate is. The parameters start at 0.0m and "BAD" respectively (as shown in Figure 6). The climate-parameter gradually decreases and gets better as more object are shot and transformed. Figure 7 shows the parameters towards the end of a session.

The application was developed to be used with the Virtuix Omni, a VR treadmill that enables the user to use their physical legs to walk or run in any direction. The user is locked in place by a frame around their waists, and and uses special sandals on a convex base. The sandals are strapped on over the user's shoes, and because the sandals and the base are low-friction, the user can run against the incline while staying in place.

2.5.3 The Stanford Ocean Acidification Experience

The Stanford Ocean Acidification Experience is an environmental VR application developed at Stanford University, and is used in the environmental VR study conducted by Fauville et al. (2021). It a linear, audio-narrated experience that follows carbon dioxide molecules from an emission source through the atmosphere and to the ocean. Absorbing carbon emissions turns the ocean increasingly corrosive. The user is transported to a Mediterranean reef with naturally high acidification, where corroded shells of sea snails are visualized. It is explained that continued emissions and ocean acidification severely threatens all shelled life in the ocean, potentially

Figure 8: The Stanford Ocean Acidification Experience.
Source: youtube.com/watch?v=LjQMc9TxkKg&t

resulting in the collapse of the food web.

The interactions are very simple and used only at specific times during the experience. As such, the application relies heavily on storytelling and visualizations, moving the user from scene to scene automatically.

2.5.4 Greenland Melting

Figure 9: Greenland Melting.
Source: youtube.com/watch?v=WNdyRvcBaCQ

Greenland melting (Figure 9) is an environmental VR short-film created by Frontline, Nova and Emblematic, and centers around the melting ice caps and glaciers, and the warming processes responsible. The user is a passive observer following scientists (recorded and represented in 3D) across different locations, explaining their work and what they have learned. The audio-narration are enhanced by helpful overlays and animations, visualizing the decline of the ice.

The application has been made exceptionally detailed with the help of a range of techniques. On their website, they reveal that the application is made by using dimensionalized 360° video, high-fidelity CG models, multi-layered 3D data visualizations, high-resolution photogrammetry and live holograms. The user is able to move around in the immediate area.

2.5.5 Summary

In summary, these applications are all environmental VR applications available in PC-VR. Environmental tasks are featured in Rising Sea Levels only, but in an abstract fashion. With the exception of Visualizing Climate Change, they are linear experiences. Their general focus is increasing the user's concern about environmental consequences.

While my application will also visualize environmental impacts in the future, the visualized impacts will reflect the user's actions. The unique feature of the application will be presenting tangible and individually accessible environmental actions, where the carbon reductions are visualized.

3 Problem definition process

This section presents the problem definition process.

3.1 Preparatory project

Prior to this thesis, a preparatory project was conducted in partnership with REACT [Jacobsen 2020]. The objective of the project was to propose a framework for a VR application intended to increase awareness of individual contributions to climate change in High School students. The application would be developed over several iterations, the first of which being this masters project.

3.1.1 Initial outline of the application

In the document stating the purpose and tasks of REACT [Rogozhina 2020], an initial outline of the application was formulated. The outline served as a starting point for establishing the framework and design of the application to be made, and the relevant excerpt of the document can be found in Appendix A. The document communicates that household consumption is responsible for 72% of greenhouse gas emissions when the emissions are associated with the final goods and services [Hertwich and Peters 2009]. The application outline focuses on individual climate contributions as a response to this fact. Furthermore, the document specify four main challenges that undermine individuals' potential to mitigate their emissions [Dubois et al. 2019] [Moberg et al. 2019] [Lujala et al. 2015] [Lorenzoni and Hulme 2009] [Stoknes 2014]. The challenges are:

1. lack of knowledge about the dominant role of individuals in driving climate change,
2. confusion about which consumption areas lead to substantial emissions,
3. perceived remoteness of climate change impacts on Europe, and
4. perceived pointlessness of individual actions if they are not part of a large-scale effort.

The outline aims to address these challenges using VR technology. The limitless situations and perspectives that VR enables the users to experience [Freina and Ott 2015] should make it possible to reduce the perceived temporal and spatial distances to the consequences of climate change through visualizations. VR experiences can place the user in a model of their local area, and enable them to experience simulated time-traveling to visualize the local impacts of climate change. VR may also be a purposeful choice as it is indicated that it may be used as a tool for empowerment [Fauville et al. 2021] and pro-social behaviour change [Ahn et al. 2013]. It could prove purposeful to visualize collective climate action in the application in a uplifting manner, to encourage behaviour change and empower the user to take real-life actions.

The outline states that the VR application should use of both 360°-videos and content programmed in a game engine to present interactive scenarios where the user should be able to move from one scenario to another as they do different individual actions. The actions should translate to carbon footprints reductions, financial gains, and health benefits, and should be treated as representative of collective actions across high-income countries. The visualized impacts should thus change according to the user's actions, and is aimed at provoking empathy and emotional responses. Inaction should worsen the visualized climate change impacts, while each action should reduce the visualized climate change impacts. The final goal is for the user to achieve a 45% carbon footprint reduction and be transferred to the ideal, low-carbon version of the city in the future.

In the early meetings with REACT, they said that they wanted High School students as the target audience for the application, and that it should be used in classroom setting. The reasoning behind this was that they are the future decision-makers, and will experience the consequences of climate change to a greater degree than the older population.

3.1.2 The process

The initial outline and early meetings with REACT served as a starting point for the preparatory project, and the intention of the preparatory project was defined; it would aim to establish how to design a VR application to purposefully supplement environmental education at local High Schools, and help the students understand the environmental consequences of their individual actions [Jacobsen 2020].

Through literary research, exploration of similar environmental VR applications, questionnaires, discussions with REACT and a group interview with local High School teachers, important challenges to current environmental education were identified and a design for the VR application was proposed.

Multiple challenges related to environmental education were found. In contrast to other subjects of natural science, the nature of the subject makes it impossible to conduct practical experiments at schools, and the invisible processes involved does not enable the teachers to teach anything other than descriptive knowledge of it. The education often lacks local relevancy for the students, as they generally learn about the overall processes and general outcomes, but does not focus as much on the local impacts. Powerlessness is another challenging aspect of the subject, as students don't think that their actions have meaningful impact. These challenges results in a lack of personal connection to the subject and their own carbon footprint.

3.1.3 Proposed design

In the end, details from the initial outline were adjusted and expanded upon. Based on the data gathered throughout the process, including an interview with REACT representatives, the

Table 2: Proposed requirements from preparatory project.

Type	ID	Priority
Multiple scenarios	R1	The app should consist of multiple scenarios.
Change scenarios	R2	The app should move the user to a new scenario at the appropriate time.
Make choices	R3	The user should be able to choose between different alternatives in some, or all, scenarios.
Effect of choices	R4	The user's actions will translate into changes to carbon emissions, financial gain and health benefits
See result	R5	The app should simulate the consequences of the user's actions in the final scenario.
Reach goal	R6	In order to succeed, the user must achieve a 45% reduction is carbon emissions.
Single-player	R7	The app should be a self-contained single-player experience.
Choice of HMD	R8	The app should run on a standalone HMD.
Language	R9	The app should use Norwegian as chosen language.
Mapping between action and outcome	R10	Choices made will represent a sizable group in order to factually represent big changes to the future.
Scientifically accurate	R11	As much as possible, effects of emission cuts must be scientifically based.
Main hub	R12	A representation of the user's house will act as the main hub.
Upgrades	R13	There house and objects within can be upgraded to be more environmental.
Give feedback	R14	The app should give the user feedback on the emission cuts of their choices.
Sequence of scenarios	R15	The chronogoly of the scenarios should be free to choose.

requirements in Table 2 were proposed.

The result of the project describes a single-player VR application where the user is placed in their pretend home in Trondheim. Actions can be performed to make that house more carbon-friendly, and the user has the ability to project themselves to year 2050, where they will experience the environmental consequences that are projected to occur. The environment will be decreasingly affected by climate change as environmental actions are performed, and there will be some other sites around Trondheim where the user can see the environmental impacts.

Year 2050 was chosen as the destination for time-travelling in dialogue with REACT. According to REACT, it should be far enough into the future for substantial impacts to manifest, but near enough for the students to visualize in terms of their own age, as they will be in their late fourties and early fifties.

The idea of using the students' pretend home as the basis of the application came from Project Drawdown. Looking through the lists, most of the environmental solutions accessible to individuals revolved around household actions, generally related to reducing energy usage.

Using 360°-videos was deemed unnecessary to accomplish the intended outcome.

Table 3: Final requirements.

Requirement	ID	Description
Multiple sites	R1	The app should present multiple sites in Trondheim.
Perform actions	R2	The user should be able to perform actions.
Effect of actions	R3	The user's actions will translate into changes to carbon emissions.
See result	R4	The app should visualize the consequences of the user's actions in a simulated future.
Reach goal	R5	In order to succeed, the user must achieve a 50% reduction is carbon emissions.
Single-player	R6	The app should be a self-contained single-player experience.
Choice of HMD	R7	The app should run on a standalone HMD.
Language	R8	The app should use Norwegian as chosen language.
Mapping between action and outcome	R9	Actions made will visually represent a sizable group in order to factually reflect big changes to the simulated future.
Scientifically accurate	R10	As much as possible, climate change and the effects of emission cuts must be scientifically based.
Main hub	R11	A representation of the user's house will act as the main hub, where most of the actions may be performed.
Upgrades	R12	Parts of the house and objects within can be upgraded to be more environmentally friendly.
Give feedback	R13	The app should give the user feedback on the emission cuts of their actions.
Open approach	R14	The user will be free to choose when to do different actions, travel to pre-defined sites in the city and view future simulations.

3.2 Requirement specification

At the start of the semester, an initial meeting with me, REACT and my supervisor marked the start of this project after the preparatory project had been concluded. During the meeting, we discussed the priorities of the application to be developed. As this project would produce a prototype and be the first of many development projects, it was established that the focus of this project would be on the fundamentals. The projects would have its own animator and 3D-modeller, which would become available midway through the project. This would provide the project with the skills and tools necessary for specific models and visuals in the application.

During the meeting, adjustments to the initial requirements from the preparatory project were made and the final requirements for this project were defined, presented in Table 3. The requirements were based on input from REACT, input from teachers in the preparatory project, and literature.

To avoid confusion, wording was changed; "scenarios" would now only refer to the different versions of the future, and was replaced with "sites" when locations were referenced. The target demographic was expanded to "young people" in the research questions (Section 1.2), a simplification that would expand the user base to include students at secondary school and young adults. It would still be a priority to create something useful a classroom setting, but the application should also be feasibly used on its own.

Note that the proposed R2 (in Table 2) was removed as it was affected by changes to R15. Thus, the IDs are shifted, meaning that R3 in the final requirements correlates to R2 in the proposed requirements, R4 correlates to R3, et cetera.

3.2.1 Requirement 1: Locations

This requirement specifies that the user should be able to visit different areas of Trondheim. Although not explicitly specified, the sites should all conform to R4, having a visualized future where some impact(s) are visible, such as wildfire increases, droughts, floods or fish collapse.

The wording of the proposed requirement (Table 2) failed to address local relevancy by omitting the location, although it was mentioned elsewhere. RQ1 relates to increasing knowledge of climate change where traditional methods struggle, and findings from the preparatory project indicated that increasing the users' personal connection through local relevancy was an important area where VR could purposefully contribute, as the traditional climate education often focuses on the global perspective (Section 3.1.2). Having the experience be centered in Trondheim might make them better understand how they will be affected by climate change in the future. People are more likely to express concern for climate change if they perceive a low spatial, temporal and social distance related to the effects of climate change [Spence et al. 2012]. Because VR enables experiential learning through direct experiences [Kwon 2019], and people with direct personal experience of natural-hazard damage are more likely to be concerned about climate change [Lujala et al. 2015], it is purposeful to locate the experience in Trondheim.

3.2.2 Requirement 2-3 and 13: Actions

The second and third requirements are responses to RQ2, asking how to visualize environmental choices. These requirements state that there should be interactive actions available for the user, and that these should affect the user's carbon emission parameter. R13 simply formalizes that when the users make a choice that affects their carbon emissions, they should be shown some sort of information or animation.

Embodying the virtual body should make them perceive themselves to be executing the actions personally, and using gestures and spatial movement to move around, interact with objects and perform tasks that should contribute to internalizing information relevant to climate change and environmental actions [Weisberg and Newcombe 2017].

The proposed requirement of having multiple alternative choices (R3 in Table 2) was simplified in order to reduce the scope of the project. It was decided that simple actions would suffice, where the user is presented some straightforward task, and that the actions could be expanded to involve different alternatives in future iterations of the project.

Originally, REACT also wanted that actions to translate into financial gains and health benefits. This would be an interesting mechanism indeed, highlighting the complexity and competing interests that exists in the real world, but this was deemed out of scope for this project, as it would require a lot of work to be meaningfully implemented. It was agreed that these parameters should be reevaluated in future iterations of the project.

3.2.3 Requirement 4: Effect of actions

The fourth requirements states that the app should visualize the environmental consequences of the user's actions in a simulated future. As suggested by Fauville et al. (2021), future trajectories should be visualized based on carbon emissions. Using VR as a means to create direct experiences [Kwon 2019] may lower the perceived distance to climate change and hence increase the level of concern [Lujala et al. 2015] [Spence et al. 2012].

Perspective-taking tasks are indicated to increase empathy towards the embodied [Hamilton-Giachritsis et al. 2018] [Ahn et al. 2016] [Herrera et al. 2018], and embodying the user's future self where environmental impacts damage the user's local area may therefore increase empathy towards themselves.

Simulating hazardous consequences of climate change in the real world would likely be dangerous and very expensive. For this reason, it is a perfect fit for VR, as VR is well-suited to simulated situations that are expensive, time-consuming, impractical or infeasible in the real world [Freina and Ott 2015].

In dialogue with the REACT, we concluded that the future visualizations should always be available to the users (see R14 in Table 3), and so the wording of R4 was updated to accordingly. The requirement is intended to contribute to answering the main RQ, as the visualized future will vary with the executed actions (R3) and hopefully increase awareness and concern of individual contributions. The manner in which the future should be presented is unspecified, making this open for a number of different approaches. The chosen approach is discussed in Section 3.3.

3.2.4 Requirement 5: Reach goal

The fifth requirement states that the end goal of the application is for the user to achieve a 50% carbon reduction. This goal was defined by REACT in the application outline, although it was changed from 45% to 50% for simplification.

3.2.5 Requirement 6-7: Technology

Requirements #6 and #7 states that the app should run on standalone VR headsets, and that it should be a self-contained single player experience. REACT did not wish to over-complicate the development with online or multiplayer components at this point, and we concluded that this could be added during future development if deemed necessary.

Currently, Oculus' standalone HMDs are the cheapest and most user-friendly VR HMDs available on the marked. The Oculus Quest and Oculus Quest 2 have simple and polished operating systems, a substantial library of VR content, and a reasonable price. As stated in RQ2, the application should strive to be user-friendly. In order to maximize the potential reach and the user-friendliness of the application, these HMDs will be the target devices that the application will run on.

3.2.6 Requirement 8: Language

Although the experience could feasibly be presented in English to increase the size of the audience, it was concluded that using an international language would undermine the feeling of local relevancy discussed in R1 (Section 3.2.1), and as such, the language of the app should be Norwegian.

3.2.7 Requirement 9-10: Factual representation

An issue highlighted by the teachers in the preparatory project was that exaggerated environmental consequences or disproportional effect of actions would not serve the purpose of this application, as users would quickly lose interest and disregard the application as inauthentic and misleading. To factually represent the effects of emission cuts and the visualized future, R10 was added.

At the same time, the teachers were concerned that the users would feel powerless if the application showed them that they have no power as individuals. Therefore, they emphasized that the application should be empowering and communicate collective action to make the visualized impacts realistic.

When communicating the need for collective actions, apps and games often make the user's actions have disproportionately large effects. Although it may be implicit that the player or user represents a large group of people, it is not always clearly communicated. R9 requirement was added to ensure that this important detail was included in one form or another, but did not specify how to visualize it.

3.2.8 Requirement 11-12: Main content

Practically every consumer choice made by individuals affect carbon emissions directly or indirectly, which leaves unlimited possibilities in the choice of actions to be presented. However, the project demanded actions that had a substantial impact, and that could be quickly and purposefully implemented. The actions should be realistically executable by individuals to make environmental actions as tangible and accessible as possible. Project Drawdown presents a number of environmental solutions that are actionable by individuals, most of which related to the household. The conclusion was that the content should revolve around actions taken in and around the user's pretend home as described in these requirements. The actual actions to be implemented was not specified.

Presenting the user's home as part of the solution is intended to empower the user to act pro-socially. Embodying a pretend version of themselves contributing to pro-environmental behaviour in their local area where climactic consequences are visualized is intended to increase empathy for their future selves and the people around them, and should in turn increase awareness and concern about individual contributions to climate change.

3.2.9 Requirement 14: Open approach

The final requirement relates to the freedom of the user. I have been warned not to railroad the users, meaning I should not create a set path for the users to follow, with little to no freedom to choose how to approach the experience. Instead, I was encouraged to enable the users to explore freely, choosing whether to perform actions or not, when to travel to other sites, and when to go to the future. Facilitating the exploratory capacity innate to the technology should motivate the user to learn [Beheiry et al. 2019], and Markowitz et al. (2018) suggests that the more exploration users conducts, the more they learn.

3.3 Addressing remaining issues

With the requirements defined, the development could soon commence, but some critical details remained. The development tasks were still very open and creatively challenging, and I had to decide how to implement the mechanism of time traveling, how to visualize carbon dioxide emissions, how to visualize collective action, and what specific actions to implement.

Anatomy of the future scenarios

First of all I needed to establish how the future visualization would work. Time-travelling had been established as a desired feature, and it had been decided that users should be able to time-travel whenever they want.

In the Stanford Ocean Acidification Experience, when visualizing the difference between a healthy reef in the present and a visualized unhealthy reef in the future, the user is simply moved from one scene to another scene, in the same manner as the rest of the experience. This would not work in my application, as the user should themselves choose when to time-travel. Greenland Melting presents visualized futures and pasts in the same manner, with no user control. Rising Sea Levels in Trondheim (RSLT) does not involve time-travelling, as you are permanently in the future and the effects of your actions are immediately visualized.

I figured that the way to make free-to-choose time-traveling meaningful was to continuously update the future visualization based on the actions performed by the user up to the point of time-traveling, so that actions have an immediate effect, similar to Rising Sea Levels. To implement this, every individual action should translate into a change to the future. In other words, the visualized future should directly reflect the user's of carbon emission parameters. To make it as interesting as possible, the visualization should consist of multiple impacts, such as water height, temperature and extreme weather increase, droughts, floods, et cetera. Visualizing the future as a collection of different impacts would realistically resemble the reality, I concluded.

Time-traveling

The next issue was how to transition from the present to the future. I considered creating stationary, handheld or wearable "portals" in which the future could be seen or visited. A "magic door" could allow the user to pass through and into the future, a handheld magnifying glass could reveal the "hidden knowledge" of the future, or the user could use a wearable such as a set of glasses to see into the future.

Although I found the ideas intriguing, I thought it would be purposeful to make the future gradually unfold instead of switching between two discrete "versions" of the scene, similar to RSLT. I wanted the user to feel like they were actually watching time fly by very fast, instead of abruptly jumping three decades into the future, intending to decrease the user's perceived temporal distance to climate change.

A continuous transition from the present to the future, indicated by the sun moving across the sky rapidly as years fly by, was the solution. The user should be able to see the future parameters change real-time.

Time-travelling triggering mechanism

Next, I needed a trigger for the transition. I considered creating a handheld device that the user could pick up and activate, perhaps looking like a high-tech or futuristic machine, but concluded that a simple clock would suffice, activated by touching. The clock face should be animated to show time passing by, synchronized with the rapid sun cycles.

Carbon emission visualization

For tracking the user's carbon emissions (CEs), I considered a textual counter as a UI element on an object, similar to RSLT where indicators are placed on the gun (Figure 6 and Figure 7). Instead, I decided to make it more "physical" and utilize objects and animations to make it more tangible. I considered representing the CEs the same way the ball-and-stick models in the Stanford Ocean Acidification Experience is used to visually represent carbon dioxide molecules(Figure 10). This would make the objects recognizable, but because I wanted the user's entire carbon footprint to be represented as a low number of objects, I did not want to use models that represents individual CO_2-molecules and cause confusion, so I decided to use something more abstract.

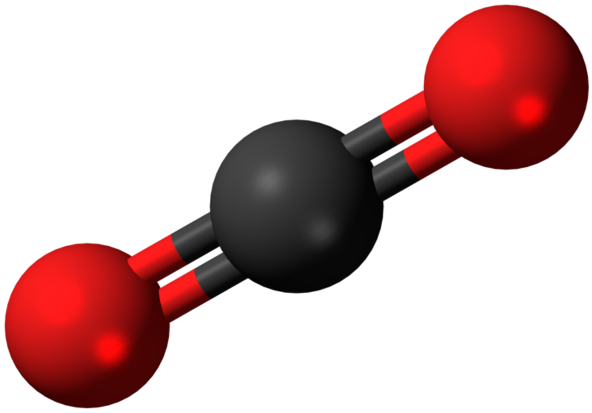

Figure 10: A ball-and-stick model of a carbon dioxide molecule. Source: Wikimedia Commons

I wanted to create something reminiscent of smoke and contamination. For this purpose, I figured dark spheres with animated black fog around them would work. One such sphere, or molecule, would correspond to a percentage of the user's total CEs. I wanted the CE tracker to represent them visually, and I decided to place the molecules on the user's virtual body. More specifically, I made them orbit the wristwatch, intending to create a mental connection between the carbon dioxide, time, and the future that the wristwatch took you to.

I was very uncertain of how to best animate the CE cuts, but concluded with a simple animation; when an environmental action is performed, the corresponding number of molecules should leave orbit and float in front of the player for some seconds, increasing in size and then exploding in a audible "pop". This way, the user could see how many parts of their total footprint the action corresponded to.

Tasks

It had been decided that the available actions should be possible to perform in a household setting, but the actual actions had not yet been specified. Project Drawdown presents a variety of CE reducing solutions on their website, but many of them are agricultural, industrial and technological solutions that require large, coordinated projects that are out of any one individual's capacity. By filtering out these solutions, I made a list of solutions that individuals can execute. Sorting by potential emission reductions, I found the most effective solutions, presented in Table 1 in Section 2.1.2.

Although switching to a plant-based diets proved to be the most efficient household solution, I found the scope of the issue too broad, requiring a lot of consideration and work to meaningfully implement, as there are numerous approaches to present this specific issue. Food culture is also a touchy subject, and because I did not want the application to be interpreted as too critical or confrontational, I chose not to prioritize this solution.

The first two tasks, I decided, should be installing a solar panel and replacing energy in-

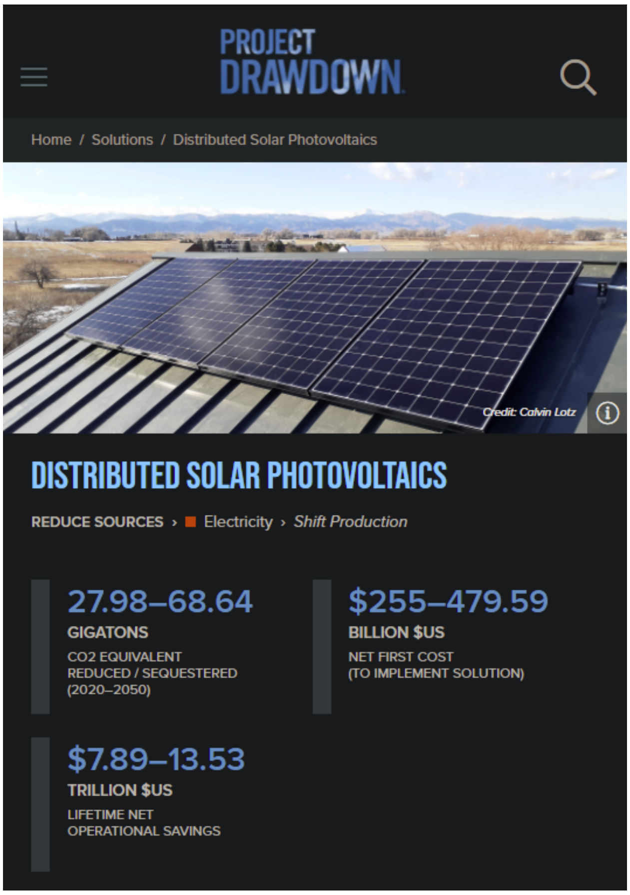

Figure 11: Screenshot from Project Drawdown's webpage. Source: Drawdown

efficient lights with LED lights. These are among the top four individually actionable solutions ranked by emission cuts, and should be both easily implemented and easily performed by the users.

Visualizing collective action

The last issue to address was related to R9 (Section 3.2.7), stating that the actions taken should visually represent a sizable population. This was a daunting and creatively challenging tasks, and in the end, I had only one idea I thought could work; I could create "copies" of the user and mirror the user's movement in a recursive manner, creating a visualization similar to the effect of having mirrors be placed symmetrically and watching as your mirror image is multiplied many times. The user should see a seemingly infinite number of people imitating their movement, and be informed that these are other people doing the same things as you. This should0communicate that we're all in the same boat, and watching everyone "contributing" the same may be an empowering experience.

4 Process

This section presents the development process. The results are presented in Section 5, but key findings are summarized between the iterations. Table 5 in Section 5 shows an overview of the testing sessions.

4.1 First iteration

4.1.1 Task prioritization

For the initial iteration, the very basics needed to be implemented, and I prioritized

- adding the house,
- creating the first actions,
- translating actions to emission reductions,
- visualizing emission reductions,
- varying the future based on different levels of emissions and
- creating a time-traveling animation.

The priorities were proposed to and approved by REACT in the first meeting.

4.1.2 Development

City model

The application required a 3D-model of the city of Trondheim, and Trondheim Kommune (the local municipality) had made such a model available online. Because of the limited performance of Oculus Quest, the model could not be used in its entirety.

I concluded that the model would have to be cut into small pieces and exported with high- and low-quality texture versions. Thus, I could use a high-quality segment for the segments closest to the user and low-quality segments for the segments further away. The most distant segments could be disabled entirely. This would let the user access the whole model without performance issues, but I lacked 3D-modelling experience and had to use a temporary solution until I had access to the necessary expertise later in the project. A previous project at IMTEL had segmented the model(roughly 2km x 2km), and although smaller segments would be preferred, one such segment could run on the Oculus Quest.

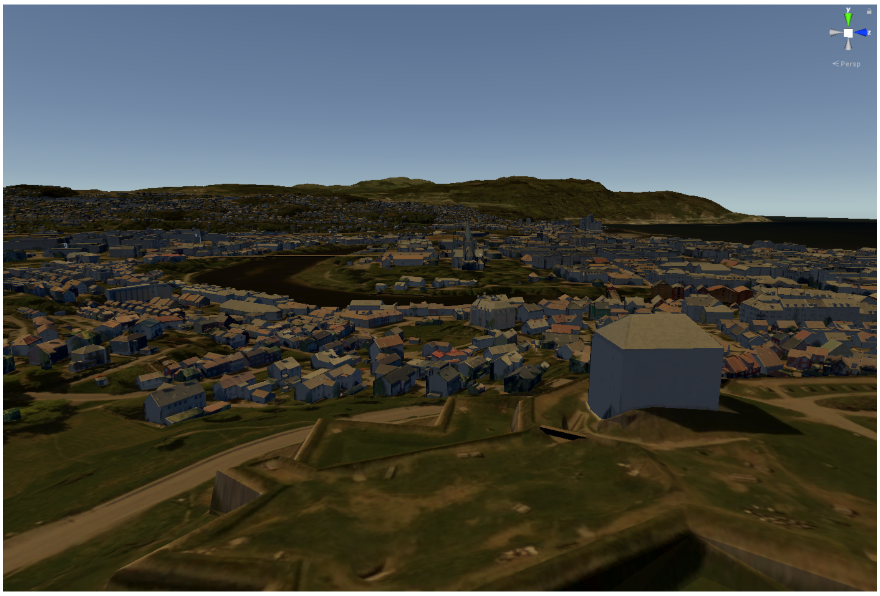

Figure 12: Model of Trondheim. Source: Kommune

House model

As I considered the layout of the house, I decided that it would be best to avoid multiple stories. Stairs can be awkward to navigate in VR, and because there was nothing that necessitated a big house, a single-story house would suffice. I found a suitable, free model through Unity's Asset Store (Figure 13). If, at some later point, the development revealed that more space was needed, I could always find a bigger house model.

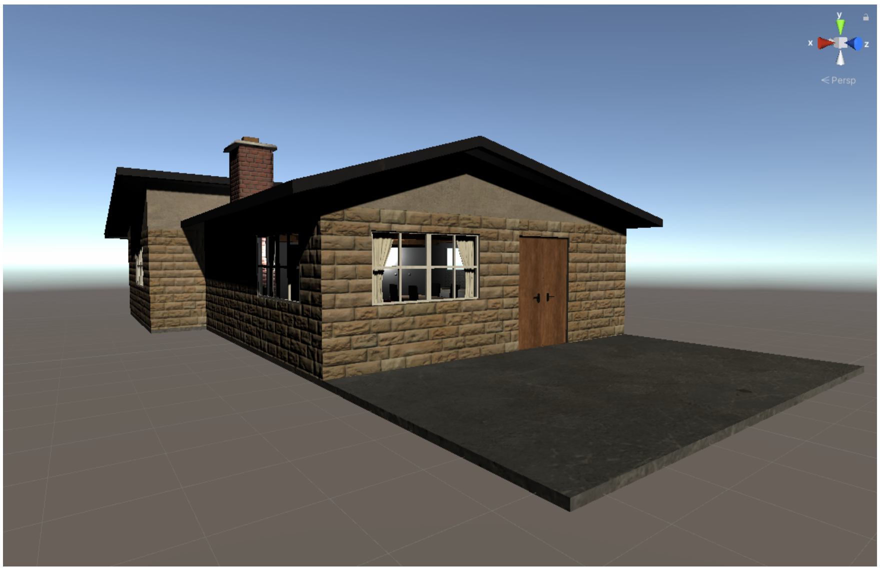

Figure 13: House model. Source: Unity Asset Store

Locomotion

For the purpose of user movement, I considered two possible modes of locomotion; teleport-based locomotion, in which the user points at a designated space and select it to make them instantly appear at that spot, or continuous locomotion, a sliding motion similar to joystick movement known from gaming. I knew that continuous locomotion generally induced motion sickness more often than teleporting did, but I suspected that reduced movement speed would be sufficient, as teleporting usually requires more time to learn for new users. Therefore, I chose continuous movement, intending to add the ability of letting the user choose the locomotion modes at a later stage. The user can use the joystick of either hand to move.

Hand models and interactions

I wanted to make the interactions as simple as possible, as VR controls can be very unintuitive and confusing to new players in my personal experience. I also wanted the tasks to be easily executed by grabbing and placing them correctly. To reflect this, I added simple hand models, with a single grabbing motion animated when the user squeezes the controllers. This is to communicate that there is only one thing to do with your rendered hands, and that is to grip things.

Time traveling

The time-traveling transition discussed in Section 3.3 was added. A day/night-cycle is gradually sped up, then down, lasting a few seconds and updating the parameters in synchronicity with the speed of the transition animation. Variable sea level was added as the first parameter, raising and lowering the water level based on the amount of carbon emission cut. When all molecules are present, the sea level will increase during the transition until it reaches it maximum projected height when the animation is fully executed, and moving back to its default height going back to the present. As actions are performed and molecules removed, the future sea level is lowered.

Triggering mechanism for time travel

With the time traveling transition in place, I added a simple triggering mechanism where the user touches a clock on their left wrist with their right hand (Figure 14). I used the placeholder model for the clock with the intention of adding working clock face in a later iteration.

Carbon emission tracker and reduction animation

The CE tracker and CE reduction animation described in 3.3 was added (Figure 14). Fifteen molecules were chosen to represent 50% of the user's CEs, all of which must be removed to get the most positive visualized future.

Identifying intractable objects

I added an object highlighter to indicate objects that are in reach and can be interacted with (Figure 15). The objects turns green when the user's hand is in reach.

Figure 14: Placeholder clock model with orbiting molecules.

Available tasks

I added the two tasks described in Section 3.3. The tasks are executed by placing the objects in a matching socket. As the user grabs an object and moves it near the socket, the socket lights up indicating that the object can be placed there. As the user lets go of the object, it automatically snaps in place.

The solar panel installation task simply consisted of placing the panel in its designated socket, but the light replacement task was more involved. The incandescent lights needs to be removed before the LED fixtures can be installed, as seen in Figure 16. When an incandescent light is grabbed by the user, the light turns off, and when it is dropped, it disappears in an audible "swoosh". Once the LED fixtures are placed in the socket (Figure 17), they light up automatically. I added four areas for the lights to be replaced.

Interactions in future scenarios

All objects are made non-interactable in the future, as I suspected it would be confusing for the users if they could perform tasks while in the future.

Figure 15: Object highlighter.

4.1.3 Intermediary test summary

The initial user tests took place at IMTEL's VR lab. There were 25 visitors in total, and they tested the application in batches of 3-5 users. I had yet to add any instructions in the application, and I instructed them on how to navigate and interact myself. The results provided me with lots of useful observational data, but I had not consider the possibility that students were English-speaking, and I had formulated the questionnaire in Norwegian. Therefore, many testers were unable to respond.

Respondents did not seem to understand why the tasks performed lead to reduced climate emissions (Figure 32), and observations substantiated this. Testers were observed to quickly understand the locomotion, and results from the questionnaire (Figure 33) support this. The object interactions were observed to be intuitive, also supported by the questionnaire (Figure 35).

The main problems revolved around usability. The continuous movement made some users nauseous, and the LED lights were not always correctly identified. Furthermore, the time-travelling mechanism was often initiated by accident. Combined with the fact that the future scenarios had few visual differences from the present, users were very confused if they were in the future are not. Most users did not time travel before executing tasks.

Because of the hygienic measures implemented at IMTEL's VR lab during the pandemic, resetting the application became troublesome during testing. After each user had finished testing, the HMD and controllers had to be were sterilized with alcohol wipes, and then put in a UV

Figure 16: Removing incandescent light.

Figure 17: Installing LED light.

radiation machine for around one minute. The machine was continuously running, as HMDs from other tests also had to be cleaned. Re-launching the application on the Oculus Quest requires knowledge of where developer applications are found, which is not easily explained to new users without visual references. Therefore, I needed to use the headsets myself in-between users, which doubled the amount of cleaning required.

4.2 Second iteration

4.2.1 Task prioritization

For the second iteration, I wanted to add more content to the experience while making the application more understandable and user-friendly. I needed the application to communicate what the tasks were and why they were environmentally friendly. Regarding time-travelling, I suspected that the users would be more likely to visit the future early if the mechanism was more clear, and I also wanted to create an introduction prior to the main content. The intention with the introduction was to introduce the user to time-travelling, the controls and present other details important for the experience.

I prioritized

- making the LED models more recognizable,
- changing the locomotion mode,
- presenting the tasks and their progression inside the application,
- changing the triggering mechanism for time-travelling,
- adding textual parameters,
- adding a new task,

- adding a reset-shortcut and
- starting to work on an introduction

These tasks were discussed with REACT over email, and they found the plan purposeful.

4.2.2 Development

LED models

Because some users had trouble identifying the LED fixtures, I added hovering labels above them, reading "LED". The text follows the direction that the user faces, and is always readable.

Locomotion

A few people got dizzy or nauseous from the continuous movement, so I switched to teleport-based movement. This is a non-continuous locomotion technique where the user is instantly re-positioned to a location of their choosing, and I suspected this would reduce the reports of cybersickness.

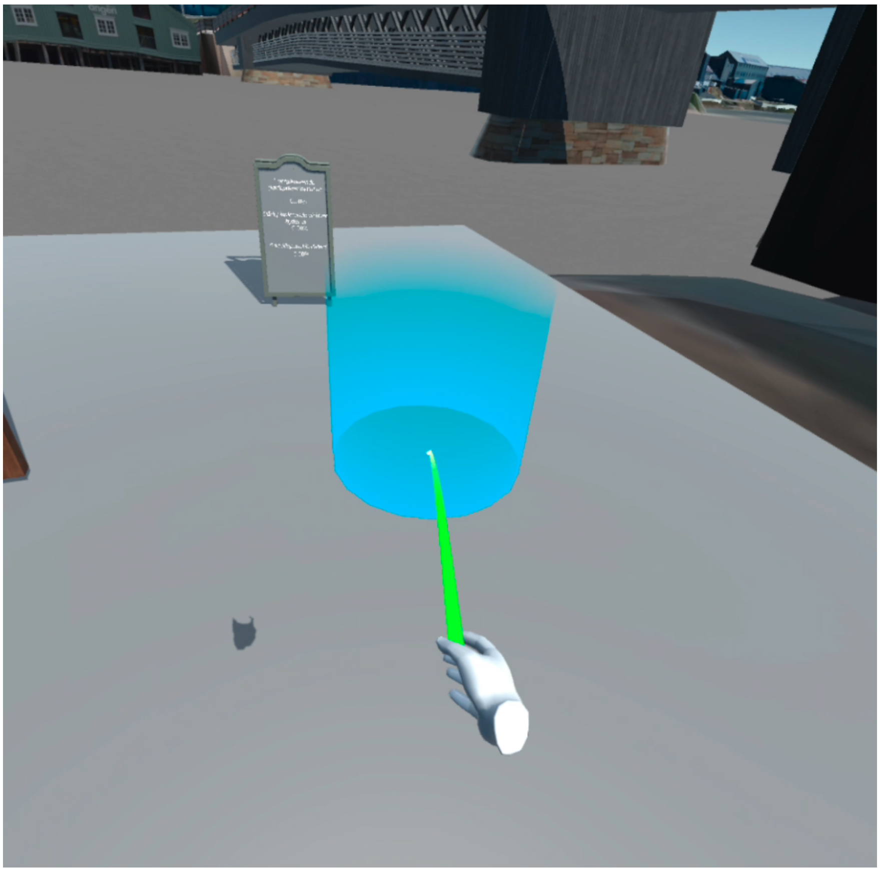

Figure 18: Teleport-based locomotion.

New task

To expand the available actions, I implemented an additional task from Table 1. Replacing poorly insulated windows with high performance ones is indicated to cut carbon emissions substantially. Because the windows in the model were of different sizes, I decided to make the windows automatically scale to their correct sizes when put in place. This way, the interactive windows are of uniform size and can be placed in any window socket. I also had to make the pre-installed windows removable. I had never used 3D-modeling software before, but managed to delete the mesh of the windows, and added them back as interactable objects in Unity. Removing the windows is done by grabbing them, and like the incandescent lights, they disappear in an audible "swoosh" when let are go of. The new windows were strategically placed around the house on the outside, each near a window (Figure 19). I also added hovering labels to them.

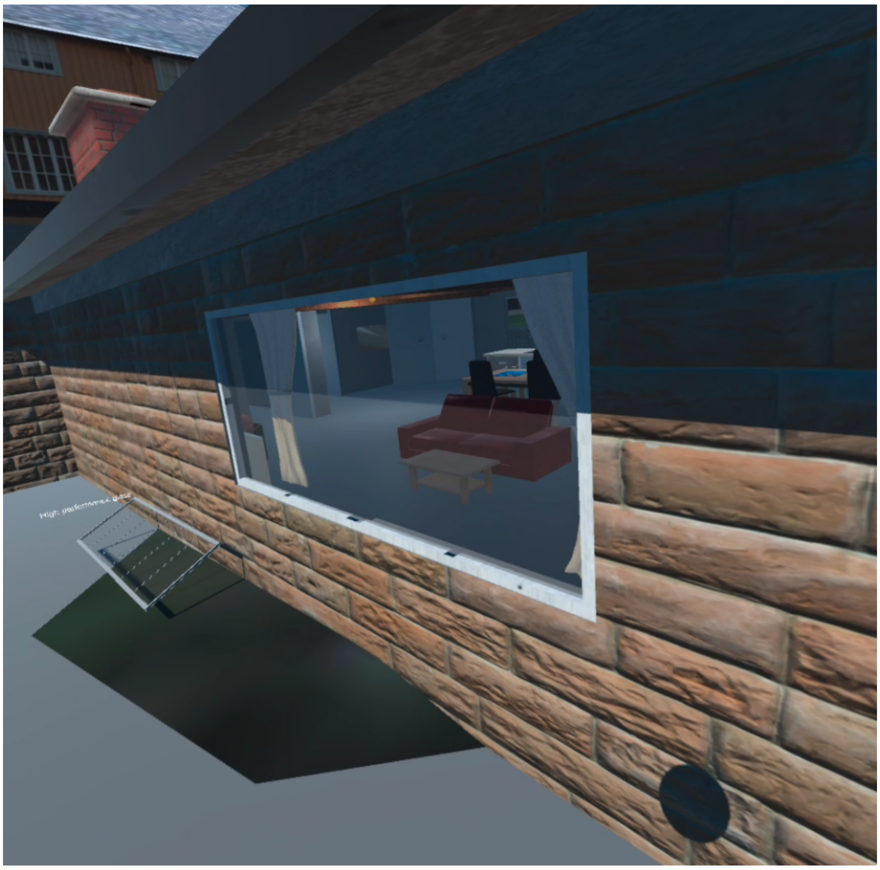

Figure 19: Replaceable windows.

Task presentation and progression tracking

The first questionnaire revealed that players were confused about what to do, despite verbal instructions given prior to the experience. I considered adding static UI elements to the user's field of view showing them the objectives and the progression, I but wanted to add something more immersive. The simplest solution I could come up with was adding a simple chalkboard to guide the user. The chalkboard (Figure 20) is placed outside the house, and presents the available tasks. It also shows the progression of the different tasks.

Figure 20: Chalk board showing the progression of tasks.

Triggering mechanism for time travel

Sometimes, users would accidentally trigger the time traveling mechanism. In order to keep the wristwatch as the initiation mechanism, I would need to tweak the interaction considerably, preferably implementing "physical hands" which would stop the user's hands to move through objects such as the clock, and also add a vibration when the mechanism was initiated by touch. However, to save time, I decided to replace the clock with a transparent sphere and make it interactable in the same manner as other objects (Figure 21). When the user grabs and the releases it, it snaps back to its position and initiates time-travelling. I placed the molecules inside the sphere, and planned to have the molecules "shoot out" of the sphere and spread out into the atmosphere when the user has released it and it snaps back. This was intended to show that the user's CEs are "released" into the atmosphere as the future unfolds. Going back to the present, the molecules would go back into the sphere. Unfortunately, this animation was not made due to time constraints.

On a related note, the "fuming" effect around the molecules was removed. The intention was to replace it an effect similar to one I was working on in the introduction (See Figure 28), but this proved technically challenging and was also not implemented due to time constraints.

Future scenarios

The future scenarios were still lacking, and the difference between a good outcome and a bad outcome were hard to spot. A strong visual indication would be showing the effects of drought in the bad scenarios, indicated by withering vegetation. For this purpose, the project required different plants and trees with gradual withering animations. In the worst scenario, the withering would be at its maximum, in the best scenario, there might only a little withering, and for every scenario in between, the it would be at some intermediate stage. The project's 3D-modeller would not be available during this iteration, but I still wanted something more to change between the good and bad scenarios. I decided to add dynamic music, meaning music that changes to reflect the actions of the user; the good outcomes should have pleasant music, and the bad outcomes should have discomforting music.

Epidemicsound.com provides royalty-free music and makes the stems (instrument tracks) of songs available. I found a comforting classical piece that had minimal variation throughout so that it could be seamlessly looped, and would also work with only the main piano track playing. I chose to make this stem play continuously throughout the experience, and made other stems fade in when transitioning to the future. If the user has cut 40-60% of their removable emissions, this is considered a "neutral" outcome and the soothing piano continues with no changes. But as the user exceeds 60%, the bass and string stems from the track are faded in, increasing in volume as the user approaches 100%, conveying a feeling of hope and excitement. On the other hand, if the user has only cut 40%, eerie and ominous strings from another track fades in during the transition, and volume is higher the closer the user is to 0% CE reductions.

Textual parameters for future scenarios

As a temporary solution until more future visualizations were in place, I added textual parameters on the left arm, indicating the current year, temperature change in the sea level rise (Figure 21). The parameters are updated real-time as the user travels forward or backward in time.

Resetting the application

The hygienic measures at the VR lab made it clear that the application needed a quick-access reset function. Without it, I had to use the headset myself in between users to relaunch the application, which would then need to be cleaned once more. I wanted to be able to restart the application without the need for visual references, and concluded that shortcuts on the physical controllers would suffice. I made it so that the application resets when both joysticks are clicked simultaneously (pressed down like a button).

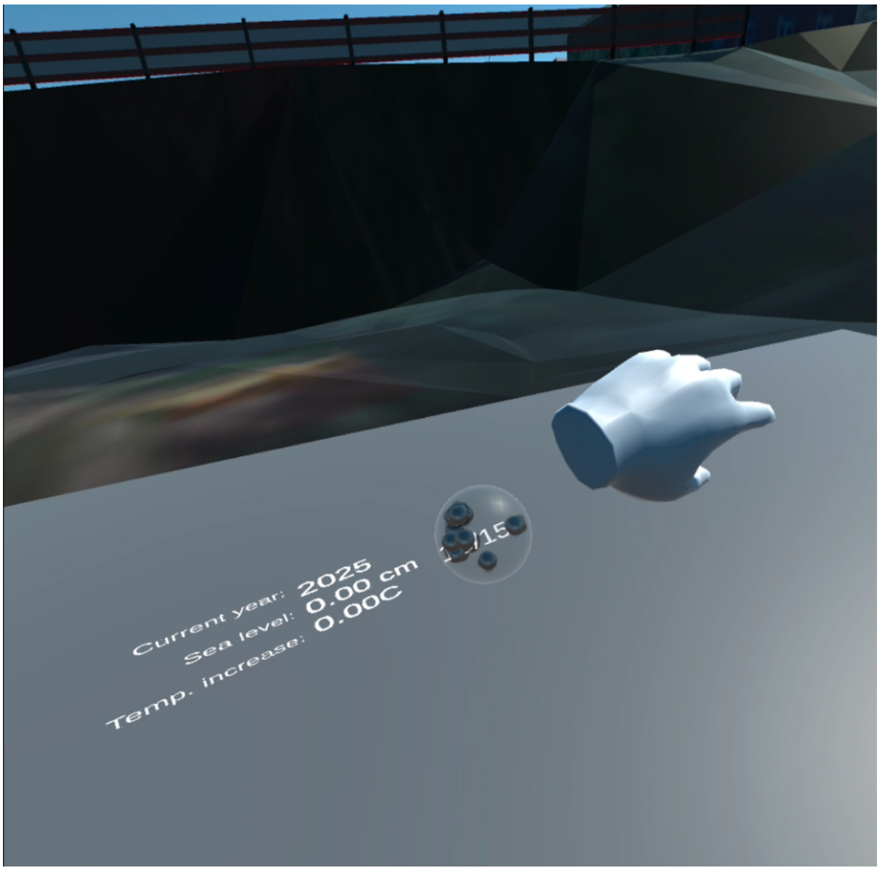

Figure 21: Temporary textual parameters.

Introduction

Lastly, I started working on an introduction to the application, which would provide the users with all the necessary information that I was currently telling them myself before testing.

4.2.3 Intermediary test summary

The second user test was also conducted at IMTEL's VR lab. The testers received the same instructions as the first test, except for details related to the tasks. Instead, they were told where to find the chalkboard presenting the tasks. Although I formulated the questionnaire in Norwegian this time, and around 15 visitors tested the application, there were very few responses. Still, the observational data from the testing proved very useful.

Generally, the application was considered more user-friendly, and there were no reports of cybersickness after the switch to teleport-based locomotion. The tasks were reported to be easy to understand and perform (Figure 31), and it was more clear why the actions resulted in reduced emissions after the chalkboard was added (Figure 32). The respondents also evaluated the application using the System Usability Scale (SUS), and the final score was 72/100. This is generally considered a satisfactory score, but I assumed that it would be lower if they had tested the application with no instructions or help, and therefore I still wanted to increase the usability of the application.

Some users still had trouble understanding the time-travelling aspects of the application. The textual parameters on the arm was not a satisfactory solution and users were still confused if they were in the present or future. The transition was not particularly good, and testers found it uninteresting (Figure 36). Furthermore, the CE reduction animation was considered unclear (Figure 37).

The questionnaire made it clear that the application would benefit from an introduction with a tutorial, where the user is shown how to interact and navigate with the virtual environment (Figure 30).

4.3 Final iteration

4.3.1 Task prioritization and re-visited requirements

Table 4: Revisited requirements. Red color indicates downgraded priority.

Requirement	ID	Description
Multiple sites	R1	The app should present multiple sites in Trondheim.
Perform actions	R2	The user should be able to perform actions.
Effect of actions	R3	The user's actions will translate into changes to carbon emissions.
See result	R4	The app should visualize the consequences of the user's actions in a simulated future.
Reach goal	R5	In order to succeed, the user must achieve a 50% reduction is carbon emissions.
Single-player	R6	The app should be a self-contained single-player experience.
Choice of HMD	R7	The app should run on a standalone HMD.
Language	R8	The app should use Norwegian as chosen language.
Mapping between action and outcome	R9	Actions made will visually represent a sizable group in order to factually reflect big changes to the simulated future.
Scientifically accurate	R10	As much as possible, climate change and the effects of emission cuts must be scientifically based.
Main hub	R11	A representation of the user's house will act as the main hub, where most of the actions may be performed.
Upgrades	R12	Parts of the house and objects within can be upgraded to be more environmentally friendly.
Give feedback	R13	The app should give the user feedback on the emission cuts of their actions.
Open approach	R14	The user will be free to choose when to do different actions, travel to pre-defined sites in the city and view future simulations.

Before initiating the third and final development iteration, I had to reduce the scope of the project, as progress had been slower than anticipated. It had become clear that the animator/modeler would not be available due to external constraints, so R4 would be the first requirement to be downgraded, as I did not have time to learn 3D-modelling and animation myself. Since there would be little point in presenting the user multiple sites around the city when there was no visualized impacts to see, R1 was also downgraded.

I had also realized it would be extremely time-consuming to create enough tasks that would realistically result in a 50% carbon cut, and had to choose between exaggerating the amount of carbon cuts from the currently available tasks and allowing the user to achieve the positive future scenarios, or to make it factually correct but disallowing the user to achieve 50% reduction. In dialogue with REACT, we concluded that it was more important for the user to achieve the good scenario in the application than to be scientifically accurate, and so R10 was downgraded.

After discussions with REACT, the priorities made for the iteration were

- improving the CE reduction animation,
- improving time-travelling transition,
- improving textual parameters,
- improving window models and
- finishing the introduction

4.3.2 Development

New window models

Most of the testers had tried to place the new windows on top of the pre-installed ones. The model used for the pre-installed windows was a tinted glass pane, but these were almost entirely invisible when they did not receive light (Figure 22). To make the window more visible, I added a horizontal and vertical bar through the glass, segmenting it into four window panes (Figure 23).

Carbon emission reduction animation

Testing had revealed that people found the CE reduction animation unclear, and it needed to be changed. I considered scrapping and re-doing the entire solution, but concluded that I should try to make the current solution better to save time. I decided that the removed molecules should still leave the CE tracker, but that they should make a notable sound and end up somewhere to be seen. I concluded that they should change color and end up on the right hand, where they would be clearly visible. I also added a short ringing sound effect when a molecule is removed. For novelty's sake, the molecules on the right hand may be lifted up and moved around, and when they are let go, they pop and disappear in a chain-reaction. Of course, I knew this would all have to be explained in the introduction, as it was not self-evident.

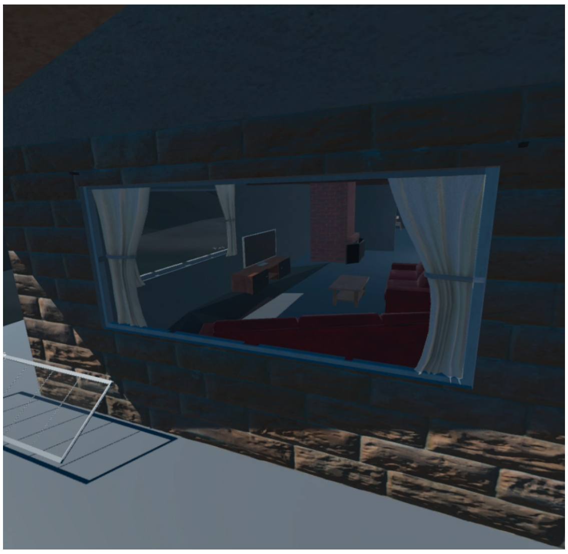

Figure 22: Hard-to-see windows in the shadows.

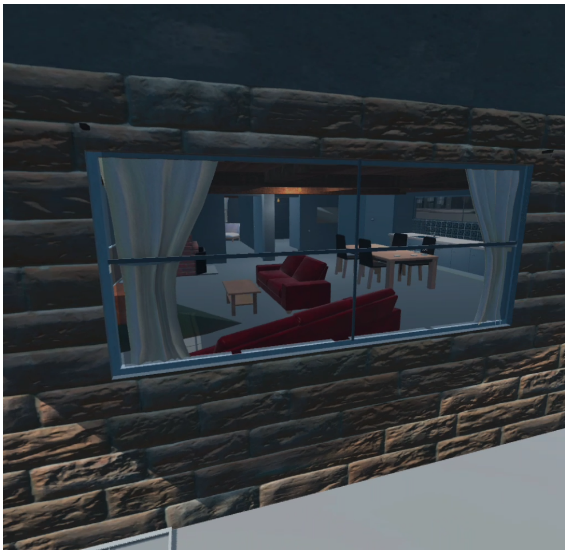

Figure 23: Updated window model.

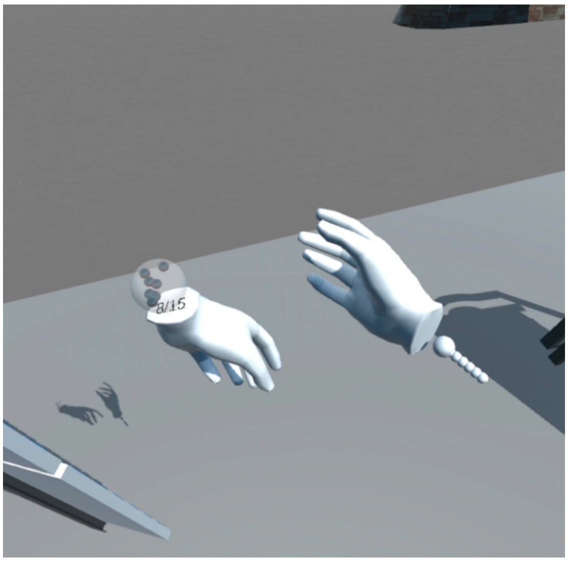

Figure 24: The molecules removed from the future are placed on the user's right arm.

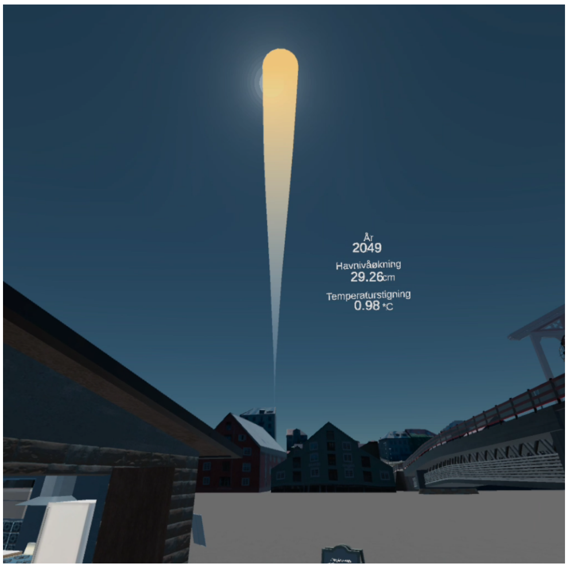

Figure 25: "Long exposure" effect on sun during the time-travelling transition.

Time traveling transition

The time-travelling transition was deemed uninteresting by the testers. I considered it important for it to be somewhat visceral, so I added a "long exposure" effect to the rotating sun (Figure 25.

Information

The parameter information on the arm proved unsatisfactory and I removed it from the arm entirely. Instead, the information appears in the user's field of view when time travel is initiated (Figure 25).

Skybox

Although the future would not contain the visualized impacts desired, I still wanted to add some minor visual changes. I created variable skyboxes, where the sun and sky can be brightened or darkened. If the user has performed few actions, the atmosphere will be more gloomy in the future, but the sky and sun will become more bright as the user performs more actions.

Scene selection and introduction

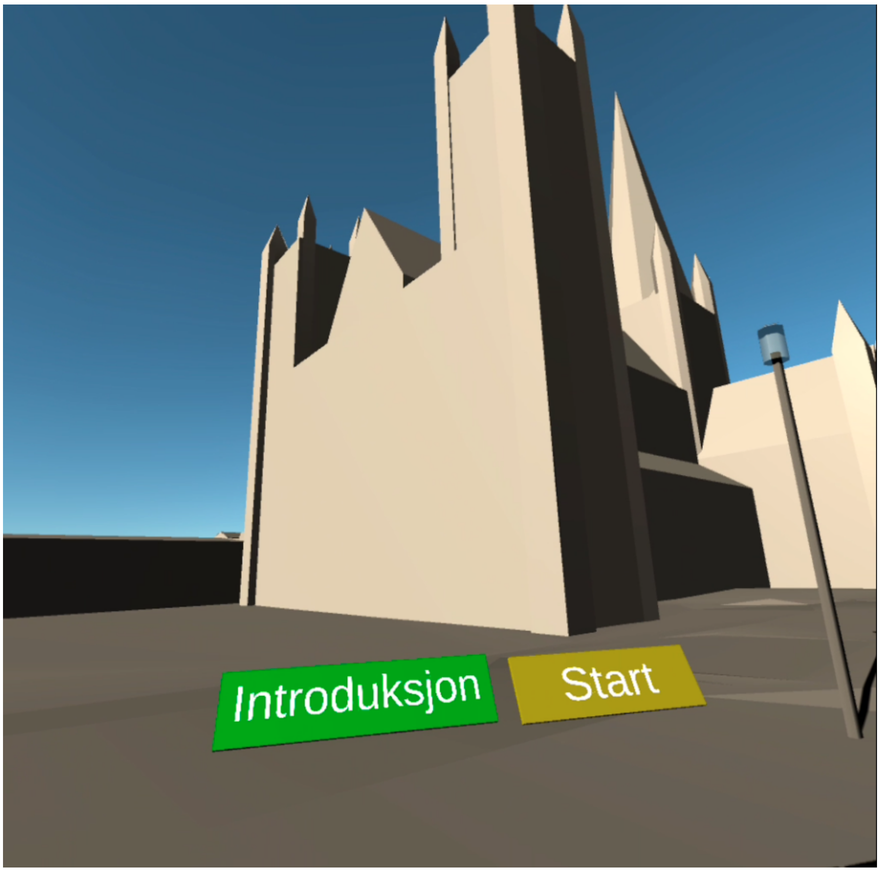

Figure 26: Scene selection.

The most important addition to the application was an introduction to be played prior to the main content. The app starts in a lobby (Figure 26), presenting the player with two choices; start the introduction, or start the main content.

Introduction

The introduction works both as a tutorial and a storytelling device. They user is taught how to interact and navigate in the application, guided by audio instructions. The audio manuscript can be found in Appendix B. The instructions must be carried out in order to progress. The first few minutes teaches the player how to grab things, how to place objects in sockets, and how to time-travel.

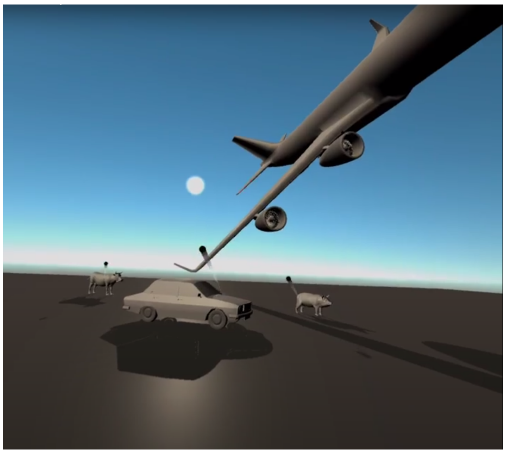

Figure 27: Visualized CE sources.

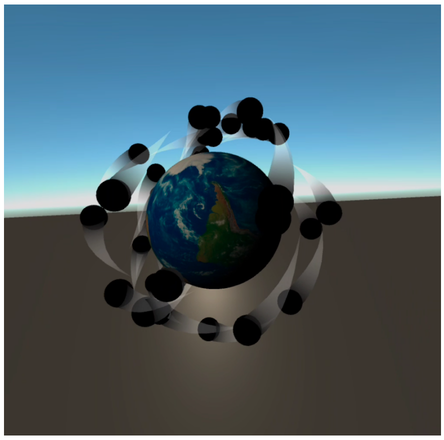

Figure 28: The user's carbon footprint orbiting the earth.

After the basic interactions are explained, the user is presented with the first of the two visualizations, the carbon footprint visualization (CFV). This visualization starts off with the narrator explaining the basics of carbon dioxide emissions while thirty black molecules, are "emitted" from four sources (a cow, a car, a pig and a plane) and travel towards a point in front of the user which they orbit upon arrival (Figure 27). The user is told that the molecules represents the user's entire carbon footprint from now and until 2050, and a model of Earth is faded in as they are explained that their emissions end up in the atmosphere. The molecules are then split into two groups of fifteen. It is explained that only half of the user's CEs needs to be removed, and one group disappears while the remaining fifteen molecules attaches themselves to the user's left arm, forming the CE tracker. After the CFV, there is a brief segment that shows and explains the CE reduction animation.

The collective action visualization (CAV) is the second visualization, and an attempt to convey to the user the actions taken within the app represent all humans. The user becomes the center of a large gathering of humanoid figures, where the figures mirror the user's exact movement (Figure 29). The user is asked to perform a simple action, and watch as everyone else does the same. The intention of the CAV was to empower and inspire the user, but also explain how the application can realistically show the user the effects of individual actions.

After the two visualizations, the user is explained that the main content places them in their pretend home by Gamle Bybro, where they can upgrade their house. It also explains that the tasks can be found on the chalkboard. Lastly, the user is taught how to teleport, and how to reset the application and move back to the lobby.

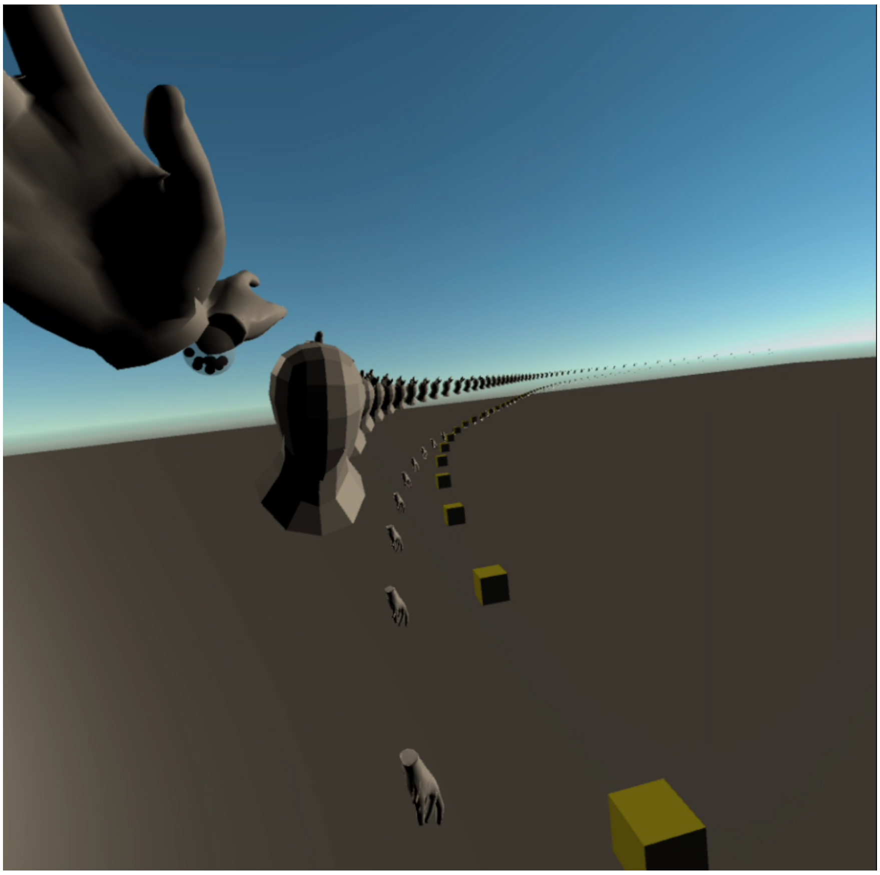

Figure 29: Moment from the collective action visualization.

5 Results

This section presents the results from the user tests and interviews. Three user tests were conducted, and two teachers were interviewed remotely. Finally, a physical interview with REACT was conducted.

A video summary of the final application can be found at the following link:

https://www.youtube.com/watch?v=mmjY-LE5T08

5.1 User testing

Table 5: Overview of user tests.

User tested	Users	Questionnaire responses	SUS score	Location	Form
25	Geography students	4	N/A	IMTEL	Multiple
15	Geography students	4	71	IMTEL	Multiple
10	Various students	7	83	Gløshaugen	Individual or in pairs

Table 5 presents an overview of the user tests conducted. The first two took place at IMTEL's VR lab at Dragvoll Campus (NTNU), where multiple users tested the application simultaneously. A couple of students from the lab, including me, prepared applications for the geography students to test at different stations. The first one had twenty-five and the second one fifteen visitors, and testing was conducted in parallel, with the visitors being split into smaller groups and moving between stations. Because of the ongoing COVID pandemic, there were strict hygienic rules. All headsets had to be sterilized with alcohol and UV radiation between users.

The third one was intended to test High School students at a local school, but was canceled a few days before because of an increase in COVID-19 infections after a few local outbreaks. Therefore, the third user test was conducted at various places with students at Gløshaugen, individually or in pairs.

5.1.1 Observations

Observations and comments were recorded by hand, and primarily used to uncover bugs and other issues.

Observations from the first user test

For the first user test, I had yet to add any instructions to the application. Therefore, prior to testing the application, the testers were instructed on how to navigate with the controllers and time-travel, and they were explained what the tasks were.

The following observations were made:

- No one had any problems with locomotion.
- Some users got cybersickness.
- Users did not correctly identify the LED lights.
- The time travelling mechanism was easily triggered by accident.
- Users were confused if they had time-travelled or not.
- The hygienic situation made resetting the application complicated and time-consuming.
- One tester, having never tried VR before, did not know what to do when the app started, and was completely frozen in place.
- Many users forgot to time-travel at the start.
- Some users forgot to time-travel altogether.
- Some users tried grabbing things while they were frozen in the future.
- Many users enjoyed exploring the city on their own.
- Users were underwhelmed by the future visualizations.

Observations from the second user test

Prior to testing the application, the users were instructed on how to navigate with the controllers, how to time-travel, how to reset the application, and where to find the chalkboard presenting the tasks.

- All users correctly identified the LED lights.
- No user reported cybersickness.
- The time travelling mechanism was not triggered by accident.
- Many users were still confused if they were in the present or the future, stating that the information on the arm was not very helpful.
- Some users had trouble remembering the mechanism of initiating time-travel.

- Some users tried installing new windows before removing the old ones because they could not see them.
- Many users enjoyed walking around in Trondheim.
- One user appreciated the music, stating it was something generally underestimated.
- Some users wanted there to be an ending screen indicating that all tasks had been finished.
- Few users tried time-travelling before conducting tasks.
- Some users forgot to time-travel altogether.
- Some users found performing the tasks satisfying.
- The textual parameters were poorly placed.

Observations from the third user test

For this user test, I gave no verbal instructions other than asking them to physically touch the button titled "Introduction".

- Many users still did not time-travel before doing tasks.
- Many users were intrigued by the CFV and the CAV in the introduction.
- One user did not time-travel altogether.
- Many users had trouble understanding the mechanism of initiating time-travel.
- A few users had trouble realizing they were in the future.
- Two users found themselves losing one or more objects. One was lost underneath the bed, and two others were thrown far away due to physics bugs.
- Two user tried to install new windows before removing the pre-installed ones
- Two users did not understand how to reset the application and go back to the lobby from the introduction.
- One user tried lifting the windows with two hands.
- Users tried using the same controller for movement and holding an object.
- Two users did not realize that either hands could be used for locomotion and interactions.
- One user mistook a button for the joystick, as it was also possible to teleport with this button.

- One user did not know where to find information about the tasks.
- Some users said that the tasks were fun.

5.1.2 Questionnaires

This section presents the findings from the questionnaires, some which have been translated from Norwegian to English. To answer the questionnaires, the participants had to agree to a consent form for privacy protection (Appendix D). The questions were answered using a 5-point Likert scale ranging from "Strongly disagree" (1) to "Strongly agree" (5). An overview of the questions asked are found in Appendix C.

Some charts have a percentage on their vertical axis to compensate for varying amounts of responses between iterations. Also note that in the last questionnaire, two testers were not presented with the three final questions.

Introduction

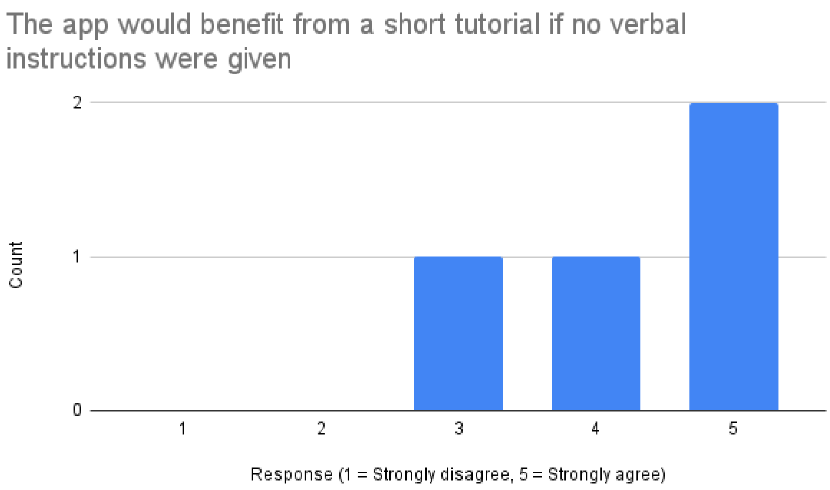

Figure 30: (Q2) Instructions and tutorial.

In Q2, users were asked if the app would benefit from tutorial if no instructions were given (Figure 30). The average score was 4.25.

Tasks

In Q2, the testers were asked if the tasks were easy to understand, and if they were easy to perform (Figure 31). The first question obtained an average score of 3.75, and the second 4.25.

In each iteration, after testing the application, users were asked if they understood why the tasks they performed reduced carbon emissions in the questionnaire. In the first user test, users were orally informed what actions to perform, but the reason that they are considered

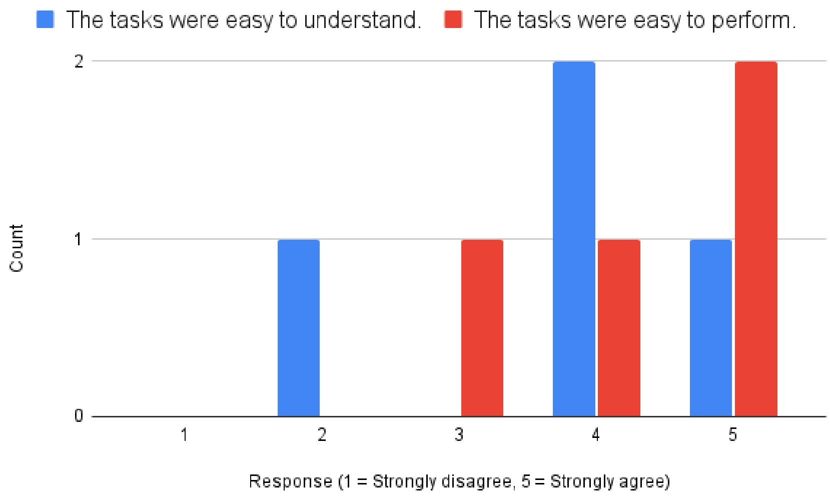

Figure 31: (Q2) Usability of tasks.

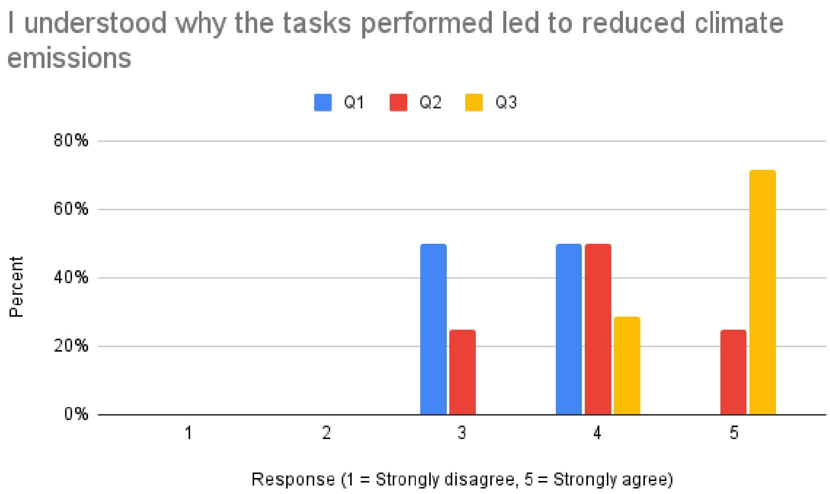

Figure 32: Environmentally friendly actions.

environmentally friendly was not communicated. The results are shown in Figure 32 (Q1 in blue), and averages to a score of 3.50.

In the second iteration, a chalkboard was added, textually presenting the available tasks (Figure 20). Additionally, the window replacement task was added, and hovering text was added above the LEDs (Figure 32). Q2 (red) in Figure 32 presents the relevant results from the questionnaire, averaging to a score of 4.00.

The final prototype made no relevant changes to the main content, but an explanation of the main content and the chalkboard was included in the introduction. Q3 (yellow) in Figure 32 presents the results, averaging to a score of 4.71.

Figure 33: (Q1) Intuitiveness of continuous locomotion.

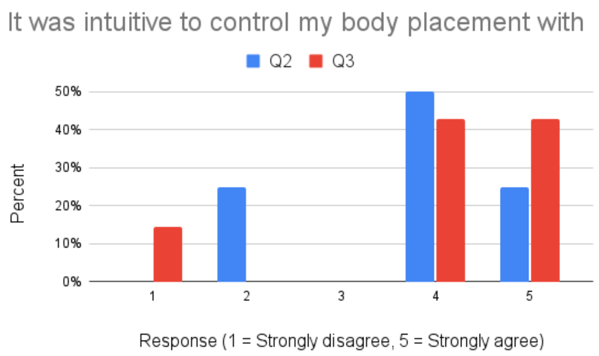

Figure 34: (Q2 & Q3) Intuitiveness of continuous locomotion.

Locomotion

The first iteration of the application used continuous movement for locomotion. Figure 33 shows how intuitive the users found the locomotion to be, averaging a score of 4.50.

The locomotion resulted in incidents of cybersickness, and so the locomotion modes was changed to teleporting movement. Figure 34 shows how intuitive teleporting locomotion was to users. The average score in Q2 was 3.75 and 4.00 in Q3.

Interactions

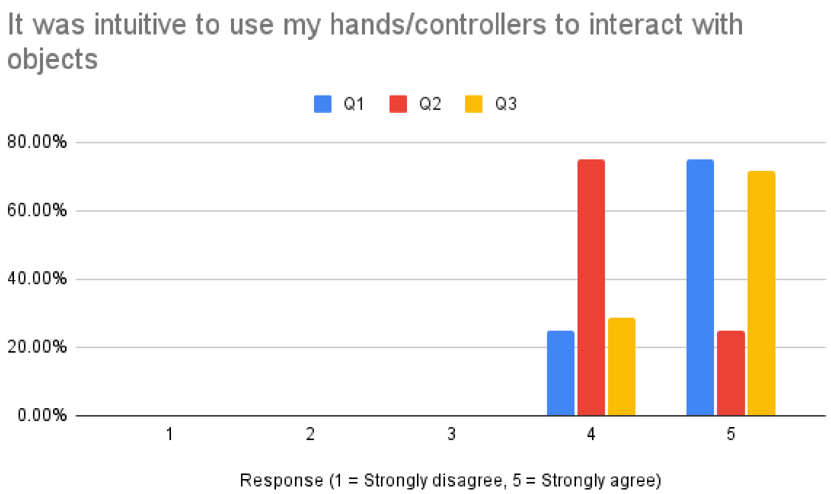

Figure 35: Usability of controllers and interactions.

The intuitiveness of the object interactions was measured in each questionnaire, presented in Figure 35. Because the score was generally high, no major changes were made between iterations. The average score was 4.57.

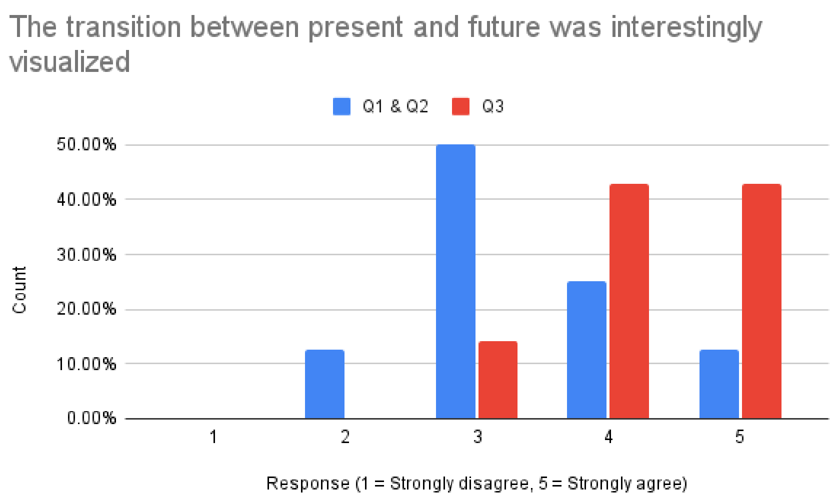

Figure 36: Visualization of time-travelling.

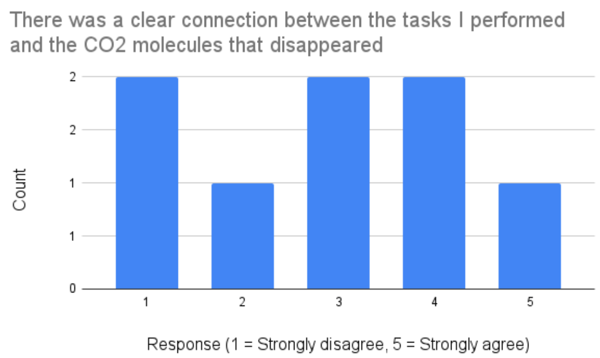

Figure 37: (Q1 & Q2) CE reduction animation.

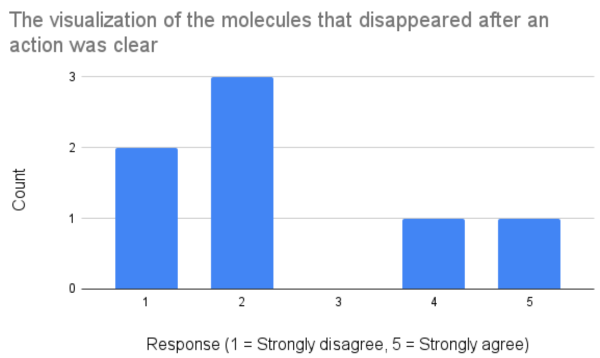

Figure 38: (Q3) CE reduction animation.

Transition

Users were asked if they found the time-travelling transition interesting in all questionnaires. Figure 36 presents the results; the average score of Q1 and Q2, before the "long exposure effect" was added, was 3.38 (blue). After the addition of the effect, the average score was 4.29 (red).

Carbon emission reduction animation

The effectiveness of the CE reduction animation was assessed in each iteration. Between the first two user tests, no meaningful changes were made to the animation, and the results from these where added together. Figure 37 shows how much user understood the first version of the CE reduction animation. The average score was 2.88.

In the third iteration, the animation was tweaked, and explained in the introduction. The results are presented in Figure 38, with an average score of 2.43. The users were also asked if they understood the connection between the sphere, the molecules and the future. The results are presented in Figure 39. Both questions had an average score of 3.57.

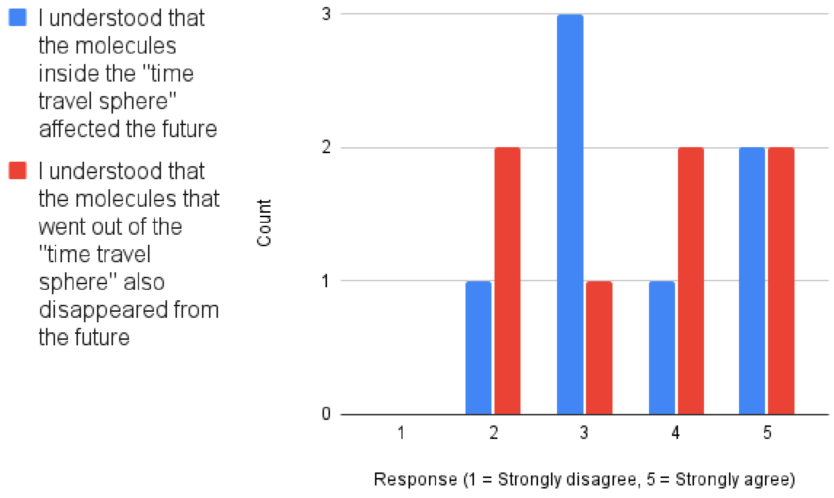

Figure 39: (Q3) Connection between CE tracker and time-travelling.

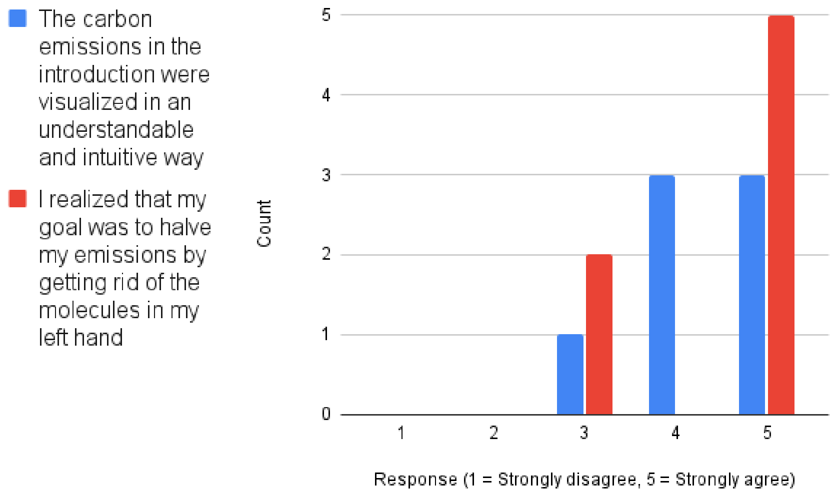

Figure 40: (Q3) Carbon footprint visualization (CFV).

Lastly, Figure 40 presents the results from Q3 asking about the effectiveness of the introduction. The first question (blue) got an average score of 4.29, and the second question (red) got an average score of 4.43.

Personalization of carbon footprints

To assess whether the introduction personalized the users' carbon footprint, the users were asked if they felt that the molecules belonged to them. The results are presented in Figure 41, and averages to 3.14.

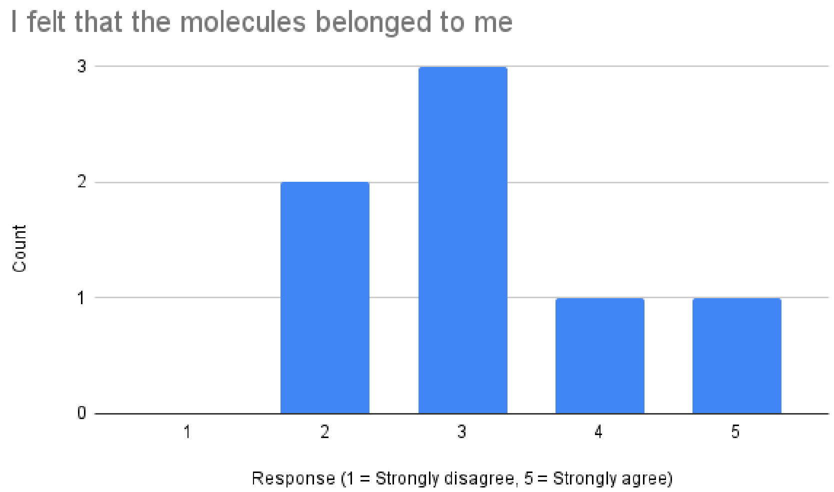

Figure 41: (Q3) Personalization of carbon emissions.

Figure 42: (Q3) Collective action visualization (CAV)

Collective Action

In the final questionnaire, two questions were asked about the effect of the collective action visualization in the introduction. The results are presented in Figure 42; The first question (blue) had an average score of 4.00, and the second question (red) Had an average score of 3.71.

Awareness and knowledge

Q3 also assessed to which degree the users were made more aware of their carbon emissions, shown in Figure 43 (red), with an average score of 3.40. The degree to which the user felt that they had learned something was assessed (blue) and got an average score of 2.71.

The users were also asked to rate the applications potential to raise awareness with some improvements made (yellow), and got an average score of 4.80.

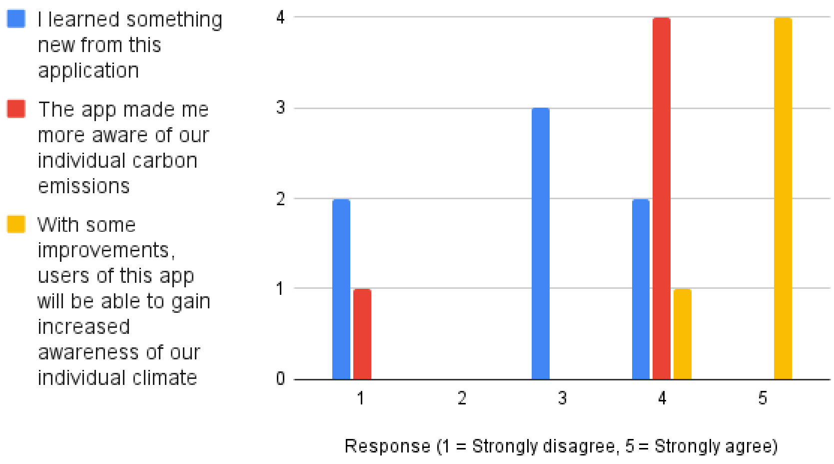

Figure 43: (Q3) Knowledge and awareness gained.

Motivation

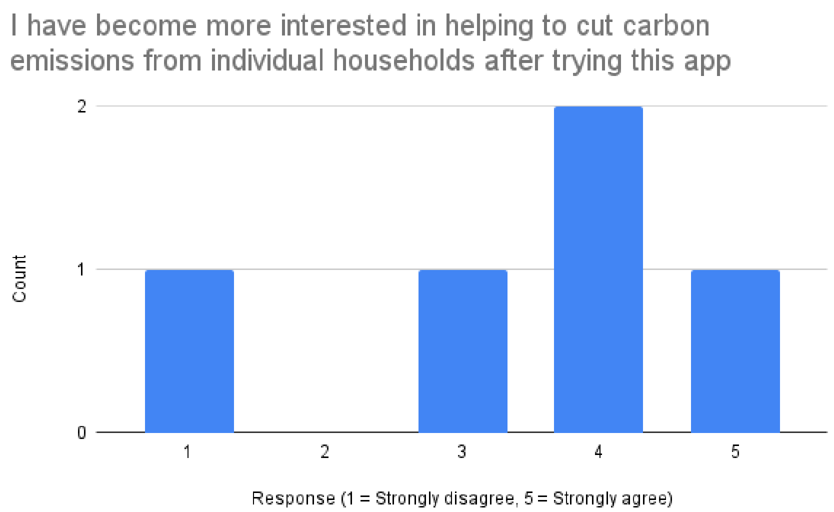

Figure 44: (Q3) Motivation for pro-social and pro-environmental behaviour.

In Q3, The user was asked if the app had made them more interested in helping reduce CE from individual households (Figure 44), and the average score was 3.4.

System usability scale

The SUS score in Q2 was 70.63, and 83.21 in Q3.

5.2 Teacher interviews

Expert interviews were conducted after the final user test. The interviews were semi-structured and conducted remotely. To protect the participants' privacy, they had to sign the consent form (Appendix D).

Two teachers from two different high schools were interviewed, providing useful qualitative data. One teacher had previously used VR in education, and the other teacher was involved in the group interview I conducted in the preparatory project. Because the interview was conducted remotely, they were unable to test the application themselves, but were shown a comprehensive video recording of the experience. The qualitative data was analyzed thematically.

Educational framework

Both teachers emphasized a wish for the app to be used in a classroom setting as part of an overall framework, with activities to be performed both before and after the students use the application. Using it as a component in such a setting will make it more impactful, and maximize reflection, behaviour change and learning outcome, they stated. For this reason, it was not considered important that the application should include all necessary detail to be used on its own, as gaps or oversimplifications would be fulfilled and explained by the teacher.

The ability to export information out of the application was considered very desirable, as this provides a point of discussion after the experience. This could be a simple PDF file with details about the actions performed, comparisons of the effectiveness of other actions or information related to the environmental impacts shown.

Increasing emotional responses

One teacher suggested that the landscape in the lobby and the introduction should be made more interesting, as it is currently quite bland. "You don't immediately get the impression that this app is environmentally related. Some sort of strong emotional response could be helpful at the start. It would be cool if the environment in the lobby was an example of what can happen if it goes too far", he said. Also, between different segments in the introduction, the environment could change, he suggested. For instance, when the user is introduced to the carbon visualization, city environments in the background could be faded in.

Energy consumption versus material consumption

The types of tasks that are presented were discussed. One teacher was sceptical that the tasks revolved around obtaining new objects to replace old ones. This could communicate that we can "buy" our way out of environmental issues, when instead we should consume less, he stated. "When you're always installing new things as a replacement for what you got, it kind of is a part of the problem, because this increases the consumption of materials", the teacher said. He proposed that a future version of the application should include more content that addresses material consumption, re-use and recycling.

Economic aspects

Involving finance in the application was considered desirable, as this is an important factor in the real life dilemmas of environmentalism. We've grown accustomed to spending money on material objects, but the application could convey the benefits of spending money on experiences over things, one teacher suggested.

Quantity of tasks

Both teachers expressed wishes for more tasks to be added. It was suggested that there should be more tasks available than necessary to achieve the actual carbon reduction goal, so that the users can find different paths to achieve the necessary reductions, and compare their choices after the experience. It was also suggested that there could be "misleading" tasks that might seem to have a meaningful impact on carbon emissions, but turns out to be ineffective. This would serve as a useful point of discussion, and a great benefit for the learning outcomes in a larger educational framework.

Practical limits in a classroom setting

There were concerns expressed about the practical implications of the length of the experience. If there are only a handful of headsets available for the students in the classroom, the experience should be shorter than its current 12-15 minute duration, in order to minimize wait time.

Carbon footprint visualization

Although both teachers considered the CFV in the introduction purposeful, they had differing opinions on its effectiveness. One teacher thought that it should personalize the user's climate footprint, but the other suspected that it didn't, and suggested that the same could be achieved in a simple video, like he had for the purpose of this interview.

It was pointed out the application lacks an explanation of how much carbon dioxide one molecule represents, and it was suggested that there could be a visualization of how far a family car would have to travel to emit a corresponding amount, or how many plane rides or kilos of meat it would correspond to.

They both thought it was a good idea to have the user's carbon footprint represented as a few molecules, but questioned the necessity of the molecules on their hand, and also thought that the CE reduction animation needed improvement.

Collective action visualization

One teacher thought that the "people" appearing in the introduction was a fun concept, but that the low number of them made it underwhelming, and was not sure if it would have the intended effect. The other teacher suggested that a similar approach could be used in the main content as well, as many environmental actions require a lot of people to execute, such as planting a forest or creating bicycle infrastructure.

The teachers considered the priority of this visualization to be low at this stage, although simple improvements, such as improving the visuals (using more human looking models, making them have different ages, genders, and skin color) could be beneficial.

Detailed information

It was suggested that the user could have the ability to point at objects to gain access to more detailed information about it, such as how it lowers emissions. There could be a bubble containing texts, or a hologram showing 3D visualization.

Overall thoughts

The overall concept was considered purposeful, and the teachers stated that application would contribute with something meaningful to environmental education in its current form. They were positive to the way that the user is able to move forward and backward in time, that it takes place in a recognizable local area and that the available tasks are tangible actions that individuals can do. Although more visualized impacts were desirable, they felt that the application made the importance of individual actions clear. The application was not deemed to be instructive.

5.3 REACT interview

A concluding interview with REACT was conducted to establish whether the prototype was satisfactory, and what the next tasks would be for future work. After testing the application, they were altogether satisfied with the prototype, and very eager for the work to be continued.

One of the main features desired was an initial storytelling component in the main content. After the introduction, when the main content is initiated, the user should be immediately be presented the future visualizations. Here, the user should be able to see the sea level increase, but also black smoke in the distance and withered vegetation nearby. These "topics" should be explored through storytelling, preferably by the user selecting one of them in some manner. The storytelling component may be audio narration like the one in the introduction. During storytelling, the reason for the state of the selected topic will be explained (the high water is because the West Antarctic ice is melting, withered vegetation is because of droughts, etc). Furthermore, the following points were discussed.

- The visualized sea level increase can be made higher as to visualize the result of the West Antarctic ice melting.

- More realistic solar panels should be implemented. There should be more than one, and they should be installed somewhere on the house that maximizes sunlight, such as the roof.
- More visualized consequences; variable vegetation should be added around the house. Trees and vegetation should become withered in the future if few carbon cuts has been made, but survive if the player archives a high carbon emission reduction.
- An insulation task should be added, and combined with the currently available window upgrade, there should be some heat loss visualization. However, if the visualization is challenging to implement, other issues should be prioritized.
- The objects should give some indication that they are able to be picked up, other than turning green when the user's hands are nearby. For instance, all intractable objects could light up until you get closer to them. Another possibility is simply adding UI markers to the objects.
- The app should remind the user to visit the future when they have performed the tasks.
- The carbon emission tracker should be changed, as it is easily forgotten when it is out of sight. The new solution should be constantly visible, or appear when a change has occurred.
- Development of the collective action visualisation should only involve updating the visual aspects in the introduction(different skin tones, genders, ages, etc) at this stage.
- Creating enough tasks to enable the user to realistically achieve the 50% carbon emission reduction should be prioritized at a later point.
- The way the tasks work is purposeful, and it is good that they are individually actionable.
- The way the future is presented was deemed satisfactory.

6 Discussion

This chapter, the results are discussed, and the limitations of the projects are reflected upon.

6.1 Comparison to related work

Table 6: Comparison to related work.

	Visualizing Climate Change	Rising Sea Levels	Stanford Ocean Acidification Experience	Greenland Melting	This application
Environmental VR application	Yes	Yes	Yes	Yes	Yes
Storytelling	No	No	Yes	Yes	Partly
Locally relevant to Trondheim	Yes	Yes	No	No	Yes
Visualizes carbon emissions	No	No	Yes	No	Yes
Time-constrained	No	Yes	Partly	Yes	No
Perform carbon reducing actions	No	Partly	No	No	Yes
Free exploration	Yes	No	No	No	Yes
Playable on standalone HMD	No	No	No	No	Yes

The two applications developed at IMTEL both are centered in Trondheim, making them locally relevant. Visualizing Climate Change in Trondheim in Trondheim (VCCT) may be considered a pure visualization of future environmental consequences, enabling freedom of exploration, but with no environmental tasks for the user to perform. Rising Sea Levels in Trondheim (RSLT) uses a high-tempo gamification approach where the rising sea level is used as a dangerous mechanism to escape, but the urgency might leave little time for reflection on the actual implication of this. The game presents environmental actions, these are not realistically grounded as they are "magically" executed by playfully shooting the targets with a gun. Neither of these two application attempts to visualize and personalize the user's carbon emissions.

The two other application, the Stanford Ocean Acidification Experience (SOAE) and Greenland Melting (GM), are centered around areas outside Norway. Although there are glaciers in Norway and a lot of shelled species in Norwegian waters, these are arguably not very relatable to Norwegians or directly relevant in their lives. The applications incorporate storytelling and convey information about future consequences of climate change, but only SOAE visualizes carbon emissions. Neither application presents actionable tasks to mitigate the effects of climate change.

All the application, with VCCT as the exception, are linear experiences. They are also time-constrained; GM automatically progresses the story, and RSLT is a race against time, while SOAE is partly time-constrained, as the experience waits for the user to execute interactions at some key points.

While all of the applications above use PC-VR, this application uses a standalone HMD for its ease of use. The application is centered in Trondheim, with freedom of movement and no time-constraints. The user's carbon emissions are visualized, as is and environmentally friendly actions are available. Although not originally planned for, the application incorporates some narrated storytelling in the introduction.

6.2 Evaluation of requirements

Table 7: Revisited requirements. Red color indicates downgraded priority.

Requirement	ID	Description
Multiple sites	R1	The app should present multiple sites in Trondheim.
Perform actions	R2	The user should be able to perform actions.
Effect of actions	R3	The user's actions will translate into changes to carbon emissions.
See result	R4	The app should visualize the consequences of the user's actions in a simulated future.
Reach goal	R5	In order to succeed, the user must achieve a 50% reduction is carbon emissions.
Single-player	R6	The app should be a self-contained single-player experience.
Choice of HMD	R7	The app should run on a standalone HMD.
Language	R8	The app should use Norwegian as chosen language.
Mapping between action and outcome	R9	Actions made will visually represent a sizable group in order to factually reflect big changes to the simulated future.
Scientifically accurate	R10	As much as possible, climate change and the effects of emission cuts must be scientifically based.
Main hub	R11	A representation of the user's house will act as the main hub, where most of the actions may be performed.
Upgrades	R12	Parts of the house and objects within can be upgraded to be more environmentally friendly.
Give feedback	R13	The app should give the user feedback on the emission cuts of their actions.
Open approach	R14	The user will be free to choose when to do different actions, travel to pre-defined sites in the city and view future simulations.

The application's greatest weakness is arguably its limited visualizations of environmental consequences in the future, and although subtle differences are implemented, R4 should generally be considered unfulfilled. R1 should be considered unfulfilled for the same reasons - although it is possible to move freely around in the city model, the intention of the requirement was to present some visualization of future consequences at the site(s), which it currently does not.

The application can be said to visualize future trajectories based on carbon emissions, but as the visualizations had their priority downgraded, this is only to a limited degree. As the user embodies a pretend version of themselves where environmental impacts are small or subtle, the empathy increase towards the user's future self or others is likely to be severely reduced. If there is little to empathize with, it likely contributes to a lesser increase in concern and awareness of climate change.

Three different interactive and environmental actions were added, and thus R2 is fulfilled. Although the actions are simplifications of their real-life counterparts, they mirror reality without being too involved. Adding realistic installation of windows, for instance, would not be purposeful as this is a very time-consuming process.

The actions require the user to move around in the virtual environment, carrying objects and installing them correctly, and should contribute to internalizing the relevant information [Weisberg and Newcombe 2017]. However, relevant information is arguably lacking; the effect of the actions (R3) were considered unclear due to sub-optimal CE reduction animation (R13) (Figure 37 and Figure 38). Furthermore, the emission reductions of the actions does not correctly reflect the actual emission cuts; R5 was prioritized over R10 after I realized that they were mutually exclusive in the scope of this project (as discussed in Section 4.3.1). This may be one reason that the learning outcome was reported to be low (Figure 43).

The application does translate the user's actions into changes to the user's carbon emissions, and feedback is given when the the actions are performed, even though the solution may be sub-optimal. For this reason, R3 and R13 should be considered fulfilled.

It is possible for the user to remove 50% of their carbon emissions, fulfilling R5, but this is at the expense of scientific realism, as the actions that reduce the user's carbon emissions don't add up to 50% cuts in reality. Thus, R10 is unfulfilled. As long as there are too few actions available to realistically achieve a 50% CE reduction, these two requirements are mutually exclusive.

The application is completely without online or multiplayer components, and thus self-contained. This means that R6 is fulfilled. It also runs on the Oculus Quest, and thus R7 is fulfilled, although the city model is somewhat resource demanding and the application runs at a slightly sub-optimal frame rate. The Oculus Quest 2, however, runs the application seamlessly.

The spoken language in the introduction and the language of texts is Norwegian, fulfilling R8. As previously discussed in Section 3.2.6, I concluded that using an international language would make the experience seem less local. I considered it important to make the experience be locally centered to the users in order to increase the relevancy of the topic, and in turn increasing their concern and awareness of climate change.

The CAV in the introduction was implemented as a direct response to R9. The questionnaire did not directly ask if the users found it informative, but it is indicated that that visualization was impactful, and people seemed to understand the intent during observations. The initial plan was simply to communicate to the user that the application scales the effect of their actions to realistically visualize future changes, but it proved to be a unique opportunity to invoke a feeling of empowerment in the user by showing that simple actions can yield large results when everyone contributes. To some degree, users found the visualization to be empowering (Figure 42).

The requirements related to the house, R11 and R12, were fulfilled. The application centers around the user's pretend home, which can be upgraded to be more environmentally friendly.

In the application, the user is able to freely choose when to travel to the future, and when to perform an action, and so, R14 is fulfilled. However, there are no sites with meaningful content other than around the house, which makes the ability to visit them superfluous. To encourage exploration, there should be more tasks to perform, more visualizations to experience, and more sites to explore. This will motivate the user and increase learning [Beheiry et al. 2019] [Markowitz et al. 2018]

6.3 Evaluation of results

Due to the low number of respondents, it is hard to draw final conclusions, but I will nonetheless present and evaluate the results for what they indicate.

In Q2, 75% of respondents agreed or strongly agreed that the tasks were easy to understand and to perform (Figure 31), and the interactions were not changed afterwards. In every questionnaire, 100% of the respondents deemed the interactions intuitive (Figure 35). The teleporting locomotion was also generally regarded user-friendly, with 75% of respondents reporting that they found the controls intuitive in Q2 and 86% in Q3. The final SUS score of the application was 83, which is considered fairly good, and suggests that the application is user-friendly. However, I also observed behaviour that indicates that the application can be improved in this area. For instance, some users tried to use one hand to teleport while holding an object in it, which is currently not possible and a detail I did not consider. It might be an unnecessary limitation if interacting this way turns out to be natural for usersIf it is not changed, it would be purposeful to teach the users how to move while holding an object in the introduction. In at least one other case, a user was observed trying to lift a large object with two hands, which is not possible in this application, and is another detail that could purposefully be added to the introduction. A few other cases were observed where users tried placing objects on top of other, pre-installed objects, even though they were perfectly visible. To address this, the old object could automatically be removed when the new object is placed on top of it, or the user could be taught this detail in the introduction.

When asked if the users understood why the tasks they performed were environmentally friendly, the percentage of respondents that agreed or strongly agreed increased from 50% in Q1 to 75% in Q2, after the chalkboard was added. This increased again to 100% in Q3, after the introduction was added with further explanations.

The time-travel transition was not considered very good in Q1 and Q2, with only 33% responses stating that it was interesting (Figure 36). After adding the "long exposure" effect, this number increased to 86% in Q3. To me, it was important to make the transition intuitive and interesting, so that the user actually feels like they are transported to and from the future. My thinking was that the future may seem more "real" if the user is shown the continuous passage of time, instead of an instant jump, with the intention of lowering the perceived temporal distance to future consequences and thereby increasing awareness and concern of climate change.

Throughout all testing sessions, there were issues related to time traveling. Many were observed to be confused regarding if they were in the future or in the present, and many generally forgot about the mechanism, especially at the start. As discussed in the interview with REACT, besides improving the mechanism, a solution could automatically be presented the future to the user at the beginning of the main content.

Furthermore, the approach to connecting the CE tracker, the CE reduction animation and time-travelling was not successful. The CE tracker and the CE reduction animation were confusing or unclear to the testers (Figure 37 and Figure 38), the teachers, and REACT, as was their connection to the future (Figure 39). As interacting with the sphere takes you to the future, the idea was to show that molecules inside the sphere influence the future. When an environmental task is performed, one or more molecules leave the sphere, which was intended to show that they no longer influence the future. This detail was mentioned in the audio script, but emphasizing it might have helped make it more clear. In my original plan, the molecules were to be "shot out" of the sphere and spread out into the environment and the atmosphere when initiating time travel. When reversing the time, the molecules would find their way back to the sphere. This additional animation might have influenced the results, but this is hard to say.

In Q3, the testers did not feel a great sense of personal connection to the molecules (Figure 41). This may be because the CFV did not make the emission sources feel personal. If the user was more involved with the emission sources and interacted with them instead of passively observing them, it might result in an increase in personal connection to the molecules. Another reason that the user did not identify with their visualized CEs might be because of the small presence they had in the main content. If the carbon emissions had a larger presence in some way, and the CE reductions were animated in a more purposeful manner, perhaps more users would feel like the molecules belonged to them.

Generally, the two main visualizations in the introduction proved purposeful. 86% felt that the CFV was intuitively visualized, but only 71% understood that the main goal was to remove the molecules connected to their arm, with the reminder choosing the neutral response (Figure 40). Examining the audio script, I realized that this may not be entirely clear, and it should be more explicitly stated to remove any doubt about it.

Assessing the effect of the CAV presented somewhat polarizing results (Figure 42). 29% strongly disagreed that the visualization made them feel that they were many working towards the same goal, while 57% strongly agreed. This was not an optimally formulated question, but observations suggested that testers were generally intrigued by the visualization. The other question related to the CAV was not formulated well either, but 71% reported that they agreed or strongly agreed that the visualization made an impression. In theory, this could mean any sort of reaction, but at the very least, it provokes some emotional response. While the questionnaire could have asked less ambiguous questions, an alternative ending to the visualization could be that the figures merge into the user, visualizing that the user embodies multiple individuals and potentially increasing a sense of unity and shared goal.

The learning outcome reported in Figure 43 was low, and the application is arguably lacking in educational content. There is little information about the effectiveness of the actions and how much CO_2 one molecule actually corresponds to. If the user had been given some comparisons of what one molecule represented and the actions had realistically reflected the amount of carbon they reduced, the learning outcome would likely improve. The limited visualized impacts are likely to be another contributor to the low learning outcome. The future visualizations are underwhelming, and present little information to the user. Despite the lacking learning outcome, users reported that the application made them more aware of individual carbon contributions (Figure 43). It was overwhelmingly reported that the application can raise awareness of individual climate change contributions, given that the application receive some improvements.

In Q3, when asked if the application made them more willing to contribute to reducing CE from individual households, 60% of respondents reported that they agreed or strongly agreed (Figure 44). This indicates that the application successfully encourages pro-social behavior to some degree.

While the observations made were useful, it would be beneficial to record the users' testing sessions. The Oculus Quest has built-in screen recording capabilities, but this could not be used as it lowered the frame-rate of the application considerably. However, the Quest is capable connecting to a PC and run PC-VR content. If the application was run in this manner, it would enable recording sessions without lowering the frame-rate.

6.4 Evaluation of research questions

Main RQ: How can VR help young people become more aware of their individual contributions to climate change?

The initial task description (Appendix A), REACT's main project document [Rogozhina 2020], and findings from the preparatory project [Jacobsen 2020] guided the definition of the main RQ. Although conclusions are hard to draw, findings suggest some key areas important for making young people more aware of their personal climate change contribution with VR.

Embodying different actors in perspective-taking situations are shown to increase empathy and pro-social behaviour. Embodying the user's future self where environmental impacts damage the user's local area is one perspective-taking approach, and should raise concern and awareness around individual contributions to climate change. Empathy-building and perspective-taking will be discussed further under RQ1. To create a purposeful perspective-taking situation to increase empathy, visualizing the carbon footprint of the user is important.

In their literature review, Freina and Ott (2015) conclude that the main motivation for using VR in education is to simulate situations that are hard or impossible to experience otherwise.

There are many reasons why different situations are infeasible or impossible to execute, one of which is physical inaccessibility. Perceiving our own carbon footprints is an example of this, as carbon dioxide molecules are invisible. "Materializing" the user's carbon footprint through visualizations is therefore a natural area where VR can meaningfully contribute, and findings from Fauville et al. (2021) suggest that comprehension of climate change at the micro and macro levels may be helped by visualizing carbon dioxide molecules in environmental education. In my application, the user is introduced to a visualization of their personal emissions in a segment in the introduction, explained in Section 4.3. Testers were visibly intrigued by the visualization during testing, and Figure 40 shows that 85% of the respondents agreed or strongly agreed that the visualization was understandable and intuitive. Results from the expert interviews also indicates that the visualization is purposeful, but one expert, after seeing a summarizing video of the application, was not convinced that the visualization necessitated immersive VR. This may be the case, as the visualization does not involve the tactile interactivity that VR arguably should utilize [Kwon 2019]. Involving gestures in the visualization could contribute to internalizing the relevant information and increase learning [Weisberg and Newcombe 2017]. In the Stanford Ocean Acidification Experience, the user does simple touching interactions to progress the story, and similar touching interactions could be included instead of passively showing the user some carbon emitting sources. The interaction could also be more involved; for instance, the user could "use" the sources, such as actively moving a miniaturized plane from point A to point B, and observing the emissions gather and contribute to their carbon footprint. Making the user actively experience or interact with some of the main sources of their emissions could make them increasingly feel that the molecules were theirs, and thus increasing awareness of their carbon footprint and contribution to emissions.

The other aspects deemed important for raising awareness of individual contributions to climate change was presenting different environmental choices and visualizing the emission cuts that follows. Results from the preparatory project suggested that actions should be tangible and realistically actionable, and the results from this project suggest that the application succeeds in this. Unfortunately, the solution for the CE reduction animation was shown to be unsatisfactory. I will discuss the environmental choices and the CE reduction animation in detail under RQ2.

Figure 43 in final questionnaire indicates that the application made the users more aware of their individual carbon emissions. Users overwhelmingly thoughts that the application could achieve more awareness with some improvements.

RQ 1: How can VR increase knowledge of climate change that is difficult to achieve through traditional means?

In the preparatory project prior to this master thesis, findings from a group interview of High School teachers identified multiple challenges related to traditional environmental education.

One of the main challenges was that the local relevancy was missing, as the students are most commonly taught the global perspective. This made it hard for their students to establish a personal connection with the subject, and of their own emissions. Another challenge was that the students felt powerless in the grand scheme of things, and that they felt their actions did not have any impact. The invisible nature of the subject was another hurdle identified, and the teachers found it impossible to teach anything other than descriptive knowledge because the subject does not lend itself to practical tasks and experiments.

VR is able to address the lack of practical experiments in the subject by providing the user practical tasks to perform and visualizing the actions' hidden emissions. The tasks should require active gesturing and movement, facilitating direct experiences which should support experiential learning [Kwon 2019]. This provides first-hand experiences contrary to the descriptive information provided in traditional environmental education settings. The actions will be further discussed in RQ2.

In the study of Fauville et al. (2021), it was suggested that visualizing different future trajectories of the environment based on carbon emissions would increase understanding of climate change, and enabling the users to explore the impacts in their local area should have increased effectiveness. This is substantiated by another environmental- and educational VR study, suggesting that the more exploration the user engages in, the higher the learning outcome should be [Markowitz et al. 2018]. Centering the main content around Gamle Bybro was deemed purposeful by teachers and REACT, as the area is well known to citizens of Trondheim, where the target audience lives. Users should also be able to view future impacts at other locations around the city. This was originally intended to be implemented in a similar manner to Warvik (2019), where the user can roam the entire city, but in the end, other tasks were prioritized. Around Gamle Bybro, some local impacts are visualized, although the future visualizations are lacking in content and can only be considered partly implemented in the application. Results from the expert interviews, and findings from the user tests indicate that the application would greatly benefit from more visualized impacts in the future. Additionally, a storytelling component in the main content was proposed by REACT, explaining the visualized impacts. Despite lacking impacts, many users enjoyed exploring the city, and were visibly intrigued to see a digital version of their local area.

To address powerlessness and lack of personal connection with climate change, Fauville et al. (2021) suggest showing the users the environmental consequences of their everyday choices, as perspective-taking may provoke empathy and increase the user's personal connection to climate change and their own emissions. Traditional perspective taking methods requires imagining different situations, which are cognitively demanding [Zaki 2014]. Because VR simulates the situations instead of relying on imagination, it is easier to provoke empathy. The application puts the user in the shoes of their future selves, doing environmentally friendly actions and observing as the visualized impacts are mitigated. Increasing empathy for the struggles and challenges that their future selves and others will have to deal with is indicated to promote pro-social or pro-environmental behavior [Ahn et al. 2013] [Hamilton-Giachritsis et al. 2018] [Herrera et al. 2018]. 60% of users reported that they were more interested in contributing to reducing emissions from individual households after trying the app (Figure 44), which indicates that the application made the users more motivated to contribute positively to society.

The application visualizes the user's carbon footprint with the intention of facilitating a personal connection to their personal carbon footprint, but when asked if they felt that the carbon emissions belong to them (Figure 41), only 29% of the respondents agreed or strongly agreed. A personal connection to their CEs may not be necessary to increase awareness of individual contributions to climate change, and emphasizing the user's personal responsibility too much may not be purposeful. Still, with more visceral visualized impacts, and the storytelling component suggested by REACT, the application might achieve a higher degree of personal connection and empowerment.

RQ 2: How can a VR application be developed that visualizes environmental actions with a high level of user-friendliness?

The VR application was developed with user-friendliness in mind. The amount of available interactions were intentionally limited, and the introduction teaches the user all the necessary controls. This proved to be a purposeful simplification, as there were no neutral or negative responses to the questions about the intuitiveness of the object interactions in any iteration (Figure 35).

The tasks themselves were also found to be user-friendly. The actions are minimalist, consisting of objects that should be grabbed, moved and placed correctly. Figure 31 indicates that users found the tasks to be both easy to understand, and easy to perform. Because a few users were found to lose objects due to bugs or inaccessible areas, there should be a mechanism to mitigate the problem. One solution is to add a countdown-timer to the objects which starts when the player has moved them (to any other place than the correct target), and re-spawns the objects at their initial position when the time is up.

The first iteration of the application used continuous movement, which all respondents found intuitive (Figure 33). However, a number of users reported nauseousness due to the way they moved, indicating cybersickness [Rebenitsch and Owen 2016]. Because this affects the overall experience negatively [Somrak et al. 2019], the mode of locomotion was changed to teleporting movement for the remainder of the project. After changing the mode of locomotion, the controls were found to be less intuitive, even after the tutorial was added (Figure 34). More importantly however, there were no cases of cybersickness observed, but testing this using the Simulator Sickness Questionnaire would be advantageous.

The final prototype ended with SUS score of 83, which indicates that the application has a high level of usability.

Results from the preparatory project indicated that environmental choices should be grounded in reality and be actionable and understandable if the users were to learn about environmental actions. For instance, if some large tasks realistically involves many people, this should be factually represented so that the magnitude of the tasks are not understated. For this reason, this application presented actions that are actionable by individuals, such as replacing energy-inefficient windows at home. The tasks were confirmed by experts and REACT to be purposeful. The presented actions are tangible and understandable, as shown in Figure 32, where testers of the final prototype (yellow) reported to understand why the tasks presented were environmentally friendly. For the best results, there should be enough actions that users can take different paths to achieve the goal.

Currently, the tasks are of a permanent nature, and revolves around making houses more environmentally friendly. These are not actions performed on a day-to-day basis, and one teacher suggested that there should be actions that address material consumption, which is more relevant in day-to-day life. Project Drawdown provides no such solutions, so the effectiveness of the actions would have to be obtained elsewhere. Furthermore, both teachers suggested adding enough tasks to enable multiple paths to success, and that economic factors should be incorporated, as environmental actions are often tied together with economy. Lastly, it was suggested that the user should be able to access additional information about the actions in some way.
To learn about environmental choices, the emission reductions of said choices should be visualized. My solution was to track their emissions visually and use an animation for when their CEs were reduced by performing an environmental action. Although the intent of the solution was to make the tracker 3D and utilize immersive interactions, the solution proved sub-optimal. Figure 37 shows that the first version of the CE reduction animation was unclear, and Figure 38 reveals that the new version was not an improvement, despite explicitly explaining the animation in the introduction. Although the expert interviews concluded that visualizing the user's carbon footprint as a few molecules was purposeful, they also thought that the current solution was unsatisfactory, as did REACT in their interview. An easy solution is to present the user's CEs as a textual counter on the surface of some object object, similar to the solution in Rising Sea Levels (Figure 6 and Figure 7), or to create a more traditional UI interface that follows the user's field of view.

Findings from the preparatory project and this project strongly indicate that the actions preformed should affect the visualized future in order to better understand environmental choices. The solution described in Section 3.3 was deemed purposeful by experts and REACT themselves, but because changes in circumstances related to the availability of the animator/3D-modeller and the prioritization of other tasks, the visualized future is lacking in environmental impacts. Participants in the user test, the interviewed teachers, and REACT themselves all called for more visualized impacts. The results suggest that the user should be able to experience multiple impacts, such as droughts, extreme weather, rising sea levels, floods and/or landslides.

On a related note, Figure 39 shows that the connection between the molecules in the carbon tracker and the time-traveling mechanism was unclear. The intention was to communicate that the molecules inside the sphere affected the future, and stopped affecting the future when they were removed from the sphere. This connection was lost to most users. It could be helpful if the audio manuscript in the introduction explained that the molecules inside the sphere will affect the future, and that they stop affecting the future when they leave the sphere, but the mechanism could be disconnected from the carbon tracker entirely, and initiating time-travelling in another manner, such as pressing a button.

6.5 Limitations

There were multiple limitations that affected this project. Well-visualized environmental impacts are needed to learn about local consequences and provoke emotional responses so that the user can learn, build empathy for their future selves and become more aware of individual CE contributions. Downgrading the priority of the requirements was necessary, but this naturally resulted in uninteresting visualizations, affecting the results.

The ongoing COVID-19 pandemic was a limiting factor. It made the user tests harder to conduct, and my visit to a local High School for final user testing was canceled because of local outbreaks. Although it was possible to use the workstations at the lab, activity at the lab seemed to have decreased during the pandemic, and for the most part, I also chose to work from home. I've found that a common work-space environment where casual conversations and interactions with other students can occur naturally is very helpful to my work process. We might exchange tips and help each other out, and this was something valuable that disappeared from my day-to-day work.

The number of respondents to the questionnaires, especially to the first two, was very low. For Q1, this was due to the fact that I had written the questionnaire in Norwegian while the testers were international students. This was not the case in Q2, but it still received few responses. The third user test was conducted differently to the first two, where 1-2 users were tested simultaneously instead of 3-5, and I prepared PCs to be used to answer the questionnaire instead making the users use their smartphones. Had I done the first two user tests similar to the third one, I might have received more responses.

Some questions in the questionnaires were substandard, and variations across iterations made it hard to compare results. Because of this, only results with well-formulated questions were presented in Section 5. Some useful questions were also omitted, such as how the user liked the VR controls, previous VR experience, feeling of presence, whether they make environmental choices in their life, etc.

7 Conclusion

This section summarizes the thesis and the contributions, and presents recommendations for future work.

7.1 Contributions

The main contribution of this project is a new VR application to raise awareness about individual contributions to climate change. Results indicate that VR can be used to achieve this by visualizing the user's baseline carbon footprint, presenting environmental choices, visualizing their emission reductions and experiencing environmental impacts based on personal emissions. Although the related applications also visualize future impacts of climate change, presenting individually executable environmental actions is a feature unique to the application. By embodying a version of their future selves and empathizing with the future situation they will find themselves in, the users can be expected to increase pro-environmental behaviour. Despite limitations related to visualized consequences, users reported an increased willingness to contribute to mitigating individual household contributions to climate change after trying the application.

7.2 Summary

Climate change is a challenging issue, and extensive changes to society are required to mitigate the consequences. Individual household consumption is a substantial contributor to climate change, and raising awareness of this issue is important for meaningful changes to happen. Using VR to address this issue can be useful. I believed that increased awareness of individual contributions to climate change could be attained by presenting the user with tangible environmental actions that individuals can perform, translating these actions to visualized reductions of carbon emissions, and visualizing future consequences locally based on the user's carbon emissions. Despite limited visualized consequences, the results indicate that the application may increase users' awareness of the subject and motivate them towards pro-social behaviour, but conclusions are hard to draw and more work is required. Still, the responses were optimistic towards the project, and it was indicated that VR is a purposeful technology to be applied to the problem.

7.3 Future work

The CE tracker and the CE reduction animation were found to be unsatisfactory, and should be reworked. A simple solution could involve a textural CE counter statically connected to the user's field of view, or placed on some object, with a simple particle effect indicating changes to emissions instead of a CE reduction animation. Utilizing the immersive, interactive and the 3D nature of VR is preferable whenever possible, but a bland and working solution is better than an interesting but confusing solution. Related to the CE tracker and CE reduction animation, the mechanism for initiating time traveling should also be revisited, and the user should be reminded that they can visit the future to see their progress. The environmental impacts in the visualized future should be improved. The rising sea levels can benefit from improved visuals and an underwater effect, and according to REACT, an increased height. The visualized future should also benefit from additional impacts, such as droughts indicated by withering vegetation. If possible, the user should be able to visit other local sites affected by the impacts. Some of the visualized impact should be explained, and potentially visualized, in a storytelling component in an initial visit to the visualized future.

Improvements to the solar panel task is needed. There should be multiple solar panels, and they should preferably be placed on the roof. In this case, it will be necessary to find a way for the user to access the roof. Also, a new task should be implemented, where the user upgrades the insulation of the house. This should have a considerable effect on CE reductions (See Table 2 in Section 3.1.3). According to REACT, these are the two most important things to do related to the in-app tasks. If feasible to implement, the insulation task and the window task could also be paired with visualizations of heat loss in the house.

There are also improvements that can be made regarding usability. The ability to simultaneously hold an object and teleport with the same controller should be considered. Currently, the other controller must currently be used for movement when one controller holds an object. Grabbing large objects (such as windows) with two hands may also be considered implemented. These were both interactions that were attempted by users in the final test. If not implemented, it might be purposeful add something to the introduction to teach the user how to move and hold an object simultaneously, and that large objects can be grabbed with one hand. In the same vein, the introduction should include a segment that teaches the user to remove an object from the socket before adding another object, as quite a few users thought that the original object would automatically be removed.

Another usability improvement would be to give an indication that objects are interactable, other than turning green when the user's hands are close. One solution would be to temporary highlight all objects the first time you see them, or permanently adding simple UI markers to them similar to the text currently used.

Classroom usage will greatly benefit from the ability to export information out of the application for discussion purposes. This can be as simple as a PDF summarizing the environmental actions performed and some related data, but the more relevant information that is included, the better.

Both the CFV and the CAV in the introduction can be improved. The figures used in the CAV can be made more human-looking and diverse, and perhaps "merge" with the user at the end, and the CFV could involve interactive components to let the user get a stronger sense that the visualized emissions belong to them personally.

The application will benefit from having more tasks generally, but tasks related to material consumption would be an especially useful addition, as the current ones are all energy-related. Although likely very resource-demanding, the optimal situation would be having enough tasks available to exceed the CE reduction goal in the application, so that users can explore different paths. Incorporating economics into the actions is also likely to be advantageous, as this is often an important influencing factor.

The visual environment in the scene selector and the introduction can be upgraded and used to better reflect the nature of the subject. For instance, instead of placing the user outside Nidarosdomen (Figure 26), scene selection could be used to provoke an emotional response at an early stage by taking place in a climate change affected environment, such as a farm abandoned after droughts or a house submerged in the sea.

Bibliography

S. J. G. Ahn, A. Le, and J. Bailenson. The Effect of Embodied Experiences on Self-Other Merging, Attitude, and Helping Behavior. *Media Psychology*, 16(1):7–38, 2013. doi: 10.1080/15213269.2012.755877.

S. J. G. Ahn, J. Bostick, E. Ogle, K. L. Nowak, K. T. McGillicuddy, and J. N. Bailenson. Experiencing Nature: Embodying Animals in Immersive Virtual Environments Increases Inclusion of Nature in Self and Involvement with Nature. *Journal of Computer-Mediated Communication*, 21(6):399–419, 2016. doi: 10.1111/jcc4.12173.

S. N. Barak, B. F Fimreite, F. Hagen, T. T. E. Høgelid, A. M. Karlsson, M. E. Nylund, and Å. Staldvik. Rising Sea Levels in Trondheim. Bachelor's thesis, Norwegian University of Science and Technology, 2019.

M. E. Beheiry, S. Doutreligne, C. Caporal, C. Ostertag, M. Dahan, and J. B. Masson. Virtual Reality: Beyond Visualization. *Journal of Molecular Biology*, 431(7):1315–1321, 2019. doi: 10.1016/j.jmb.2019.01.033.

H. Creagh. Cave Automatic Virtual Environment. In *Proceedings: Electrical Insulation Conference and Electrical Manufacturing and Coil Winding Technology Conference (Cat. No.03CH37480)*, pages 499–504, 2003. doi: 10.1109/EICEMC.2003.1247937.

C. Donalek, G. Djorgovski, S. Davidoff, A. Cioc, A. Wang, G. Longo, J. Norris, J. Zhang, E. Lawler, S. Yeh, A. Mahabal, M. Graham, and A. Drake. Immersive and Collaborative Data Visualization Using Virtual Reality Platforms. In *2014 IEEE International Conference on Big Data (Big Data)*, pages 609–614, 2014. doi: 10.1109/BigData.2014.7004282.

Drawdown. Solutions. URL https://drawdown.org/solutions. (Accessed: 05.08.2021).

G. Dubois, B. Sovacool, C. Aall, M. Nilsson, C. Barbier, A. Herrmann, S. Bruyère, C. Andersson, B. Skold, F. Nadaud, F. Dorner, K. R. Moberg, J. Ceron, H. Fischer, D. Amelung, M. Baltruszewicz, J. Fischer, F. Benevise, V. R. Louis, and R. Sauerborn. It starts at home? Climate policies targeting household consumption and behavioral decisions are key to low-carbon futures. *Energy Research & Social Science*, 52:144–158, 2019. doi: 10.1016/j.erss.2019.02.001.

G. Fauville, A. C. M. Queiroz, L. Hambrick, B. A. Brown, and J. N. Bailenson. Participatory research on using virtual reality to teach ocean acidification: a study in the marine education community. *Environmental Education Research*, 27(2):254–278, 2021. doi: 10.1080/13504622.2020.1803797.

J. B. Ferrell, J. P. Campbell, D. R. McCarthy, K. T. McKay, M. Hensinger, R. Srinivasan, X. Zhao, A. Wurthmann, J. Li, and S. T. Schneebeli. Chemical Exploration with Virtual

Reality in Organic Teaching Laboratories. *Journal of Chemical Education*, 96(9):1961–1966, 2019. doi: 10.1021/acs.jchemed.9b00036.

L. Freina and M. Ott. A Literature Review on Immersive Virtual Reality in Education: State Of The Art and Perspectives. In *Proceedings of eLearning and Software for Education (eLSE)*, 2015.

C. Hamilton-Giachritsis, D. Banakou, M. G. Quiroga, C. Giachritsis, and M. Slater. Reducing risk and improving maternal perspective-taking and empathy using virtual embodiment. *Scientific Reports*, 8, 2018. doi: 10.1038/s41598-018-21036-2.

F. Herrera, J. Bailenson, E. Werisz, E. Olge, and J. Zaki. Building long-term empathy: A large-scale comparison of traditional and virtual reality perspective-taking. *PloS One*, 13(10), 2018. doi: 10.1371/journal.pone.0204494.

A. Herrmann, H. Fischer, D. Amelung, D. Litvine, C. Aall, C. Andersson, M. Baltruszewicz, C. Barbier, S. Bruyère, F. Bénévise, G. Dubois, V. R. Louis, M. Nilsson, K. R. Moberg, B. Sköld, and R. Sauerborn. Household preferences for reducing greenhouse gas emissions in four European high-income countries: Does health information matter? A mixed-methods study protocol. *BMC Public Health*, 18(71), 2017. doi: 10.1186/s12889-017-4604-1.

E. G. Hertwich and G. P. Peters. Carbon Footprint of Nations: A Global, Trade-Linked Analysis. *Environmental Science & Technology*, 43(16):6414–6420, 2009. doi: 10.1021/es803496a.

B. R. Jacobsen. Raising Awareness of Individual Contributions to Climate Change with Virtual Reality. Specialization project, Norwegian University of Science and Technology, 2020.

K. Kilteni, R. Groten, and M. Slater. The Sense of Embodiment in Virtual Reality. *Presence: Teleoperators and Virtual Environments*, 21(4):373–387, 2012. doi: 10.1162/PRES_a_00124.

Trondheim Kommune. Bymodell Trondheim. URL http://kart.trondheim.kommune.no/3d_bymodell/. (Accessed: 03.01.2021).

C. Kwon. Verification of the possibility and effectiveness of experiential learning using HMD-based immersive VR technologies. *Virtual Reality*, 23(1):101–118, 2019. doi: 10.1007/s10055-018-0364-1.

I. Lorenzoni and M. Hulme. Believing is seeing: laypeople's views of future socio-economic and climate change in England and in Italy. *Public Understanding of Science*, 18(4):383–400, 2009. doi: 10.1177/0963662508089540.

P. Lujala, H. Lein, and J. K. Rød. Climate change, natural hazards, and risk perception: the role of proximity and personal experience. *Local Environment*, 20(4):489–509, 2015. doi: 10.1080/13549839.2014.887666.

M.E. Mann. Greenhouse gas, 2019. URL https://www.britannica.com/science/greenhouse-gas. (Accessed: 04.08.2021).

D. M. Markowitz, R. Laha, B. P. Perone, R. D. Pea, and J. N. Bailenson. Immersive Virtual Reality Field Trips Facilitate Learning About Climate Change. *Frontiers in Psychology*, 9:2364, 2018. doi: 10.3389/fpsyg.2018.02364.

K. R. Moberg, C. Aall, F. Dorner, E. Reimerson, J. Ceron, B. Sköld, B. K. Sovacool, and V. Piana. Mobility, food and housing: responsibility, individual consumption and demand-side policies in European deep decarbonisation pathways. *Energy Efficiency*, 12:497–519, 2019. doi: 10.1007/s12053-018-9708-7.

NOAA. Carbon dioxide, 2021a. URL https://climate.nasa.gov/vital-signs/carbon-dioxide/. (Accessed: 04.08.2021).

NOAA. Climate change: Global temperature, 2021b. URL https://www.climate.gov/news-features/understanding-climate/climate-change-global-temperature. (Accessed: 04.08.2021).

B.J. Oates. *Researching Information Systems and Computing*. SAGE Publications, 2005. ISBN 9781446235447.

L. Rebenitsch and C. Owen. Review on cybersickness in applications and visual displays. *Virtual Reality*, 20:101–125, 2016. doi: 10.1007/s10055-016-0285-9.

I. Rogozhina. React website, 2019. URL www.react-project.com. Accessed 16.06.21.

I. Rogozhina. React proposal, 2020.

D. Saredakis, A. Szpak, B. Birckhead, H. A. D. Keage, A. Rizzo, and T. Loetscher. Factors Associated With Virtual Reality Sickness in Head-Mounted Displays: A Systematic Review and Meta-Analysis. *Frontiers in Human Neuroscience*, 14:96, 2020. doi: 10.3389/fnhum.2020.00096.

M. Slater and S. Wilbur. A framework for immersive virtual environments (five): Speculations on the role of presence in virtual environments. *Presence: Teleoperators & Virtual Environments*, 6:603–616, 1997.

M. Slater, B. Spanlang, and D. Corominas. Simulating Virtual Environments within Virtual Environments as the Basis for a Psychophysics of Presence. *ACM Transactions on Graphics*, 29(4), 2010. doi: 10.1145/1778765.1778829.

S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. Avery, M. M. B Tignor, and H. L. Miller. *Climate Change 2007: The Physical Science Basis. Working Group I Contribution to the Fourth Assessment Report of the IPCC*, volume 1. 2007.

A. Somrak, I. Humar, M. S. Hossain, M. F. Alhamid, and J. Hossain, M. A. Guna. Estimating VR Sickness and user experience using different HMD technologies: An evaluation study. *Future Generation Computer Systems*, 94:302–316, 2019. doi: 10.1016/j.future.2018.11.041.

A. Spence, W. Poortinga, and N. Pidgeon. The Psychological Distance of Climate Change. *Risk Analysis*, 32(6):957–972, 2012. doi: 10.1111/j.1539-6924.2011.01695.x.

P. E. Stoknes. Rethinking climate communications and the "psychological climate paradox". *Energy Research & Social Science*, 1:161–170, 2014. doi: doi.org/10.1016/j.erss.2014.03.007.

J. L. R. Tamayo, M. B. Hernández, and H. G. Gómez. Digital Data Visualization with Interactive and Virtual Reality Tools. Review of Current State of the Art and Proposal of a Model. *Journal ICONO 14*, 16(2):40–65, 2018. doi: 10.7195/ri14.v16i2.1174.

M. W. Warvik. Visualizing climate change in Virtual Reality to provoke behavior change. Master's thesis, Norwegian University of Science and Technology, 2019.

S. Weisberg and N. Newcombe. Embodied cognition and STEM learning: overview of a topical collection in CR:PI. *Cognitive Research: Principles and Implications*, 2, 2017. doi: 10.1186/s41235-017-0071-6.

J. Zaki. Empathy: a motivated account. *Psychological bulletin*, 140(6):1608–1647, 2014.

Appendix

A Excerpt from REACT document

Task 3.5: Interactive scenarios using VR technology (Prasolova-Førland, Rød)

The results for student and public responses to the materials from Tasks 3.3 and 4.2 will guide the selection of scenarios for future climate change impacts. The selected scenarios will be implemented as 3D experiences using VR and 360° videos with interactive elements and information about each visualized impact. The interactive VR tool will allow test users to move from one VR experience to another through an interactive choice of individual actions or a waiting time signifying inaction and will aim at provoking empathy and emotional response. While choosing inaction, a test user will follow the worst-case scenario and will be exposed to an increasingly worsening reality. In contrast, each significant individual action will be translated into a carbon footprint reduction, financial gain and health benefits10 and will put the user on track of an intermediate scenario with less pronounced climate change impacts. The effects of individual actions will be treated as representative of collective actions across high-income countries in order to demonstrate the final goal of this project. If the user succeeds to reach a 45%-carbon footprint reduction, he/she will be transferred to the future city (the Venus project).

B Audio manuscript

Hei! Gjennom denne introduksjonen vil lære deg å navigere, og du vil bli forklart noen konsepter. Til høyre for deg er det en knapp. Når den lyser grønt, kan du berøre den med hånda for å gå videre. Prøv dette nå.

Bra! Forran deg står det en boks. Prøv å løfte den ved å ta hånda di bort og klemme med pekefingeren el ler langfingeren.

Her har du en liknende boks, men den har en tilhørende sokkel. Plassér den i sokkelen sin.

På venstrehånda di har du fått ei kule. Ved å dra og slippe i denne, reiser du i tid. Gjør dette nå for å gå inn i fremtiden.

Nå er du på vei inn i fremtiden. Overgangen varer noen sekunder.

I fremtiden vil du kunne se konsekvenser av handlingene dine. Objekter er derimot fryst fast, og du må tilbake til nåtiden for å interagere med dem. Dra og slipp kula igjen for å dra tilbake.

Mange av aktivitetene vi mennesker gjør, resulterer i karbonutslipp. Når karbonutslippene fra tjenester og varer tilskrives sluttbrukeren, står individuelle husholdninger for 72% av de globale utslippene. Forran deg ser du noen av de mest kjente utslippskildene, men det er mange flere.

De 30 svarte molekylene du ser her, representerer de fremtidige karbonutslippene dine fram til 2050. Disse molekylene slippes ut i atmosfæren, og medfører klimaendringer. For å forhindre de verste konsekvensene av disse endringene, må vi halvere vårt eget utslipp de neste årene.

Her ser du utslippene dine delt i to. Den høyre halvdelen trenger vi ikke ta hensyn til; du kan tenke at de er de vanskeligste molekylene å kvitte seg med.

Den andre halvparten kan du derimot gjøre noe med, og disse 15 molekylene er avgjørende for hvordan fremtiden vil være. Jo flere du klarer å bli kvitt, jo bedre blir det. Molekylene vil bli med deg rundt, festet på venstrehånda di.

Se på hendene dine. Når du gjør en handling som kutter ned på utslippene dine, vil molekyler fjernes fra framtiden, og disse klimakuttene samles på din høyre hånd for oversikts skyld. Om du vil, kan du løfte disse vekk. Når du slipper dem, vil de sprekke og forsvinne.

Det nytter selvfølgelig ikke at du er alene om å kutte utslipp dine. Se til siden. Når du gjør noe i denne appen, representerer det hele jordens befolkning. På denne måten kan vi visualisere endringene i fremtiden.

Sett boksen i sokkelen, så vil du se at alle andre vil gjøre det samme.

Når du starter opp, vil du bli plassert i ditt hjem. Huset ditt er plassert ved Gamle Bybro. Her kan du gjøre noen enkle miljøvennelige oppgraderinger, og underveis kan du besøke fremtiden for å se hvordan karbonkuttene påvirker nærmiljøet.

Utenfor huset ditt står det ei krittavle. Gå til tavla og les for å se oppgavene du kan gjøre for å kutte på karbonutslippene dine.

Helt til slutt må du lære å forflytte deg. Dette skjer ved teleportering. Se på hendene dine, her har kontrollerne blitt synlige. Dytt joysticken fram og sikt med hånda for å teleportere. Du kan avslutte en økt og gå tilbake til lobbyen ved å trykke inn begge joystickene samtidig. Når er klar kan du gjøre dette, og gå videre til hovedinnholdet.

C Questionnaires

C.1 First questionnaire

1. Hvordan stiller du deg til følgende utsagn?

   (a) Plasseringen av huset var hensiktsmessig mtp. å føle høyden på det potensielle havnivået

   (b) Det var en klar sammenheng mellom handlingene jeg gjorde og CO2-molekylene som forsvant

   (c) Jeg forstod hvorfor de utførte oppgavene medførte reduserte klimautslipp

   (d) Det var intuitivt å bruke hendene/kontrollerne til å løse oppgavene

   (e) Det var intuitivt å styre plasseringen min med joystick'ene(styrespakene til tomlene)

   (f) Overgangen fra nåtid til fremtid var visualisert på en livlig og intuitiv måte

   (g) Å koble CO2-molekylene fysisk til ens kropp kan øke tilhørlighet til dem (personliggjøre eget klimaavtrykk)

   (h) Jeg hadde lyst å få vekk CO2-molekylene fra kroppen min

2. Har du noen forslag til forbedring?

3. Var det noe spesielt du likte med app'en?
4. Var det noe du mislikte med app'en?

C.2 Second questionnaire

1. On a scale from 1 to 5, how would you rate the following statements?
   (a) I was given adequate verbal instructions to start using the app.
   (b) The app would benefit from a short tutorial if no verbal instructions were given.
   (c) It was intuitive to use my hands/controllers to interact with objects.
   (d) It was intuitive to control my body placement with the joysticks (thumbsticks)
   (e) The transition between present and future was interestingly visualized.
   (f) The mechanism for initiating the time-travelling transition was interesting.
   (g) I noticed differences in the future depending on the amount of removed carbon(performed tasks).
   (h) The tasks were easy to understand.
   (i) The tasks were easy to perform.
   (j) I noticed CO2 molecules disappearing as I performed tasks.
   (k) There was a clear connection between the tasks I performed and the CO2 molecules that disappeared.
   (l) I understood why the tasks performed led to reduced climate emissions.
   (m) I wanted to get rid of the CO2 molecules.
   (n) The use of Virtual Reality makes the tasks more fun and intuitive to perform.
   (o) The experience made me more aware on the environmental consequences of people's individual actions.
   (p) The experience provided me with new perspectives or insights into climate change.
   (q) Learning about environmental consequences of individual actions through experiences in Virtual Reality has significant advantages over other traditional media(documentary, article, phone app, PC game, etc).
2. Do you have any suggestions for improvement?
3. Was there anything special you liked about the app?
4. Was there anything you disliked about the app?

C.3 Final questionnaire

På en skala fra 1 (sterkt uenig) til 5 (sterkt enig), hvordan vil du svare på disse utsagnene?

1. Det var intuitivt å bruke virtuelle hender til å løse oppgavene
2. Det var intuitivt å teleportere meg rundt med joystickene(styrespakene til tomlene)
3. Det gjorde inntrykk på meg da jeg var med alle de andre "menneskene" i introduksjonen
4. Jeg hadde en følelse av at vi var mange om samme mål
5. Karbonutslippene i introduksjonen var visualisert på en forståelig og intuitiv måte
6. Jeg skjønte at målet mitt var å halvere utslippene mine ved å kvitte meg med molekylene i venstre hånd
7. Jeg følte at molekylene tilhørte meg
8. Visualiseringen av molekylene som forsvant (fra venstrehånda) etter en handling var tydelig
9. Jeg forstod at molekylene som var inni "tidsreise-kula", påvirket fremtiden
10. Jeg forstod at molekylene som gikk ut av "tidsreise-kula", også forsvant fra fremtiden
11. Jeg forstod hvorfor de utførte oppgavene reduserte klimautslipp
12. Overgangen fra nåtid til fremtid var visualisert på en livlig og intuitiv måte
13. Jeg lærte noe nytt av denne appen
14. Jeg har fått et litt anderledes perspektiv på egne utslipp
15. Appen gjorde meg mer bevisst over de individuelle karbonutslippene våre
16. Jeg har blitt mer åpen for å kutte egne klimautslipp etter å ha prøvd denne appen
17. Jeg har fått mer lyst til å bidra til at karbonutslipp fra individuelle husholdninger kuttes etter å ha prøvd denne appen
18. Med noen forbedringer vil brukere av denne appen kunne oppnå økt bevissthet over de individuelle klimautslippene våre

C.4 System Usability Scale

On a scale from 1 to 5, how would you rate the following statements?

- I think that I would like to use this system frequently.
- I found the system unnecessarily complex.
- I thought the system was easy to use.
- I think that I would need the support of a technical person to be able to use this system.
- I found the various functions in this system were well integrated.
- I thought there was too much inconsistency in this system.
- I would imagine that most people would learn to use this system very quickly.
- I found the system very cumbersome to use.
- I felt very confident using the system.
- I needed to learn a lot of things before I could get going with this system.

D Consent Form

Taking part in the research project

” Immersive Technologies for Learning and Training ”

This is an inquiry about participation in a research project where the main purpose is to to explore the potentials and limitations of Immersive Technologies (virtual/mixed/augmented reality, VR/MR/AR) for learning and training in different areas, as a part of master student projects at Innovative Technologies for Learning (IMTEL) VR lab. To conduct this research, we will need to investigate the development and use of immersive technologies for learning and training in various contexts, including learning of language and mathematics, virtual field trips, remote learning in COVID-19 context, visualization of climate change, immersive visualization of lab experiments, workplace training, visualization of medical procedures and anatomy and other projects. In this form we will give you information about the purpose of the project and what your participation will involve.

Purpose of the project
To conduct this research, we will need to analyze the use immersive technologies for learning and training in various contexts, including learning of language and mathematics, virtual field trips, remote learning in COVID-19 context, visualization of climate change, immersive visualization of lab experiments, workplace training, visualization of medical procedures and anatomy and other projects. The goal is to develop innovative learning methods and tools using immersive technologies.

Who is responsible for the research project?
NTNU, Department of Education and Lifelong learning is the institution responsible for the project.

Why are you being asked to participate?
You are asked to participate because you are a potential user of educational applications developed as a part of this project and have visited our lab/expressed interest in immersive technologies. Your feedback is important for develop innovative learning methods and tools.

What does participation involve for you?
You will be ask to test immersive applications for learning and training purposes and then give feedbacks in the form of questionnaires and interviews/group interviews.

Participation is voluntary
Participation in the project is voluntary. If you chose to participate, you can withdraw your consent at any time without giving a reason. All information about you will then be made anonymous. There will be no negative consequences for you if you chose not to participate or later decide to withdraw.

Your personal privacy – how we will store and use your personal data
We will only use your personal data for the purpose(s) specified in this information letter. We will process your personal data confidentially and in accordance with data protection legislation (the General Data Protection Regulation and Personal Data Act). Any data that can be traced to individual participants will be kept confidential and anonymized before being used for research purposes. Parts of the sound recordings will be transcribed (written down) and stored electronically. All source data will be handled and stored in accordance with the existing regulations by NTNU as the responsible institution and only persons associated with the project (IMTEL VR lab research personnel and master students) will have access to them.

What will happen to your personal data at the end of the research project?
The project is scheduled to end 31.12.2021. All data will be anonymized at the end of the project, e.g. audio and video will be deleted when transcripts and analysis of data are completed, except for selected video and photo material to be used for research purpose. These and anonymized recordings from the inside of the virtual environments may be used for demonstrations in research context in such a way that no information will be linked to individuals. Scientific reports and presentations from this study might contain recordings from the VR/MR/AR sessions, questionnaire results, anonymized photos/videos from the sessions and anonymized citations from the interviews.

Your rights
So long as you can be identified in the collected data, you have the right to:
- access the personal data that is being processed about you
- request that your personal data is deleted
- request that incorrect personal data about you is corrected/rectified
- receive a copy of your personal data (data portability), and
- send a complaint to the Data Protection Officer or The Norwegian Data Protection Authority regarding the processing of your personal data

What gives us the right to process your personal data?
We will process your personal data based on your consent.

Based on an agreement with NTNU, NSD – The Norwegian Centre for Research Data AS has assessed that the processing of personal data in this project is in accordance with data protection legislation.

Where can I find out more?
If you have questions about the project, or want to exercise your rights, contact:
- Ekaterina Prasolova-Førland (Department of Education and Lifelong Learning, NTNU)
- phone: +47 99 44 08 61, email: ekaterip@ntnu.no
- NSD – The Norwegian Centre for Research Data AS, by email: (personverntjenester@nsd.no) or by telephone: +47 55 58 21 17.

Consent form

I have received and understood information about the project **Immersive Technologies for Learning and Training** and have been given the opportunity to ask questions. I hereby declare my consent that my data in relation to Immersive Technologies for Learning and Training may be stored, documented and used for research and educational purposes as described above. I give consent for my personal data to be processed until the end date of the project, approx. 31.12.2021

(Signed by participant, date)

NTNU

Norwegian University of
Science and Technology