The Impact of Graphical Fidelity on Physiological Measures of Stress in a Virtual Reality Urban Environment

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Abstract:

Navigating urban environments is a prevalent phenomenon in modern times which raises some complications as heavily trafficked areas within urban environments have shown to raise the stress levels of pedestrians. Virtual reality studies indicate that it is possible to recreate stress through exposure to virtual traffic and with that the goal of this report was to discover the required (if any) level of graphical realism to obtain these stress levels within Virtual Reality. Two geometrically identical virtual environment prototypes were designed and implemented. One prototype featured the application of the high-fidelity graphics and the other low-fidelity graphics. Each prototype featured a dynamic traffic system and an endless virtual locomotion solution using an arm swinging method. The experiment consisted of two groups (one for each prototype) of 16 participants that would traverse along the same specific route within their respective prototype. The study indicated there was a difference in the graphical realism between the prototypes and that some similar stress levels were found between real life and both virtual environments, however the cause and effect of stress within our experiment remain inconclusive.

Contents

Preface

This project is done by group MTA221008 from Aalborg University on the 4th. semester Medialogy master program under the supervision of Markus Löchtefeld. The project spanned from the 1st. of February to the 25th of May.

The reference style used in this report is the American Psychological Association (APA for short) decimal point is used for decimal separation. Dates are written: year, month, day.

The authors would like to give special thanks to the participants of this project, who took part in the experiment and Markus Löchtefeld for supervising the project.
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Chapter 1

Introduction

Navigating urban environments is common among pedestrians and cyclists, whether they travel for the sake of travelling or in order to attend school, work or other events. However, there are many complications in navigating the urban environment. This comprises of different challenges, e.g. the predictable aspect of road crossings and junctions with light indicators, and the unpredictable congested traffic, road work or obstructing vehicles.
It has been observed that certain situations in traffic can affect pedestrians' and cyclists' mental health, including stress, which in turn have had negative impact on their performance in school or at work. Being stressed has proven to affect cognitive abilities, such as learning while in school, or the ability to create or retrieve memories. This can in turn cause people to experience anxiety or sadness due to stress inducing events [Vogel and Schwabe, 2016]. Prolonged exposure to stressful events can cause long-term or even permanent damage to the quality of life and has been recorded as one of the most common reasons behind insomnia. While stress does not only occur during navigation in urban environments, it has also been recorded to occur in relation to family matters, or work and school [Bastien et al., 2004].
Stress factors in the urban environment include different weather conditions, i.e. wind or rain, the amount of traffic and certain vehicles such as trucks or other heavy duty vehicles, as well as the speed of the vehicles driving by. Not only are the previously mentioned factors contributors to stress, but also generally lowers the comfort level of pedestrians and cyclists [Nuñez et al., 2018] [Bigazzi et al., 2022]. In contrast to this, it is also possible to affect pedestrians and cyclists positively, by having elements such as trees, or fewer loud vehicles. This causes their satisfaction and comfort level to increase, and can potentially be useful for traffic planners to satisfy both motor vehicles, pedestrians and cyclists [Jensen, 2007].
In order to reduce the amount of stress experienced by pedestrians, it would be beneficial to find a cheap and time efficient platform to conduct traffic simulations on which would also provide similar stress responses as real life.
The platform that this project will be using is Virtual Reality (VR) as it has been shown to provide high immersion and to be suitable for simulating different traffic related tasks. A study was conducted that used a VR head mounted display (HMD) combined with a racing wheel to assess the participants driving competencies. The study deemed VR to be superior to the current standard used to assess driving skills. Benefits of using VR were stated as being dynamic and able to quickly produce new virtual content, and to be an easy and convenient environment for observing users and logging their data [Juřík et al., 2021].
Studies have shown that stress can be achieved using VR [Mudassar et al., 2021], where

a study proved that closing proximity to simulated autonomous vehicles can cause stress to pedestrians when trying to cross a road. However, this study lacks evaluation in terms of comparison between stress levels in real-life and the virtual environment (VE). This project will therefore aim to create real-life pedestrian stress measurements as well as a comparison study between two VEs with two different graphical fidelities (high and low) that participants will be experiencing in VR to better understand what graphical lengths developers have to go to in order to recreate similar stress levels to real life.

The current body of knowledge leads to the following problem:

"How can the level of realism and attention to detail affect the users stress level in a virtual reality environment designed to simulate an active urban environment".

Chapter 2

Background Research

This section will aim to cover all the necessary research topics to both establish the foundation for the design and implementation of a prototype, as well as ensure that the knowledge gathered in the introduction is further backed up or elaborated upon. In order to understand the elements that are important in simulating a realistic active urban environment to replicate real life stress levels, it is important to research graphical elements necessary to achieve a high level of graphical realism, as well as the elements that are needed to make an individual believe that they are situated within the realistic active urban environment. Finally, understanding exactly how and what causes stress amongst pedestrians will be a key section of this chapter.

2.1 Pedestrian Behaviour

People behave differently, but also share some of the same traits when it comes to being affected by outside factors during walks.
Pedestrians' behaviour and navigation in urban environments (UE) is a topic that has been studied thoroughly. There is a considerate amount of variables at play for how pedestrians navigate UEs.
On average people (both men and women) were 1.5-2.5 times more likely to cross at a crosswalk if another person took the lead in crossing even leading to risk of injury in some cases by following the herd mentality, which is a phenomenon that appears when people conform to the beliefs or actions of the majority within a group. When measuring the stress levels of one of the "followers" the stress levels were higher as they did not consciously make the decision to cross the road, but rather subconsciously followed the "leader" [Faria et al., 2010]. A heavily crowded crossing has also shown to lead to higher stress levels for crossing pedestrians when there is little to no room to move in between other people [Osaragi, 2004].
The speed at which pedestrians crossed was dependent on the amount of lanes on the road. As the number of lanes increased so would their walking speed to cover greater distances. Pedestrians were also less likely to violate red lights as the lanes increased [Rosenbloom, 2009]. The weather has been shown to play an important role as when it comes to the willingness to wait. In hot weather conditions, participants were more eager to cross and they were also measured to be going through more stress [Bendak et al., 2021].
A study examined how pedestrians behaved when exposed to different audio stimuli [Franěk et al., 2018]. They used three groups, one control, one exposed to traffic sounds,

and one exposed to bird sounds. The experimental groups were instructed to walk a specific route while listening to their assigned soundtrack.
They concluded that the traffic noises increased the pedestrians' walking speed, while those listening to bird sounds walked slower. While the study mentioned limitations such as noises not being entirely filtered out by the headset during the route, and the bird noises not representing the natural environment since it was missing other features such as rustling leaves or wind, they argued that walking at a faster pace was a response to stressful environmental stimuli such as congested traffic [Franěk et al., 2018].

2.1.1 Takeaways: Pedestrian Behaviour

According to research, pedestrians behave differently and react to the environment. There are many factors that play a role in this such as sound, temperature and visual aesthetics. In order to successfully recreate an environment that causes stress, elements such as large crowds of people, loud or even heavy-duty vehicles should be present as pedestrians are more prone to becoming stressed in these types of environments. Weather and sound also plays a role in pedestrians' walking speed [Bendak et al., 2021] [Franěk et al., 2018]. And other pedestrians are also part of constituting which actions others take at crosswalks [Faria et al., 2010] [Osaragi, 2004].

2.2 Simulating Realism in VR

To figure out whether graphical realism has an effect on stress, it was important to establish which graphical aspects were most tied to realism. This section will research what constitutes as realism in VR. This includes ray tracing, ray casting, and different types of lighting and shadow techniques which can be used in VR. Advantages and disadvantages will be discussed for the different techniques.

2.2.1 Geometric Realism

Geometric realism can be defined as "graphical objects that has close resemblance to the real-world object being depicted", meaning that the dimensions of for instance the walls, doors and windows of a building should be the same as its real-world counterpart to achieve geometric realism [Slater et al., 2002]. There has been several studies experimenting with, what constitutes as realism in a VE. Most of these studies worked with the same fundamental of using a pitfall room [Slater et al., 2009] [Khanna et al., 2006] in order to track anxiety or presence. One particular experiment entailed having participants try to escape a survival-horror themed apartment in VR [Hvass et al., 2017a] [Hvass et al., 2017b]. One group would play with high geometric realism, while the other would have low geometric realism and graphics i.e. the low geometric realism was a reduced form of the original, specifically one fifth in terms of polygon count and texture resolution.
This consequently resulted in participants subjected to the higher geometric realism also had a stronger feeling of presence.

2.2.2 Presence & Immersion

Presence and immersion are two of the most often discussed topics when it comes to VR. The definition of immersion has evolved through time [Berkman and Akan, 2019] but recent studies regarding VEs have embraced the definition of immersion as "a quality of the system's technology, an objective measure of the extent to which the system presents a vivid virtual environment while shutting out physical reality." [Slater and Wilbur, 1997] [Berkman and Akan, 2019]. Immersion in the context of VEs can therefore be seen as a way of making users feel enveloped by an environment and with that it quickly becomes apparent why VR HMDs have immersive potential. Presence is the phenomenon of feeling like you are situated in an environment (even virtually) and thus presence has generally been referred to as the "sense of being there" [Berkman and Akan, 2019]. When it comes to VR, the term presence is normally known as spatial presence and it is the most common type of presence [Lombard and Jones, 2015]. A highly present individual in VR should have the sensation that they identify with their virtual body in the VE and consider themselves situated in the VE. When observed, the individual would be expected to behave similar in the VE to how they would behave if they were in a similar physical environment [Slater and Wilbur, 1997]. With this in mind, presence and immersion will be important for the validity of the project's prototype in terms of its translatability to real life.

2.2.3 Shadows

Commonly, there are two types of shadows; soft and hard shadows. Soft shadows include umbra and penumbra. Where umbra is the shadow region which is not in the field of a light source, and penumbra which is only partly shadowed (see figure 2.1), meaning it can see part of the light source [Kolivand and Sunar, 2013]. Hard shadows occur when there

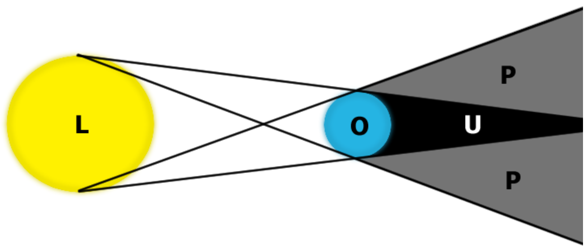

Figure 2.1: Light source (L) hits object (O), creating complete darkness (U) behind the object, and partly shadowed (P) when some light but not all light hits.

is a point light present, creating a sharp outline of the shadow of an object (see figure 2.2, left). Hard shadows are generally favourable in a scene, if the goal is to simulate concentrated light like a light bulb, or direct sunlight on a clear day. Realistically, the sun would never create perfectly hard shadows, so to realistically mimic the light of the sun we combine hard and soft shadows (see figure 2.2, right), which can occur with indirect light or if the sun is shining on a cloudy day [Birn, 2013].

Ambient occlusion (AO) also plays a role when it comes to details in shadows. AO is a shadow technique in which objects casts shadows on itself or on nearby objects (see figure 2.3). It creates depth to objects and helps to highlight finer details by casting these shadows [Birn, 2013].

Realistic shadows have according to studies shown to enhance realistic behavioural responses in VEs [Khanna et al., 2006] and therefore to simulate a realistic environment it

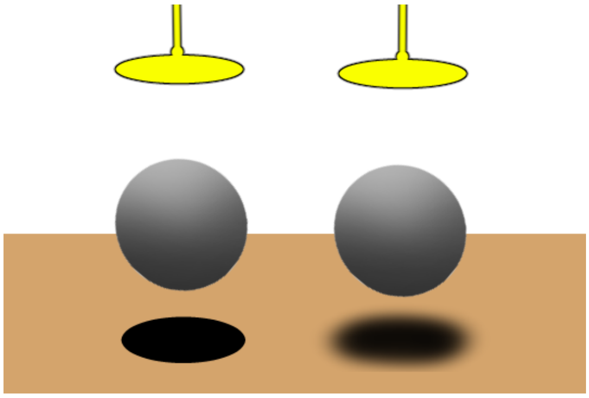

Figure 2.2: Hard shadows produce crisp outlines (Left), while soft shadows does not (Right).

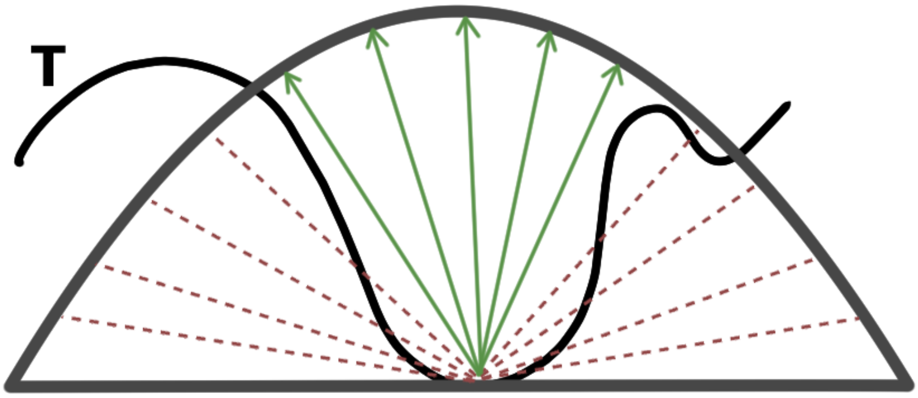

Figure 2.3: An illustration of how ambient occlusion works by casting rays from the surface of the geometry (T). The more rays that encounter another surface, the darker that particular point on the geometry will be.

would be ideal to use both hard and soft shadows, but it would be highly dependent on the simulated scene and the time of day within the scene.

Shadow map

Depth maps or shadow maps is an algorithm which provides an efficient way to render shadows. Everything is rendered from the light (see figure 2.5), and everything seen from this perspective is lit, while everything that is not visible from the light's perspective or occluded by other objects is in shadow. A depth map is generated to store the depth values within a texture, which then constitutes whether something is in shadow or lit by the light source we rendered from [de Vries, 2021]. However, the drawbacks of this algorithm is that it has a finite resolution and often needs to be adjusted in order to avoid artifacts from the geometry. Shadow mapping is also dependent on the settings of the light source, since the shadow mapping can become gritty and inaccurate (see figure 2.4, right), if the light source is covering a larger area. With enough adjustments, shadow mapping is also able to simulate soft shadows [Birn, 2013].

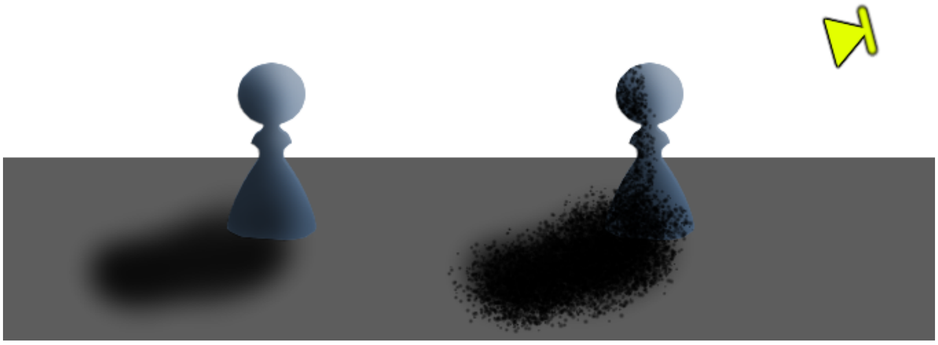

Figure 2.4: Shadow map becoming gritty with wrong settings (Right), and being more optimized and less gritty (Left).

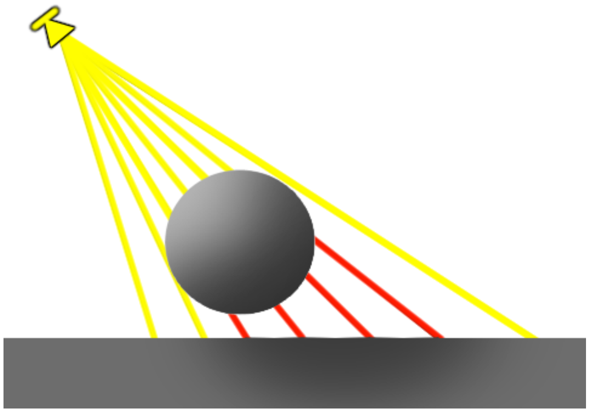

Figure 2.5: We render a scene from the light's perspective. Anything the light hits is illuminated, and everything else is otherwise in shadow. Yellow lines illustrate lit surfaces, while red lines are not lit by the light source.

Ray traced shadows

Ray traced shadows computes one pixel at a time. It does not store depth values like shadow maps do, but renders on the go, making it accurate at any resolution, however it takes longer to compute. The main advantage of ray traced shadows is that it does not create light leaks or artifacts like shadow maps. However, as it takes longer to render than shadow maps, it also uses more memory [Birn, 2013].
A study had looked into lighting conditions and ray tracing, where one group was subjected to recursive ray tracing, while another was subjected to ray casting. Ray casting did not render shadow effects or reflections, while ray tracing did, and did so dynamically according to the participants' movements. According to their physiological recordings and questionnaire, participants in the ray tracing condition experienced higher levels of presence and stress than the ray casting group [Khanna et al., 2006].
With this knowledge, it is clear that in order to experience stress within a VE, the graphical aspect has to be on par with the research, to achieve the most realistic reactions from participants.

2.2.4 Global- and Local Illumination

Lighting models such as global illumination (GI) takes the light source into consideration as well as reflective rays which reflect and "bleed" colors onto nearby objects' surfaces

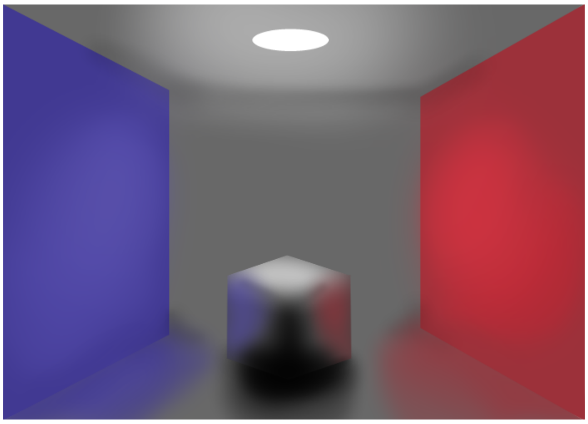

Figure 2.6: Example of global illumination "bleeding" color from the wall onto an object.

[Hafthorsson, 2007] (see figure 2.6). The "bleed" effect usually becomes unrealistic the stronger the shader's saturation is, making GI unable to handle it properly. While GI reflects light on surfaces to simulate indirect light, local illumination (LI) only illuminates using the light source without the light bouncing on surfaces. As such, only indirect light that contributes to diffuse illumination is considered as GI [Birn, 2013].

2.2.5 Takeaways: Simulating Realism

The main takeaways is that having a high polygon count and dynamic shadows and reflections are important. To achieve the highest possible perception of realism, models should be made with a high amount of polygons, as well as a large texture resolution. Ray tracing should also be used to simulate dynamic shadows and reflections. However, it should be taken into consideration that all of these aspects take a lot of computational power. Therefore, it might be viable to look into other solutions.
Because shadow maps use finite resolution, it works best on objects with low depth map resolution such as 512, 1024 or 2048, but increasing the resolution depletes the system's memory. If the depth map resolution goes above 4096, then it might be worth using ray traced shadows [Birn, 2013].
Apart from this global illumination and ambient occlusion can help establish more realistic lighting and highlight finer details in objects, which all help to create graphical realism.
All of this should help to establish both presence and immersion for our users. Presence and immersion are vital to the success of the experiment and will, as mentioned in section 2.2.2, help to ensure the validity of the project.

2.3 Measuring Stress

In order to measure stress, there are several methods which can be approached. Most of these methods are physiological acquired data, or objective data, e.g. the use of Electrodermal Activity (EDA), Heart Rate (HR), Skin Temperature (SKT), Blood Volume Pulse (BVP) [Chandra et al., 2021]. The before mentioned methods have previously been used to obtain data of participants' stress levels by subjecting them to scenarios in a VE where they would for example stand at the edge of a pitfall to induce stress [Meehan et al., 2002].

2.3.1 Empatica E4

The E4 wristband is a wearable device made by Empatica Inc [Empatica Inc, 2022], which consists of four sensors; photoplethysmography (PPG), EDA, a 3-axis accelerometer and a temperature sensor. The device can store data on its internal drive, but also stream the data via Bluetooth, both of which will be uploaded to the Empatica Cloud [Empatica Inc, 2022]. EDA is measured in the skin conductivity through electrodes which are influenced by the sweat glands on for example the wrist [Mobascher et al., 2009]. The sweat glands activity happens through the sympathetic nervous system, which is also responsible for activating when in stressful situations. Therefore, EDA is directly tied to the sympathetic nervous system, as a result of its rapid activation [van der Mee et al., 2021].

A comparison study was made between using the E4 and the Vrije University Ambulatory Monitoring System (VU-AMS), where they tested whether the E4 was as accurate as the VU-AMS. During a clinical study with fifteen participants in residential care, the results showed that the E4 was highly comparable to the VU-AMS in terms of recording heart rate. However, the E4 had a tendency to result in data loss due to either movement, or applying the device incorrectly, resulting in missing Interbeat Interval (IBI) to calculate Heart Rate Variability (HRV). There was as much as 37.5% data loss, and another study found it to be 45% data loss [Schuurmans et al., 2020] [van Lier et al., 2020].
A study used the E4 as a stress measurement tool during an experiments where participants were subjected to a five minute job interview, and reading aloud by themselves, on separate days. Their results indicated that the E4 yielded loss of IBI data when the participant performed a task which in turn proved to be a problem when calculating HRV. Despite the loss of data, the E4 proved to be better at discriminating stress than finger electrodes [Ollander et al., 2016].
Another study used the E4 to test its validity and concluded that the device should be used over a longer time frame with stressors such as a meeting, and should not be used for shorter events (events under 30 seconds) e.g. when being startled [van Lier et al., 2020].

2.3.2 Stress Factors

Research suggest that noise and vibration while cycling will decrease the cyclists' comfort [Nuñez et al., 2018]. Participants would be equipped with a backpack which had a noise sensor inside, and a smartphone on the bike to act as an accelerometer. Using skin conductance it was observed that stress peaks would also subsequently happen during rush hour peaks. Other stress areas included; when there was an intersection, or during unsafe traffic conditions when there was insufficient space to accommodate cyclists.
Another study, which looked into discomfort of pedestrians, suggested that general exposure to motor vehicle traffic was the most consistent contributor in terms of walking and cycling discomfort [Bigazzi et al., 2022]. They list different factors, which influence pedestrians and cyclists positively and negatively. Negative impact, which caused discomfort was congested traffic, heavy-duty vehicles and high speeds. Improper weather temperatures, lighting and wind conditions also negatively affected them. However, being in natural environments which had elements such as trees would cause the opposite. Shorter crossing distance also increased the comfort.
The positive responses to nature is further supported by a study by White and Shah where they theorize about the stress rejuvenating effects of natural environments also known as the "Attention Restoration Theory". In UEs where there are many distracting fac-

tors such as signs that are designed to grab people's attention, vehicles/or cyclists that pedestrians need to be spatially aware of to avoid injury or flashing lights of the traffic lights. These factors all deplete limited cognitive resources and requires directed attention, whereas natural environments is restorative as the attention is involuntary and effortless [White and Shah, 2019].
In 2021 a study was conducted on how pedestrians stress level were affected in VR where the vehicles were simulated versions of self driving vehicles (see figure 2.7)
[Mudassar et al., 2021]. 180 participants took part in the experiment using galvanic skin response (GSR) sensors. The results showed that the participants were stressed and that their stress levels increased as the distance from them to the vehicles decreased. This study is important as it confirms that stress can be achieved in a virtual urban environment, however it does not confirm whether the stress levels are mutual between the real and the virtual world.

Figure 2.7: The virtual environment used to measure participants stress levels in exposure to simulated virtual self driving vehicles [Mudassar et al., 2021].

2.3.3 Takeaways: Measuring Stress

When it is desirable to measure stress, it is important to obtain accurate measurements. Despite the loss of IBI data, the E4 has proved to be an accurate tool. As both HR and EDA data has been documented to be tied to the sympathetic nervous system activity [van der Mee et al., 2021] [Lin et al., 2011], these features would be the ideal data to acquire when it comes to stress.
With the E4 being a non-invasive device, a wristband makes it an ideal and easily applica-

ble device in order to measure several features with high accuracy.

2.4 Locomotion in VR

Long distance walking is one of the challenges of VR that has yet to be completely solved in order to create even more realistic and immersive VEs. For this project in particular the goal of our locomotion method within VR is tied to how realistic and immersive the aspects of the locomotion method itself is, as it is likely to have an impact on how present the participant will feel within the final prototype (see section 2.2.2). However, for the locomotion system to seem natural, motion sickness must also be controlled and have as little of an impact as possible as it could affect the results of our EDA, see section 2.3.1.

Teleportation

One of the solutions for this problem is using teleportation. This is an effective method of allowing the user to traverse large distances which typically works using the controller to point at the destination they wish to travel within the VE and then with the press of a trigger on the controller, the user will be teleported to the desired point. According to a comparison study the teleportation method was easy for participants to use and proved to be an effective locomotion method, however it lacked in the aspects such as the sensory and imaginative immersion [Boletsis and Cedergren, 2019].

Continuous Locomotion

Many HMDs come with joysticks/controllers that can be used for locomotion as well. Moving is done typically through moving the analog stick in the desired direction the user wants to walk this method is typically referred to as continuous locomotion. This method also proves to be effective in regards to locomotion and easy to use, whilst also maintaining a decent level of sensory and imaginative immersion [Boletsis and Cedergren, 2019].

Walking-in-place

Another solution is the walking-in-place (WIP) solution that allows the user to walk around within a virtual environments whilst remaining in place. This can be achieved through motion sensors that are strapped to the legs of the user which will register specific motion patterns related to walking in place. It is also possible to achieve the same effect without the motion sensors by tracking the user's orientation and position. It can distinguish between intentional- and unintentional movement. As there is no sensors involved this has the drawback of making the locomotion direction and viewing direction coincide, meaning where ever the user is looking will also be the direction they are walking in the VE [Lee et al., 2018]. The advantages of using a WIP solution is that it allows the user to maintain a high level of sensory and imaginative immersion and for the user to navigates VEs and also provides a higher level of realistic fatigue from using the method compared to locomotion devices such as the controller and teleportation [Boletsis and Cedergren, 2019].

Arm Swinging

Finally, a study at Keio University tested another solution that is focused around swinging the users arms as a form of navigation. Through an arm swinging motion similar to that of a standard walking gait the system is able to recognize the pattern and will move the user according to where the body is facing. It is able to know the forward trajectory the user is supposed to have by using the relative positional vectors of the hand controllers and HMD and thereby create a forward vector for the user. According to their study the impact of nausea symptoms, as is custom of some virtual reality locomotion methods, was significantly lessened when using the arm swing method to navigate with, compared to a WIP solution. No evidence was found to support a significant difference in presence between the two solutions either [Pai and Kunze, 2017].

2.4.1 Takeaways: Locomotion in VR

Teleportation and continuous locomotion was deemed to not provide enough presence for users, which leaves us with the choice between the WIP and arm swinging system. Both the WIP- and arm swinging locomotion system has pros and cons. The WIP system is the most realistic in terms of simulating natural walking, with the exception of not moving but staying in place, but it is also the system that introduces the highest chance of nausea symptoms.

The arm swing system on the other hand eliminates a lot of the risk for nausea but at the same time limits movement only to the upper body parts. It simulates a walking movement with the arms but does not include any leg movement at all unless turning of the full body is required.

Whilst the WIP method is in many ways is a great solution for this project, however, the risk of nausea symptoms affecting this project's experiment means that the arm swing system is the chosen solution for this project.

Chapter 3

Design & Implementation

The research done in the previous chapter as well as the problem formulation in the end of chapter 1 serves as ground for the design and implementation, and helps define clear goals for what needs to be achieved to be successful in not only recreating stress but also determining the impact of graphical fidelity.
Goals to create graphical realism and to recreate stress levels include the main takeaways from the background research (sections 2.2.5, 2.4.1, 2.1.1) and are as follows:

- Models using high polygon count and texture resolutions, both for the urban scene and the cars.
- Realistic warm weather simulation.
- Realistic environmental sounds
- Real-time shadows using ray tracing.
- Ambient occlusion to highlight finer details and global illumination to create realistic lighting reflections.
- A locomotion system that does not impact motion sickness, whilst still giving a realistic sense of movement.

The implementation and decision making behind all of these goals will be covered in the following sections. Each also with illustrations that shows the impact of the implementation.

3.1 Design Decisions

This section covers the thought process and reasons behind the design decisions. It includes the vehicles, the environment i.e. buildings, weather and sounds.

3.1.1 Cars

In order to make the simulation as realistic as possible, and for the sake of diversity we looked at buying habits in terms of the car colors that are most commonly bought and driven on European roads.
De Forenede Danske Motorejere, FDM, released an article in 2018 showcasing the *European*

Color Report For Automotive 2017 [Bregenov-Pedersen, 2018] made by German BASF, explaining the distribution of car colors in Europe. The three most popular colors were white at 29%, black and gray at 19%. While smaller cars are more colorful, cars classified as luxurious or convertibles were predominantly black.
Below is a table 3.1 with every available color in the simulation, as well as their appearance frequency as seen in FDM's article:

Color	Frequency	Hexidecimal
White	29%	FFFFFF
Black	19%	000000
Gray	19%	5A5A5A
Silver	11%	9C9C9C
Blue	10%	003DC0
Red	5%	C10002
Brown	4%	482617
Green	1%	003C0F
Orange	1%	CC5100
Yellow	1%	FFC500

Table 3.1: The most popular car colors in Europe, as well as their frequency and their corresponding hexidecimal in HSV color space.

To further increase variety we used multiple cars of different makes and models in the simulation. The cars that were chosen came from the same source that gave the inspiration to the implementation of a node based traffic system (more on this in section 3.4.1) [pablos lab, 2020]. The exact models used are those of a Volkswagen Golf R (Mk VIII) [FastestLaps, 2022] [Volkswagen, 2022], Tesla Roadster [EV Database, 2022], Audi RS7 Sportback [autoX, 2022], Ferrari Testarossa [Ultimate Specs, 2022].
In order to then get a better understanding of the measurements of a real car, the information about the Golf model [Volkswagen, 2022] was used as a base, using the length, height and width. The cars were scaled in Unity so that their dimensions in meters matched the dimensions in units in Unity, and with this 1 unit = 1 meter measurement established we build the rest of the city with those measurements in mind to ensure that the scale was 1:1, so it felt natural for the user to navigate and had high levels of geometric realism as described in section 2.2.1.
To further enact realism we wanted the cars to act as they would in the real world, both in terms of breaking, accelerating and with how their lights operate. As an example of this, we used the data sheet from the Golf [FastestLaps, 2022] and made sure that the car was able to go from 0-50 km/h. In 1.8 seconds and that at 50 km/h. It is able to travel a 100 meters in 6 seconds.

One of the most important behaviours of the car was its lighting and specifically being able to indicate when turning to inform the user. To make sure we followed the same level of realism as we had aimed for so far we used the official laws from Retsinformation [Retsinformation, 2020], chapter 2 §9, to implement the correct timing between the indicator light blinking as well as giving the light the correct color.

3.1.2 Traffic Lights

The simulation will adhere to the official laws from Retsinformation [Retsinformation, 2021], act 2510 from the year 2021 as the latest updated list of laws in terms of traffic.
According to chapter 8, §238 the traffic light signals must follow a set of rules for transitioning lights, including:

- Red-yellow: 2 seconds
- Yellow: 4 seconds
- Green: At least 6 seconds

There are more rules to this paragraph for bus signals and crossing of train tracks, but we chose to stick to these, as we only have a focus on cars in our simulation. It is worth noting however if other tests with a shift in focus were to be implemented later. §239 also states that pedestrians and cyclists' green signal should not appear later than the main road's green signal in the same direction. With this in mind we implemented the crosswalk light to adhere to this last paragraph but did not do anything in terms of specific cyclist signals as the focus is on pedestrians for this paper. The only alteration made to this were the length of the green light which ended up at 14 seconds in the final prototype.

3.1.3 Roads & Buildings

The entire city was constructed using a satellite image of the chosen location from google maps [Google, 2022]. The image was taken so that the scale adhered to the unit to meter measurements mentioned in section 3.1.1. To construct a city for the simulation, the asset package City Builder: Urban [ReversedInt, 2021] was chosen based on its compatibility with Unity's universal render pipeline (URP). The package contains a large variety of 3D models and assets ranging from benches, bins, roads, traffic lights, signs to modular buildings. This asset pack was chosen due to its close resemblance to European architecture and because of its high fidelity look. All assets have either 4k or 8k textures with normal maps. Due to the fact that the traffic lights in City Builder: Urban were uploaded as a single mesh with all lights as one texture, and therefore not able to be modified individually, another package from the Unity asset Store, Traffic Light Plus Pack [Trac Games, 2019] was chosen. This package contains different types of traffic light prefabs that are able to be assembled in a modular fashion. The package also comes with a fully automated traffic light script that we modified to fit our needs. To make the light resemble the laws stated in section 3.1.2 however, we had to implement a red-yellow option which meant altering the texture used for the red and yellow light to make a version with them both combined.

3.1.4 Weather and Audio

To simulate realistic weather, the Enviro - Sky and Weather [Haupt, 2022] package was used, available on the Unity Asset Store. The package provides day-night cycle, realistic lighting based on the suns altitude and location as well as season change, clouds, fog, different weather configurations such as rain, storm or snow and much more. It is also possible to select longitude and latitude to simulate a specific place on Earth, making it fully customizable in all aspects.
The original intent here was to have various weather presets to swap between based on weather data from [Danmarks Meteorologiske Institut, 2021] but due to frames per second

(fps) issues we had to opt for a single preset. We made this preset to adhere to the knowledge about weathers impact on stress found in section 2.1 as well as chapter 1 and made a clear blue sky with only a few faded clouds and a high sun at around 12:00 midday, to simulate warm weather conditions.
When it comes to the sounds it was important to consider the environmental effects of it. Section 2.1 mentions environmental factor such as sounds having an effect on stress for pedestrians, therefore to ensure the validity of our experiment traffic ambience has been implemented in our prototypes as well.

3.2 High Fidelity Version

To adhere to the goal of the project set in the end of chapter 1 we designed two fidelity versions of the prototype which will henceforth be referenced to as either high-fidelity (hi-fi) or low-fidelity (lo-fi).
The hi-fi version was made first with the intention to later convert it to the lo-fi version instead of the other way around.
The city was modelled and decorated with assets from City Builder: Urban. The traffic lights were made with assets from the Traffic Light Plus Pack.
The first objective was to find a route which showed traffic congestion, even outside of rush hours. For this purpose, Vesterbro in Aalborg was used due to it being a main road through the city. After having chosen the location, the location was modelled in Unity with the aforementioned assets while the traffic system was implemented separately. Figure 3.1 showcases a satellite photo of the center of Aalborg. The red dot indicates the start of the planned route, and the red line indicate the route itself. The route starts at The Wharf (a local pub in Aalborg), and ends there too. To the right is a translation of the satellite photo into Unity

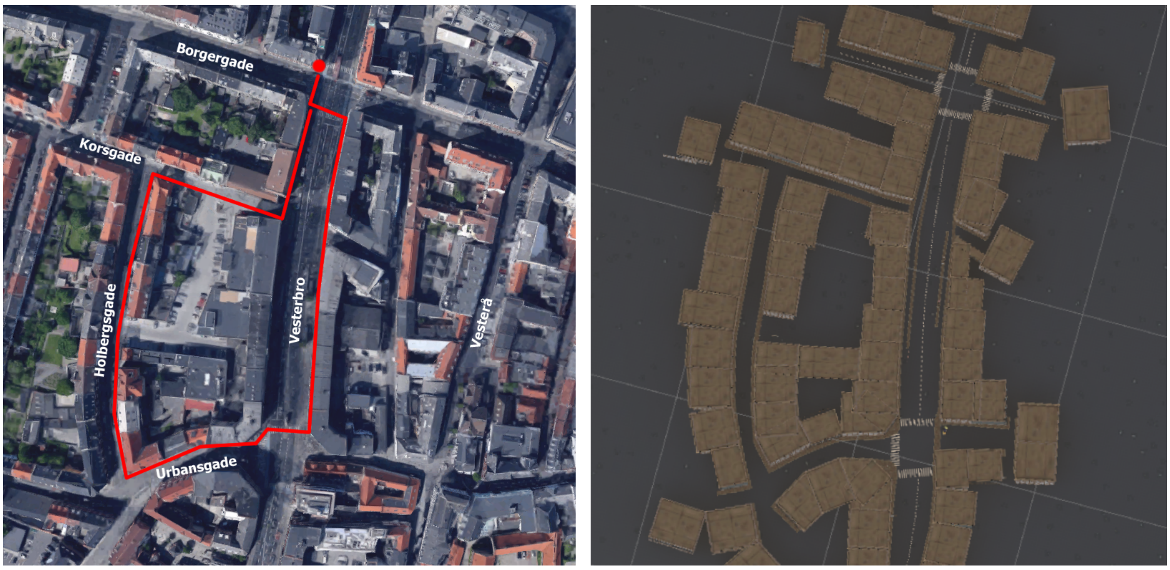

Figure 3.1: Left: Satellite photo of the part of Aalborg with plotted route. Right: Virtual environment constructed based on the satellite photo

To ensure that the simulation did not become too computationally intensive to run, only the important parts of the city were built along the given route. Buildings at the end of roads were used for blocking the camera view from seeing beyond the simulated city

boarder, even though this did not compare to the real-world counterpart. It did ensure that there was no "void" when looking around the corner in the VE.
Some of the details from the real-world city were omitted altogether or in some cases replaced with assets from the City Builder: Urban package. This was done to keep the atmosphere of the real-world counterpart going in the simulation whilst maintaining a lower amount of models to render for a smoother run time experience. All of this can be seen in the figures 3.2 and 3.3.

Figure 3.2: Left: Google Street View outside Cafe Friends. Right: Reconstruction of the street view in Unity.

Figure 3.3: Left: Google Street View of the road and bus stops opposite of a Netto on Vesterbro. Right: Reconstruction of the street view in Unity.

To decorate the city further, various low computationally intense models such as trashcans and bus stops were used to mimic the street view photo as closely as possible. Scaffolding assets were also used to decorate, but their second purpose was to block the camera and player from advancing further in other directions than the intended path.
All texture resolutions, normal maps and base maps were limited to the default texture size of the Oculus Quest 2 HMD at 2048 pixels instead of their original resolution which could go as far as 8192 pixels, due to frame drops.
The four different cars mentioned in section 3.1.1 ended up being used for the traffic simulation in the hi-fi version to create variation. The models can be seen in figure 3.4.
To adhere to the knowledge set by the graphical realism section 2.2 we also implemented both ambient occlusion and global illumination. Because our scene is mostly filled with static objects and to help better the frame rate and overall performance we chose to implement global illumination as a baked solution. Baking it means that a series of light maps are generated from the brightest light source which store all the data related to how the light was cast onto objects in the scene and how those object reflect the light onto other

Figure 3.4: Cars used in the hi-fi version, from left to right: VW Golf R (Mk VIII), Tesla Roadster, Audi RS7 Sportsback, and Ferrari Testarossa.

objects at the moment of baking. Moving the light source after will therefore only affect direct lighting and the shadows cast by the light source but not the reflected light from global illumination (indirect lighting) [Unity Technologies, 2021b].
To recreate natural shadows and mimic real sun light as mentioned in section 2.2.3 we would need to implement soft shadows into our scene. Deciding how to cast shadows in Unity is simple as it is an option available on the light source. The impact of soft shadows is clear and can be seen in figure 3.5.

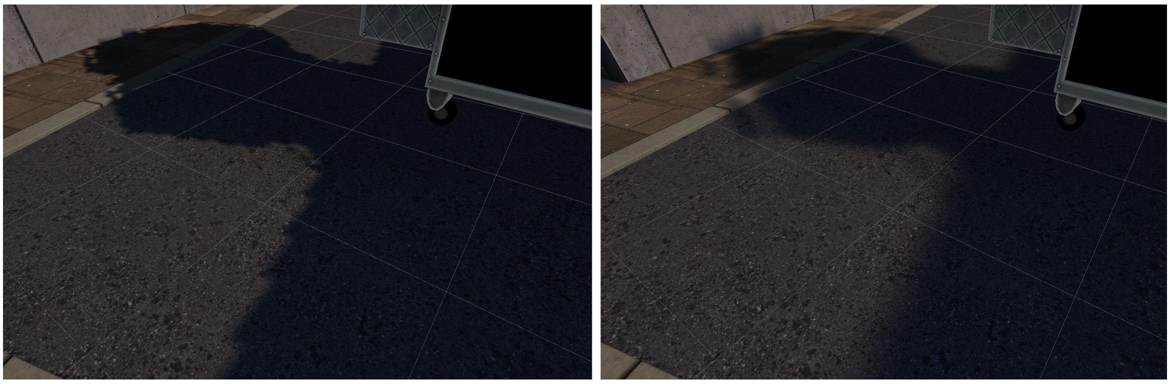

Figure 3.5: Shows the difference between hard shadows and soft shadows created from the light source that mimic the suns behaviour in our scene.

Lastly, the research mentions the importance of ambient occlusion in recreating realistic shadows to help highlight finer details within a scene as mentioned in section 2.2.3. Ambient occlusion in Unity is dependant on what pipeline is chosen and in the case of URP it is a feature inclusion onto the pipeline asset itself. The asset takes as an argument a render data file and it is this file that contains the ambient occlusion settings (the impact of ambient occlusion can be seen in figure 3.6).

3.3 Low Fidelity Version

The lo-fi version was made after the hi-fi version. It was created with the same models but with all base maps, normal maps and textures stripped off and only a base material with 32 pixel resolution applied (see figure 3.7).
The lo-fi version did not contain all the cars of the hi-fi version but simply one car: a low polygon adaptation of the Ferrari Testarossa. The car was made in Blender as a single mesh

Figure 3.6: Shows the impact of ambient occlusion on a building model in the scene. Right: With ambient occlusion. Left: Without ambient occlusion.

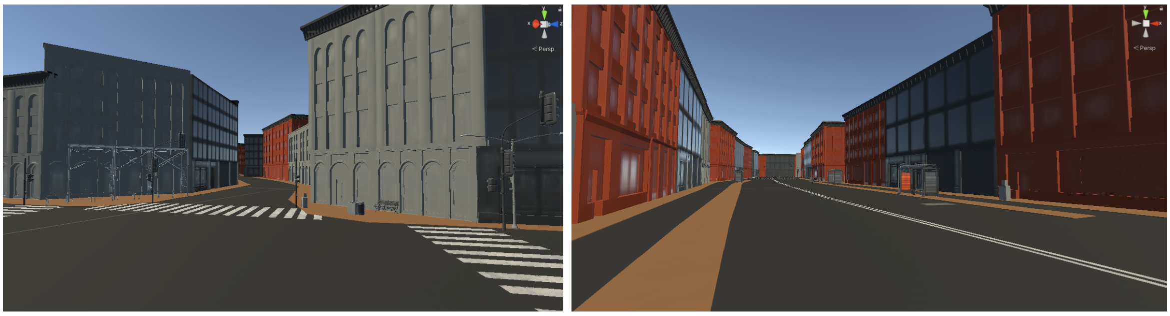

Figure 3.7: Left: Low resolution rendition outside Cafe Friends. Right: Main rode outside a Netto on Vesterbro (portrayed as the white building on the left side). These can be seen as a comparison to the hi-fi version in figure 3.2 and 3.3.

which was later divided into multiple meshes for holding the wheel, windows, indicators etc. But the main point of the car was that it had just about 300 polygons, making it a low polygon model and therefore should result in a feeling of low realism according to the research in section 2.2.
The car used the same behaviour as the hi-fi cars as stated in 3.1.1, meaning that the cutouts for break-, driving- and indicator lights were to ensure this homogeneous behaviour. The color of the car also followed the same probability table as the hi-fi cars (see table 3.1) and used the same material in Unity but without its reflective surface capabilities. A side by side comparison of the hi-fi Ferrari Testarossa and the lo-fi counter part can be seen in figure 3.8

3.4 Implementation

Part of the prototype design was to have the user navigate a VE that corresponds to a location in the real world. For this a location with moderate to high traffic density was chosen to try and simulate a more stressful environment for the user. The total distance the user would travel was approximately 640 meters and we therefore opted for a HMD with a wireless option. The **Oculus Quest 2** supported the need for a wireless option with its air link functionality and is also capable of displaying content with a resolution of 1832x1920 on both eyes at up to 72 Hz [Facebook Technologies, LLC., 2022b]. Which is

Figure 3.8: A comparison of the hi-fi and lo-fi version of the Ferrari Testarossa. The lo-fi version uses only 300 polygons.

beneficial when trying to test the impact of graphical realism on the stress level achieved in VR.
For the implementation itself we used **Unity** [Unity Technologies, 2022b]. The reason for using Unity over a tool like Unreal Engine [Epic Games, 2022] was due to the team's experience with Unity and due to the partnership between Unity Technologies and Oculus [Unity Technologies, 2022c] that means that in newer version of Unity, Oculus has a standalone implementation that is well supported and documented.
When modeling the VE most of the high polygon and high resolution assets came from external sources, however the low polygon models were made using **Blender** [Blender Foundation, 2022]. Blender was chosen due to being open source and because of the team's experience using the software.

3.4.1 Systems

The implementation of the final prototype that was used for evaluation consisted of different larger systems that all tied together to make up the experience. This section will give a brief description as well as some illustrations of how each system was implemented and how they work.

Traffic System

The traffic system is based on a map of nodes that each connect to one another (see figure 3.9), either by having a node as its next or previous node or as its link node. If a node is part of a straight road then the next and previous variable is used to determine the direction of the road whereas the link node is used to connect or "link" one road to another, thereby indicating a turn (see figure 3.10). The link variable is because of this not present on all nodes in the road, only on those that has the option for the car to turn.
There are different types of nodes and one in particular that ties into the link variable. The different types of nodes consist of: Instantiate, destroy, speed increase, speed decrease and new road. To explain the simpler nodes first then the speed increase and decrease nodes

Figure 3.9: An illustration of the entire road network in the final prototype. Seen both with and without the city around it.

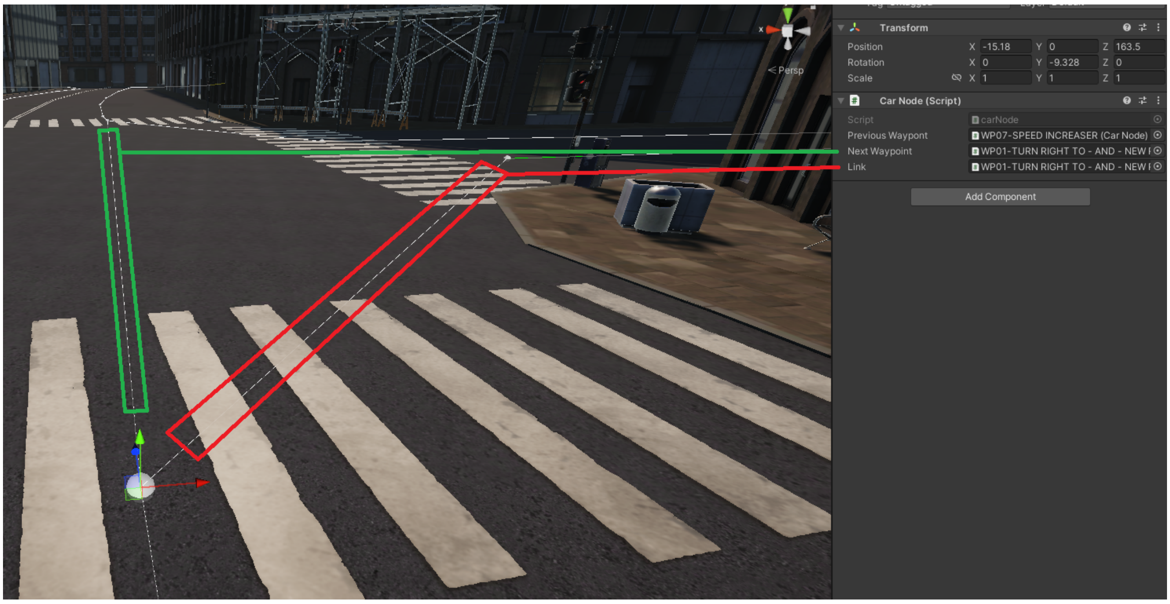

Figure 3.10: An illustration of a node when it has the link variable as an option, indicating that cars can turn onto a new road from this node. The red box in the figure is the link node and the green is the next node.

are simply used to limit the top speed of the cars between 50 km/h and 20 km/h this is done to ensure that on smaller roads and in turns the cars would not have too high of a speed which will make them go into the other lane and cause an accident with other cars. The destroy node simply destroys the game object and removes it from the list of spawned cars to remove its reference. This reference is important and is part of the last two node types but is also what makes the system in the next section work. When a car is instantiated from the instantiate node, then the car is first instantiated with the correct wheel collider [Unity Technologies, 2021d] settings (see figure 3.11) and a color randomly selected from the probabilities mentioned in section 3.1.1, before being spawned on the instantiate node (instantiate nodes are always the first node on a road). When the gameobject is spawned into the scene it is added to a list of all cars that are currently driving on that road to make sure that every car has a reference to which car is behind and in front of them. The final node type is the "new road" node and is simply used to move this reference from one list to another to make sure that if one car turns but the car in front and behind do not, then those two do not have a reference to a car that is no longer on the same road as them (This list can be seen in figure 3.12).

Figure 3.11: The car modifier script is where we input all the setting for the wheel colliders [Unity Technologies, 2021d]. Upon being instantiated the script responsible for creating the wheel collider component and attach the wheel onto the car will reference this script to get the desired values.

Figure 3.12: The list that keeps all the reference for how many cars are on a given road and in what order the cars are driving up the road. Each car will reference this list in order to see what the car in front and behind are doing.

Detection System

The detection system of the cars are entirely made up with colliders [Unity Technologies, 2021a]. In order for a car to detect another each car is equipped with a long collider at its rear, with the length of the collider being determined by the speed of the car behind it (see figure 3.13). When a car enters the rear collider of the car in front of it, it first checks to see if this is the car in front of it by referring to list of cars mentioned above, before it then starts to break. The rear collider is designed to be dynamic to adhere to different break distances at different speeds. On the car itself there is a mesh collider that uses a simplified (low vertices count) mesh of the cars body (see figure 3.13). This collider is the one that interacts with all the colliders that are set as triggers in the scene, which includes: the aforementioned rear car collider, stop and start colliders at intersections and stop and start colliders in front of crosswalks. It is also the collider that interacts with the rigidbody [Unity Technologies, 2021c] component on the car that allows the car to be affected by physics in Unity.
If a car comes up to an intersection and the light is green, the car will continue on if the cars current state is that it is already moving. However, if the light is red the car will break

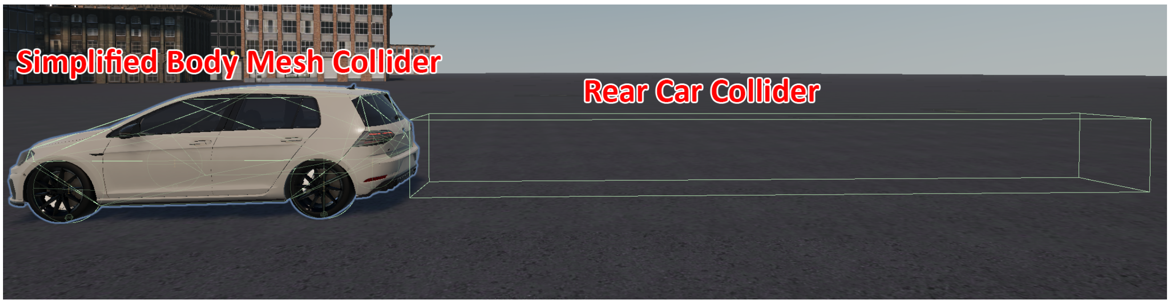

Figure 3.13: Illustration of the various colliders [Unity Technologies, 2021a] attached to each vehicle prefab used for detection. The collider on the body is of type mesh and is used when enter an intersection or another cars rear end collider. The rear end collider is to signal breaking and acceleration to the car behind.

and change its state to breaking and then to stopped. This indicates the red light to the cars behind and makes them stop as well upon entering the rear car collider. When the light then changes to green the collider attached to the intersection will change so that the tag now signals to the car that it can start accelerating. This changes the length of the cars rear collider to be the distance between the car and the one behind plus a small margin, and once the car behind exits the rear collider then it will also start accelerating (the entire collider system of an intersection can be seen in figure 3.14).

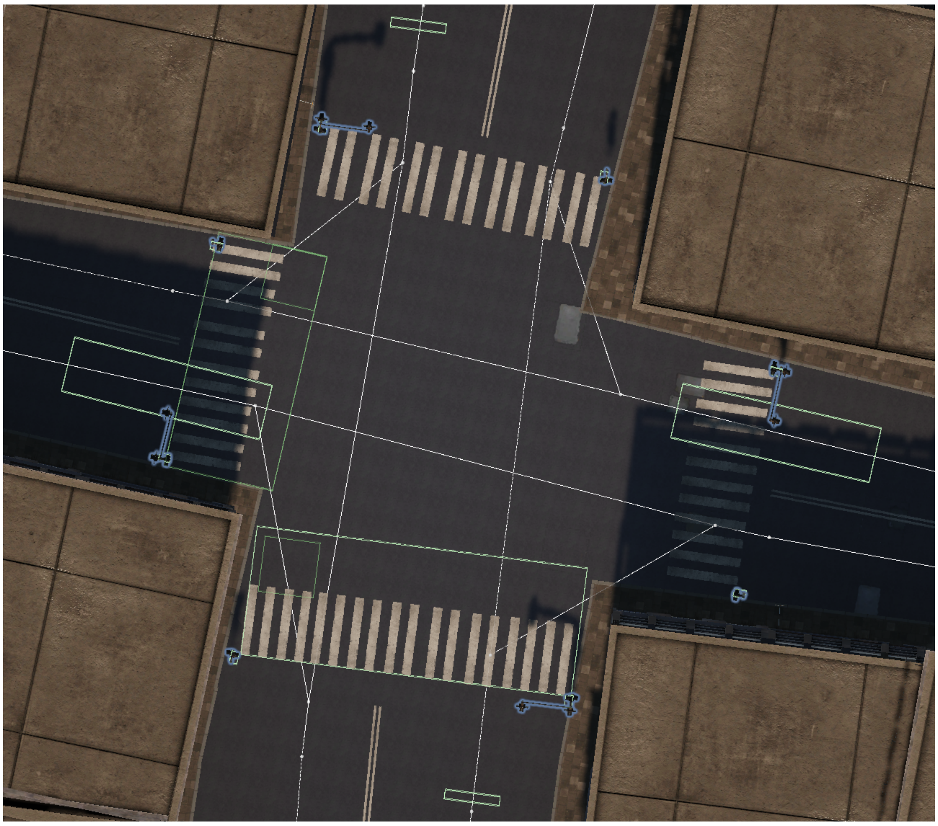

Figure 3.14: The collider system that makes up entire functionality of an intersection. Both by indicating what the color of the light is for the cars and by telling the car if there are pedestrians present inside the crosswalk areas or not.

The last set of colliders function much in the same way as the ones indicating signal light changes, but they instead makes the car check whether there is a pedestrian in the crosswalk section or not. If there is, the car will break and do the same to inform cars behind as mention above that it has stopped. If not the car will continue and do nothing. If the first case were true the car will continue once the pedestrian has left the crosswalk entirely.

Locomotion System

The locomotion system uses arm swings to determine directional movement and the speed of that movement. It detects position changes of the controllers and calculates the speed of that position change to then translate that into the speed at which the user is moving forward. A higher speed will result in a higher movement speed but will look to the user as if they are taking larger steps. The direction of the users movement is calculated by taking the forward vector of each of the controllers and adding them together to get the average forward vector between the two (see figure 3.15).
Because the user should always be able to move, the locomotion calculation happens in FixedUpdate() [Unity Technologies, 2022a]. This means that any small change in controller position will be detected unless the change value had a threshold. In order to accommodate for this and allow the user to be in full control over their movement, we made it so that the check for position changes only happens when the user holds down either the trigger button for forward movement of the grip button for backward movement this in turn allows the user to look around while moving as well, by separating head and body movement.

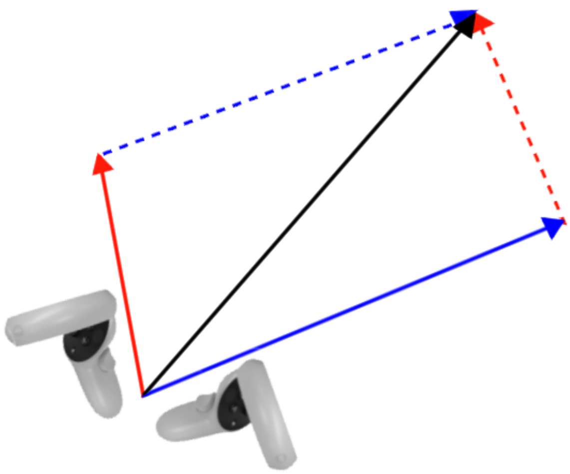

Figure 3.15: An illustration of how the direction in which the user is moving is calculated. The calculation is based on the forward vector of each controller added together.

System Limitations

A common scenario when working with VR is how to manage frame rate and more specifically how to not end up in a situation where the fps is so low that it ends up looking like a slide show. To circumvent this issue a few different approaches were used, one of which were occlusion culling and culling of 3D models. The idea here is to limit the power needed for rendering to only the models that are within view of the user and to only render them from the side that is visible to the user. This is illustrated in the figures 3.16 and 3.17.

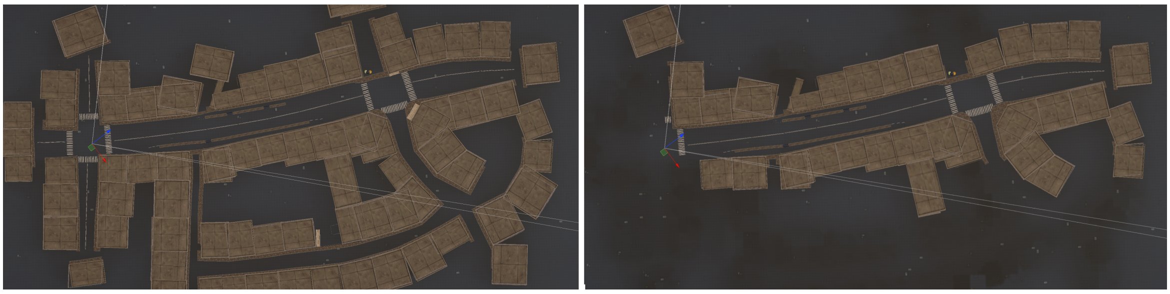

Figure 3.16: Occlusion culling and how the camera only renders what objects are visible to the user at any given time.

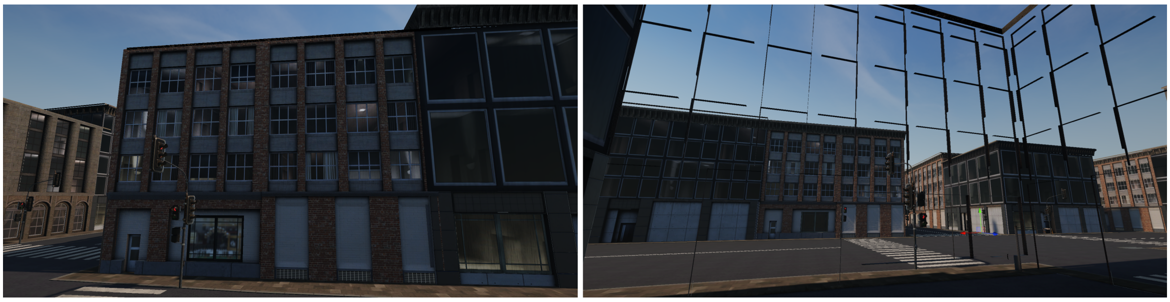

Figure 3.17: Each model is culled when viewing from outside the city and in toward the main street. This ensures textures are only rendered from the angles that are visible during the evaluation.

Another solution used to lower the frame rate was the use of "level of detail" or LOD. LOD is a way to show high detailed models both in terms of polygon count and texture resolution just to name a few, when the user is close to the object and then reduce the detail levels as the user moves farther away from the object. This acts as sort of an illusion but is not visible to the user as they would not be able to see the finer details at that far of a distance from the object anyway. So even though the model is still being rendered due to the fact that it is within the user's view, it is so in a lesser version of itself. The effect of LOD is illustrated in figure 3.18.
As a final measure to try and lower frame rate issue all textures in the scene were reduced to match the default resolution on the Oculus Quest 2 HMD at a resolution of 2048 pixels.
The success of the design goals stated in section 3 for both the design and implementation of the prototype, will be analyzed and discussed in chapter 6.

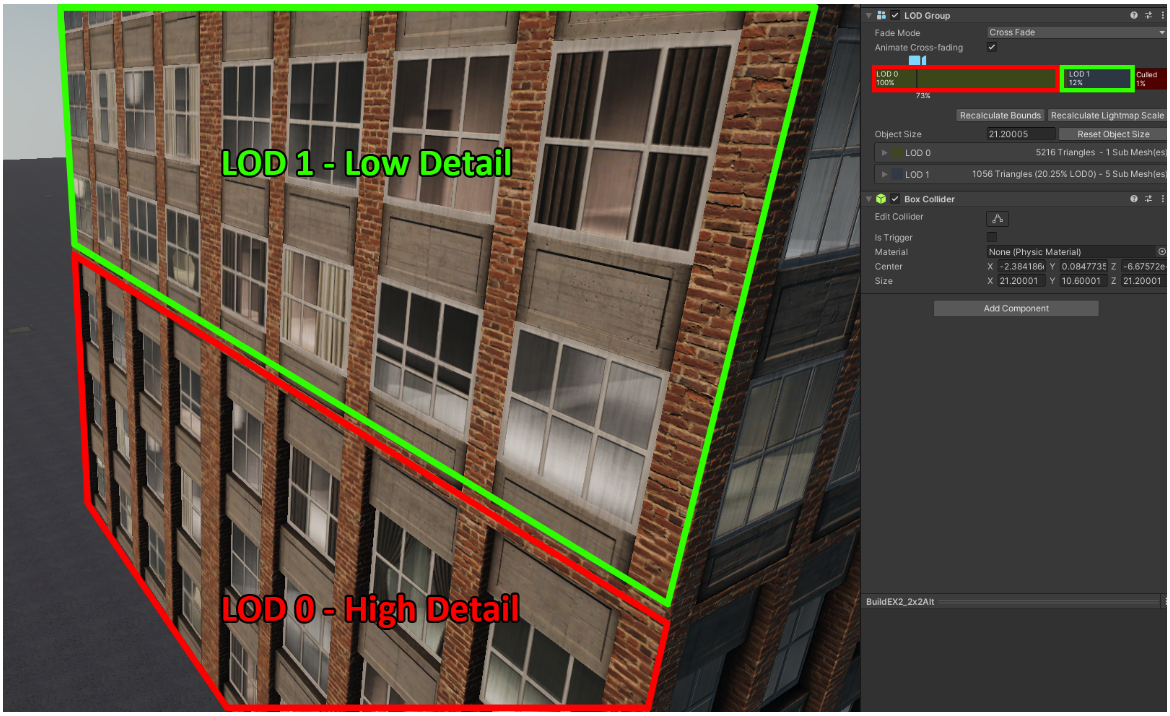

Figure 3.18: Visual representation of the different levels of detail or LOD for short that each model in the city has. The clearest indication of a visual difference is the lack of depth seen in LOD 1.

Chapter 4

Experiment

There will be two separate experiments: The real-world data collection which is set at the chosen location mentioned in section 3.2 to establish some benchmark data, and the VR tests which is set in a VE. The real-world data will be compared to the VR counterpart's results to check for similarities.

4.1 Real-World Data Collection (Benchmarks)

The data collection was not an experiment but a session of gathering information to use as a benchmark for the actual experiment. It took place in the real-world on the streets of Aalborg, Denmark. Specifically along Vesterbro and Borgergade (as mentioned in section 3.2), with the crossings being the main area of interest. This also meant that all participants would be subjected to the same condition when possible.
It was hypothesised that congested traffic, loud vehicles and crossings would cause stress as the background research points toward.

4.1.1 Participants

9 participants volunteered in the data collection (8 men and 1 woman) ranging from 21-30 years in age (*M: 27.77*, *SD: 3.23*). All participants came from the same education, and were offered an edible reward for participating.

4.1.2 Apparatus

Consent forms were given first to allow us to process the obtained data in the study. A demographics questionnaire was used to acquire an insight into the participants' lifestyle in terms of exercising. The Empatica E4 was used to record data from the participants, and a HTC U11 smartphone with the E4 Realtime app was used to stream the data to and then upload it to the Empatica Cloud upon completion. A printed out map of the route was also given to participants to follow if needed.

4.1.3 Procedure

Participants were asked to read and sign the consent form in order for the study to include their data, they would then answer a demographics questionnaire about their lifestyle

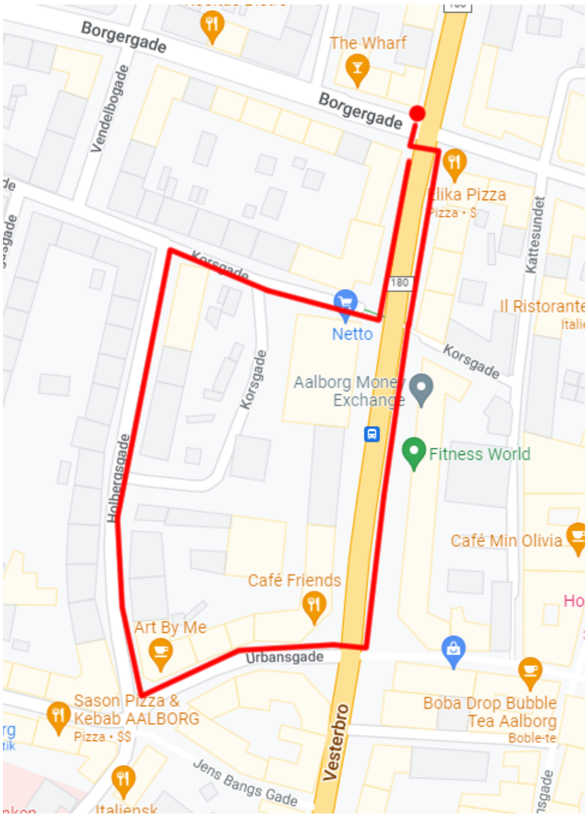

Figure 4.1: The route which participants took. The red circle marks the starting point.

in terms of exercise. They would be escorted to the starting location on Vesterbro, and instructed to equip the E4 and follow the route given as a printout 4.1.
Participants were told that they should walk at their normal pace and not rush to complete the route. The experimenters would start the data recording, and the participants would be further instructed to follow the map once the E4 had established a connection and calibrated, while the experimenters followed them a few meters behind in order to mark down if any particular traffic scenarios caused certain behaviours.
Each session walking the route took approximately 6-10 minutes depending on the participants' walking speed. The transportation from CREATE (Aalborg University building name), Aalborg, to the starting point of the route for both the participants and experimenters could take up to 10 minutes as well, depending on the traffic.

4.2 VR Test

The VR test was an experiment in which participants had to walk a simulated route of Aalborg, Denmark. Participants were tasked with walking the same route as section 4.1 and figure 4.1 illustrates. Two conditions will be tested: A hi-fi and a lo-fi version. The goal of the experiments was to achieve similarity in results between the data collection study (benchmarks) and the hi-fi version. The results will be evaluated based on the universally adopted p-value of 0.05 to determine statistically significance and has been used in previous similar research [Boletsis and Cedergren, 2019].

In terms of presence in VR we hypothesise that:

Presence $- H_1$: *There is a statistical significance between how the participants experienced presence in the two fidelities (hi-fi and lo-fi).*

Presence $- H_0$: *There is no statistical significance between how the participants experienced presence in the two fidelities (hi-fi and lo-fi).*

In terms of physiological data, we hypothesise that:

$EDA - H_1$: *There is a statistical significance between how the participants experienced stress in the two fidelities (hi-fi and lo-fi).*

$EDA - H_0$: *There is no statistical significance between how the participants experienced stress in the two fidelities (hi-fi and lo-fi).*

4.2.1 Design

The study used a between-subjects design. There was one independent variable: VR versions (hi-fi and lo-fi). The dependent variables were the participants Igroup Presense Questionnaire results (IPQ) [igroup, 2016] and E4 measurements.

4.2.2 Participants

There were 32 participants (26 men and 6 women) aging between 21-30 years *(M: 24.94, SD: 2.45)*. They were students or previous students of AAU with varying experience with VR, and were offered an edible reward for participation. The participants were also divided into two groups of 16, one group for the hi-fi version and one group for the lo-fi version. They were allocated between hi-fi version (group A) and lo-fi version (group B) with the following order: ABABAB.
The composition of each group was as follows:

- A: 14 men, 2 women, aging between 21-29 years (*M: 24.63, SD: 2.31*).
- B: 12 men, 4 women, aging between 21-30 years (*M: 25.25, SD: 2.62*).

4.2.3 Apparatus

Consent forms were printed out for participants to sign and allow the experimenters to use and process their data. The tools used consisted of a laptop containing three questionnaires: Demographics, Simulation Sickness Questionnaire (SSQ) [Kennedy et al., 1993], and the IPQ. An additional laptop for taking notes during the experiment, a desktop capable of running the simulation, an Oculus Quest 2 [Meta, 2022] to run the simulation on, a smartphone (HTC U11) to establish wireless connection between the Oculus and the desktop, and an additional smartphone (Samsung Galaxy s21 ultra 512gb.) for running the E4 Realtime app as well as the Empatica E4 itself was also used.

4.2.4 Procedure

Participants were greeted and asked to read and sign the consent form as the first thing. Afterwards they would answer the Demographics Questionnaire and SSQ prior to the experiment. They were then shown a map of the route they had to walk which they did not necessarily have to remember, since the purpose of the map was to create an overview.

The participants were then instructed on how to move around in VR, and were told to stand on the 'X' inside the VE which was their center point. They were also told that the simulation of cars had tendencies to cause car crashes, in which case they would not have to worry and the experimenters could reset the cars if needed.
Before putting on the Oculus, the participants were instructed to equip the E4 device on their non-dominant hand.
When the participant completed the tutorial of the simulation, the E4 device was turned on by the experimenters before proceeding with walking the actual route in the simulation. The participants were guided through the simulation and told which turns to take if they did not remember the route.
When the participant had completed the simulation they had to answer the SSQ again, and the IPQ. When they had completed the last steps they were thanked and rewarded with a snack as an additional thanks for participating.
Each session, including explanations, questionnaires and the simulation itself, would take between 15-20 minutes, but it was also dependent on the participants' walking speed in the simulation. The setup used for the entire procedure can be seen in figure 4.2.

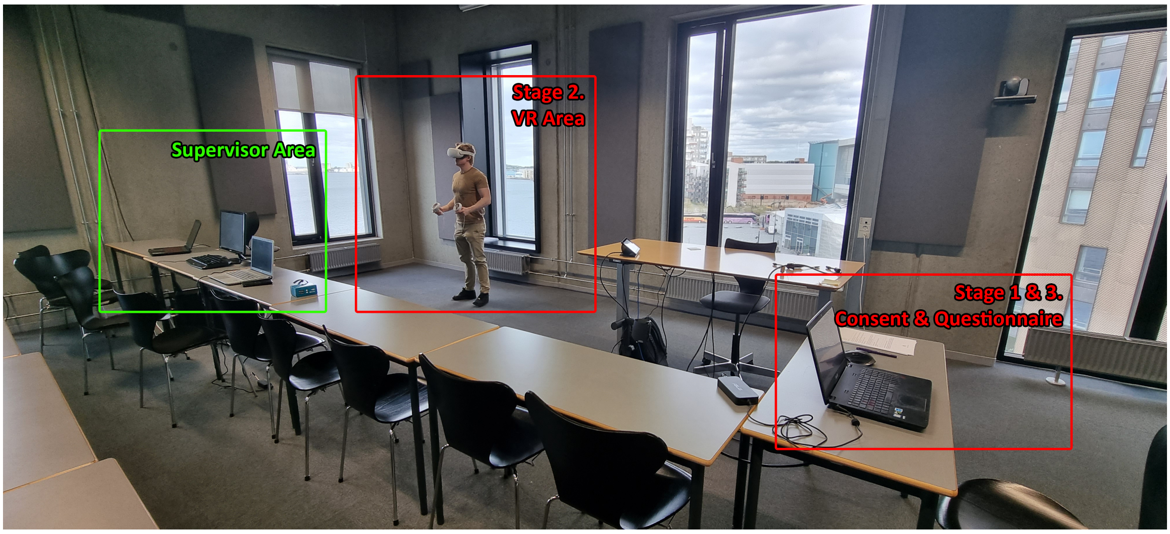

Figure 4.2: Experiment setup. Stage 1 and 3 is where the participants would get instruction as well as fill out questionnaires and consent forms. Stage 2 was the area where the test itself was conducted. Supervisor area included tasks such as overseeing the VE and taking notes.

Chapter 5

Results

This chapter showcases the results obtained from the real-word data collection (benchmarks) in terms of HR and EDA, as well as results from the VR tests, including answers from the IPQ. The benchmark results are not used as part of a statistical test but they are visually cross analyzed to the VR tests. The two VR versions are also visually cross analyzed with each other and IPQ data has been tested for statistical significance using a Mann-Whitney U test.

5.1 Calculation of Results

The EDA data from the Empatica E4 wristband were calculated using Ledapy [Filetti, 2018], a python extension that port over some functionality from Ledalab [Mathias Benedek, 2016]. From the raw data the phasic signal was extracted and filtered to reduce noise. To find the peaks of interest (the peaks that most likely stem from exposure to stimuli), we tried both height and distance as a way of thresholding what peaks should be included but with low success. We ended up using prominence to determine what a peak was and more specifically at a value of 0.0025. This is an arbitrary value chosen but was the one that filtered out the low peaks, that were most likely due to noise, for most participants. Prominence was chosen as other studies had proposed that prominence and amplitude were the most important qualities of a peak [Nath and Thapliyal, 2021]. The prominence mean of all peaks was calculated for each participant. The mean of all prominence means for all participants for both the data collection (benchmark) study and the final evaluation can be seen in table 5.1 and 5.4.
The HR data was likewise recorded with the Empatica E4 wristband, the values were loaded into Python. The HR data was read with NumPy and constrained to the first minute of the recording, and plotted with matplotlib, where the mean for each participant was calculated. These means were then combined to create an overall mean for the benchmark data collection and each VR condition: Lo-fi and hi-fi. The mean of means for both the data collection (benchmark) study and the final evaluation can be seen in table 5.1 and 5.4.

5.2 Real-World Data Collection (Benchmark) Results

The benchmark results contain the physiological data from the real-world data collection (benchmark) study, where EDA and HR are examined.

The HR data gave an average of 82.337 bpm during the first minute of the walk.
The average of the most prominent EDA peaks, during the first minute was 0.094. Results are displayed in figure 5.1.

Benchmark Version

Data Type	*Mean*	*Standard Deviation*	*Median*
HR	82.337	11.367	81.576
EDA prominence	0.094	0.145	0.033

Table 5.1: E4 data displaying mean of means, median and standard deviation of heart rate and EDA during the first minute of the walk.

5.3 VR Test Results

The VR Test section contains the same type of data as the Real-World Data Collection (Benchmark) section i.e. EDA and HR, but additionally also contains results from the IPQ. The results are analysed and compared to each other (hi-, and lo-fi version) to check for statistical significance.

5.3.1 IPQ Results

We start the analysis of the results by first looking at how the participants experienced the hi-, and lo-fi prototypes based on the IPQ, as it will be important to first establish whether or not the prototypes actually differed in the graphical realism department as per the purpose of this report's research question.
The IPQ is a questionnaire that aims to answer people's feeling of presence inside a virtual environment. The questionnaire consists of 14 questions that has been divided into three independent subscales that was discovered through a principal component analysis and also a fourth subscale which shall be known as the General Presence as it has a high loading from all 3 subscales [igroup, 2016].

- Spatial Presence - the sense of being physically present in the VE
- Involvement - measuring the attention devoted to the VE and the involvement experienced
- Experienced Realism - measuring the subjective experience of realism in the VE

The 7-point likert-scale values have been converted from 1-7 to 0-6 for analysis purposes, and thus the maximum possible score for one prototype in the radar chart is 96 if all participants scored 6 in each question. At first inspection of the chart it is apparent that the lo-fi prototype scored a noticeable amount lower in both the involvement and realism subscales, whereas there is very little difference in terms of spatial presence between the groups.

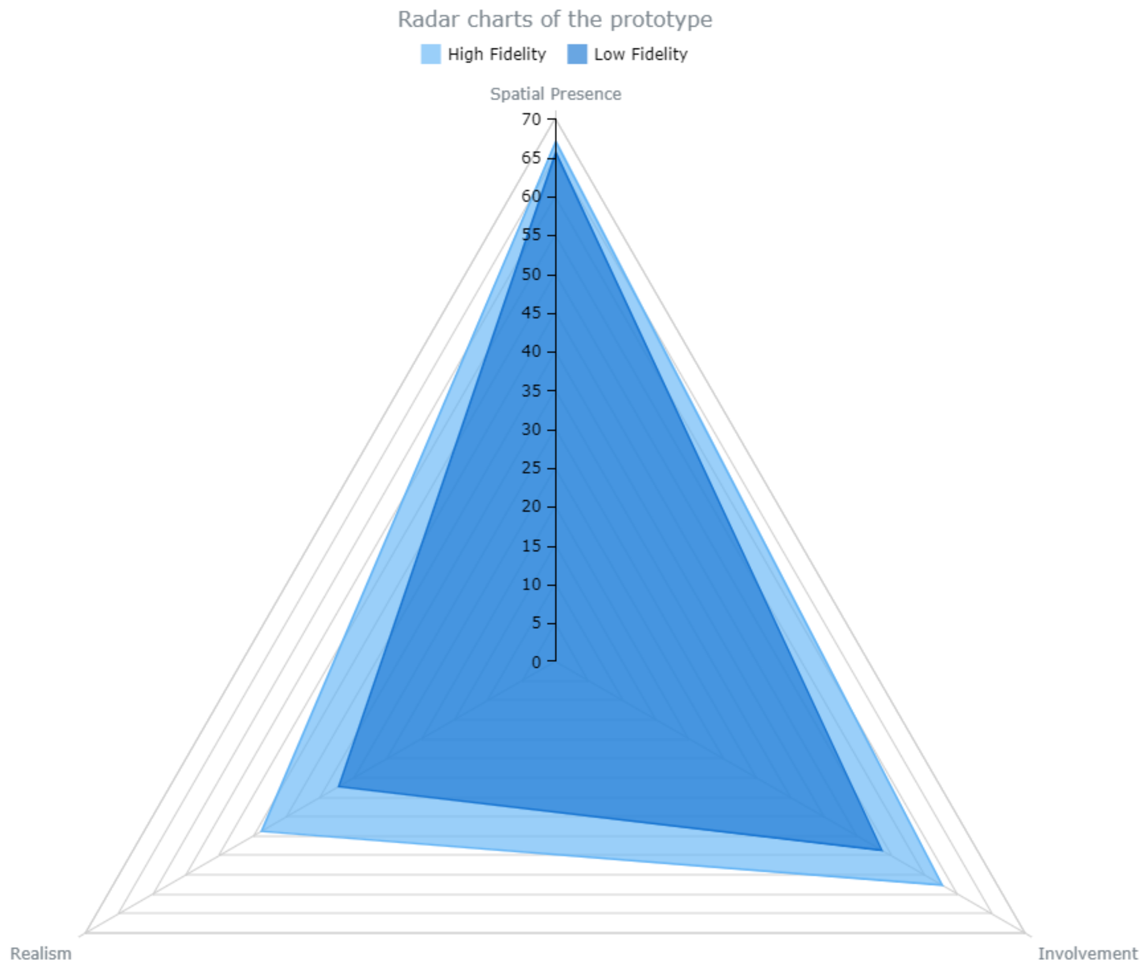

Figure 5.1: Radar chart of the scores for the different subscales. Where the light blue represents the hi-fi version and the dark blue represents the lo-fi version. Spatial presence, involvement and realism values for the hi-fi version were 67(96), 57.67(96) and 43.75(96). And the values for lo-fi were 65.6(96), 48.67(96) and 32.25(96). Where the number in the parenthesis constitutes the possible maximum score.

5.3.2 Statistical Tests

As the data gathered from the Likert-scale questionnaire is ordinal data, a Mann Whitney U test was conducted to test for significant differences between the hi-, and lo-fi prototypes. As can be seen in table 5.3 the p-values for the Involvement and Realism subscale are below the 0.05 acceptance threshold, which means that the test rejects our null hypothesis $Presence - H_0$ of the two subscales.

5.4 Empatica Data

The results from the two fidelity versions from the final evaluation. The Empatica Data contains the data types: EDA and HR, where the average HR was 81.318 for the hi-fi version and 88.361 for the lo-fi version. The average of the most prominent EDA peaks were 0.078 for the hi-fi version and 0.075 for the lo-fi version. All of these results were measured within the first minute of the simulation.

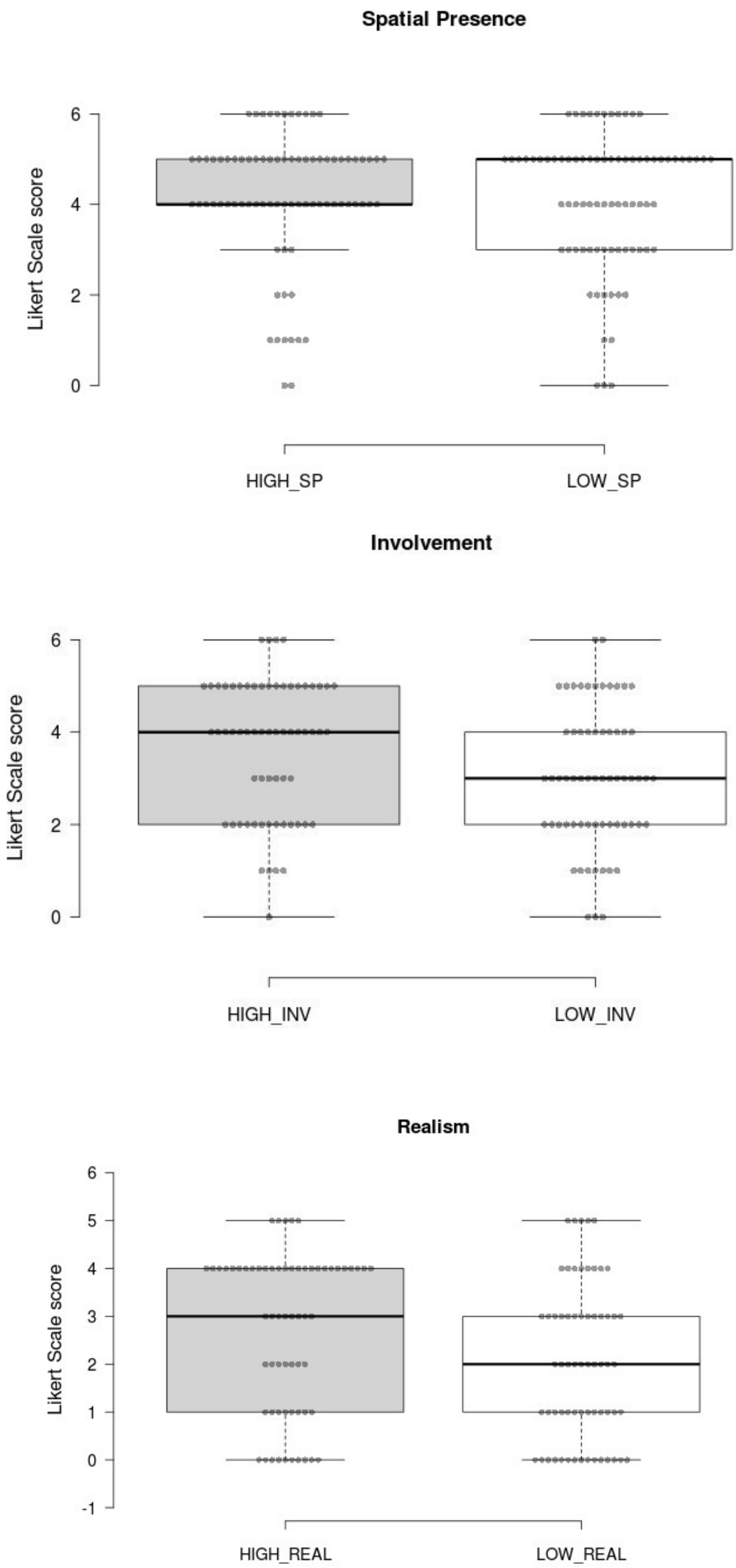

Figure 5.2: Boxplot of the three different subscales from the IPQ.

High Fidelity Version

Subscale	*Mean*	*Standard Deviation*	*Median*
Spatial Presence	4.19 (6)	1.2923	4 (6)
Involvement	3.67 (6)	0.9816	4 (6)
Realism	2.73 (6)	0.9504	3 (6)

Low Fidelity Version

Subscale	*Mean*	*Standard Deviation*	*Median*
Spatial Presence	4.1 (6)	1.1732	5 (6)
Involvement	3 (6)	1.0497	3 (6)
Realism	2.01 (6)	0.9054	2 (6)

Table 5.2: Subscales scores from the SSQ for each condition, showing mean, standard deviation and median.

Mann-Whitney U test

Subscale	*0-Hypothesis*	*P-value*	*Effect size*
General Presence	Accepted	0.952	small (0.011)
Spatial Presence	Accepted	0.7236	small (0.028)
Involvement	Rejected	0.01283	small (0.22)
Realism	Rejected	0.01106	small (0.22)

Table 5.3: Results of the Mann-Whitney U test to determine if the $Presence - H_0$ had to be rejected or retained. The $Presence - H_0$ is rejected for the Involvement and Realism subscale and retained for General Presence and Spatial Presence.

5.5 Simulation Sickness Questionnaire

It was important for us to test whether simulation sickness was present, after the participants had experienced the two prototypes, as an increase in the symptoms of simulation sickness (i.e. sweating) would artificially increase the EDA results. From the results of the SSQ in the table below we can derive that there was an increase in the experienced simulation sickness in both versions with a noticeable difference in the "nausea" subcategory. A Mann-Whitney U Test was conducted between the subcategories (Nausea, Oculomotor, Disorientation). For both versions the Mann-Whitney U test found a significant difference in the nauseous symptoms experienced with a p-value = 0.04564, 0.002433 for the high and low fidelity versions respectively.

High Fidelity Version

Data Type	*Mean*	*Standard Deviation*	*Median*
HR (HF)	81.318	12.312	76.771
EDA prominence (HF)	0.078	0.131	0.026

Low Fidelity Version

Data Type	*Mean*	*Standard Deviation*	*Median*
HR (LF)	88.361	15.293	87.432
EDA prominence (LF)	0.075	0.087	0.024

Table 5.4: E4 data displaying mean, median and standard deviation of heart rate and EDA during the first minute walk. The table shows data from both the hi-fi version and the lo-fi version, as well as the benchmarks.

Low Fidelity SSQ	**Lo-Fi Before**	**Lo-Fi After**
Nausea	30 (0-336)	49 (0-336)
Oculomotor	22 (0-336)	25 (0-336)
Disorientation	19 (0-336)	20(0-336)

High Fidelity SSQ	**Hi-Fi Before**	**Hi-Fi After**
Nausea	36 (0-336)	55 (0-336)
Oculomotor	26 (0-336)	33 (0-336)
Disorientation	21 (0-336)	30 (0-336)

Table 5.5: The table shows the difference in perceived nausea, oculomotor and disorientation form before and after the VR experience for the Low and High Fidelity versions. Numbers marked within parenthesis is the minimum score if all 16 participants in the group had answered "None", and maximum score if they had answered "Severe".

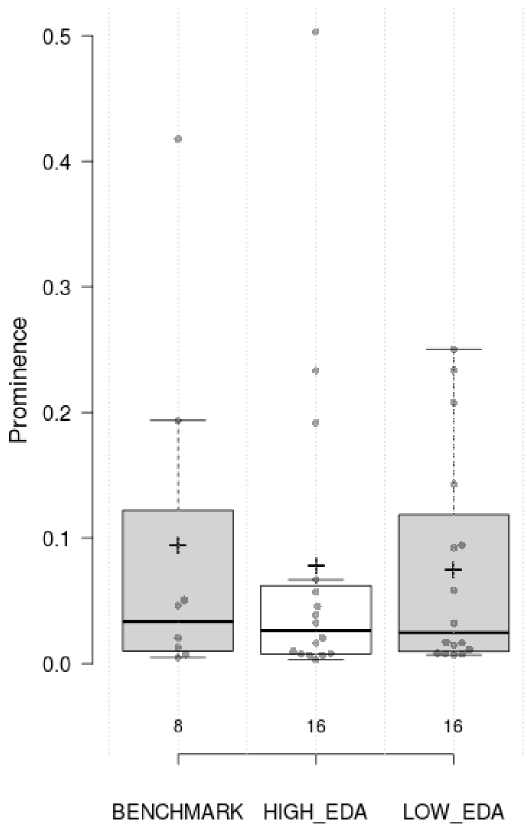

Figure 5.3: Box plot of the prominences from the real life- and virtual experiment. The pluses on the box plots indicate the mean of the group.

Chapter 6

Discussion

Discussion topics of the report includes: Discussion of results, limitations to the hardware used for the evaluation as well as imperfections and confounding variables in the setup and procedure. Future iterations of the experiment as well as future work on the prototype is also discussed to illustrate new areas of interest where the practices of this report could be applicable.

6.1 Questionnaires

Previous research stated that it was possible to recreate a level of stress in a VE similar to a real-life experience. Knowing this, we created two versions of a VE; hi-fi and lo-fi, where only the graphics changed; polygon count, texture resolution and normal maps etc., to assess to what degree stress was affected by graphical fidelity.
According to the IPQ, which was purely a comparison between hi-fi and lo-fi, the hi-fi version scored higher in all three categories; realism, involvement and spatial presence. The test indicated that there was a significant difference in how people experienced and perceived involvement and realism with a small effect size (0.22 effect size), which indicated that while there probably was a graphical difference, the magnitude of the graphical change was lower than what we aimed for. Participants did not experience a significant difference in their perception of spatial presence, which could suggest that this subscale measured the virtual reality hardware that had been used, as the questions are quite hardware related (i.e. "I felt like I was just perceiving pictures"). Since all of the participants used an Oculus Quest 2 HMD which of course had the same hardware specifications; resolution, refresh rate etc. it made sense that this subscale showed no significant difference. Overall we feel there is evidence to suggest that our $Presence - H_1$ hypothesis is retained and our $Presence - H_0$ hypothesis is rejected as the results of the two subscales: involvement and particularly realism, was deemed significantly higher in the hi-fi version.

6.2 Empatica Data

Data from the E4 showed that the average heart rate for the data collection (benchmarks), as well as the hi-, and lo-fi versions were similar. However, the lo-fi version managed to obtain a higher average than its counterpart version and the benchmarks. There could be many reasons for this, and it can be seen that the participants in the lo-fi group might just be in worse physical condition and thus with the prototype requiring them to swing their arms constantly for a few minutes, would amplify their heart rate slightly. Another likely possibility would be that the lo-fi version looked too much like a video game with the more vibrant colours, simplistic graphical elements. This was supported when participants stated that they felt like it was a game and wanted to "complete it" faster. If we look at figure 6.1 it is evident that the 25-75% quartiles showcasing the average walking speed of their completion time, that the lo-fi group is slightly higher, which supports the theory that participants felt like it was more of a game they had to complete and thus caused the higher heart rate to occur. It is also a possibility that the E4 device simply misread some of the signals if the device became loose from the wrist due to the movements of participants during the experiment (see section 2.3.1).

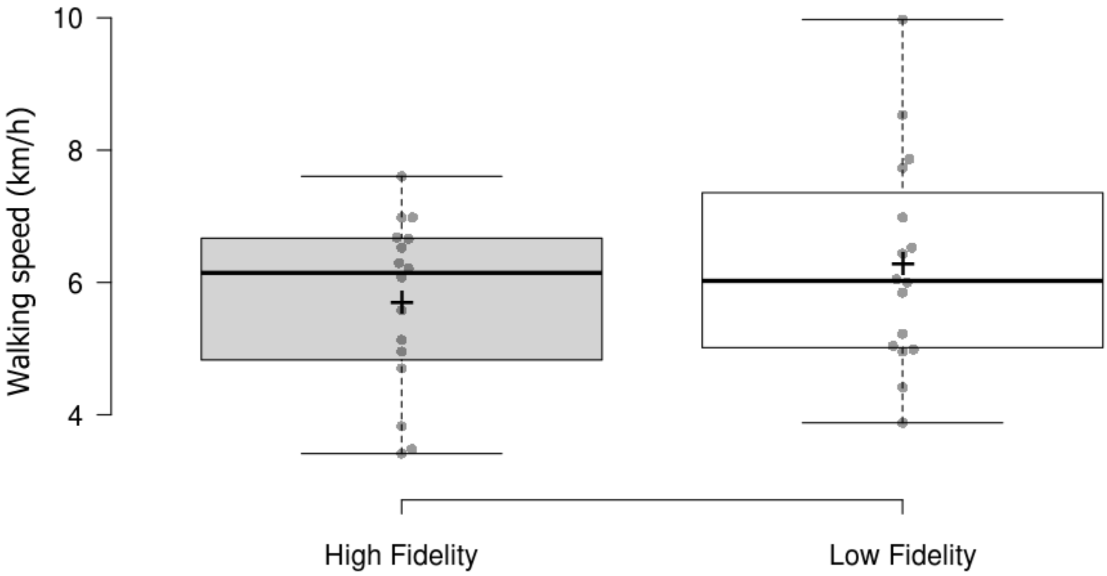

Figure 6.1: Box plot showing the virtual walking speed in km/h of the participants within the two prototypes. The speed is calculated through the use of the completion time and the virtual distance covered. The pluses on the box plots indicate the mean of each group.

When it came to the EDA data, we looked at the filtered phasic data (see section 5.1) to see when and where participants exhibit physiological responses to the stimuli of the prototype. When looking at figure 5.3 it is evident that the 25-75% quartile of the lo-fi and the benchmarks are quite similar whereas the hi-fi's data points are quite concentrated, but all three groups share similar medians of 0.033, 0.026 and 0.024 for the benchmark, hi-fi and lo-fi respectively.
From visual inspection of the graphs it was evident that within each experimental group there were similar EDA graph behaviours that emerged or repeated, however during a cross group comparison it becomes more difficult to establish similar behaviour between them. Within the benchmark EDA graphs there was a predominant feature of three peaks that emerged. There were some graphs in the lo-fi group that showed a similar behaviour. Vaguely similar patterns with three peaks could be found in the hi-fi data, but they differ even more in terms of behaviour. (see figure 6.2). However, these comparisons should be taken with a grain of salt as it is difficult to analyze/compare the graphs as the virtual and real-world tests differed in traffic density and when there was red/green light, thus leading to participants being exposed to different sets of stimuli within the first minute that these graphs represents. All graphs depicting peaks and prominence can be seen in

Appendix B.

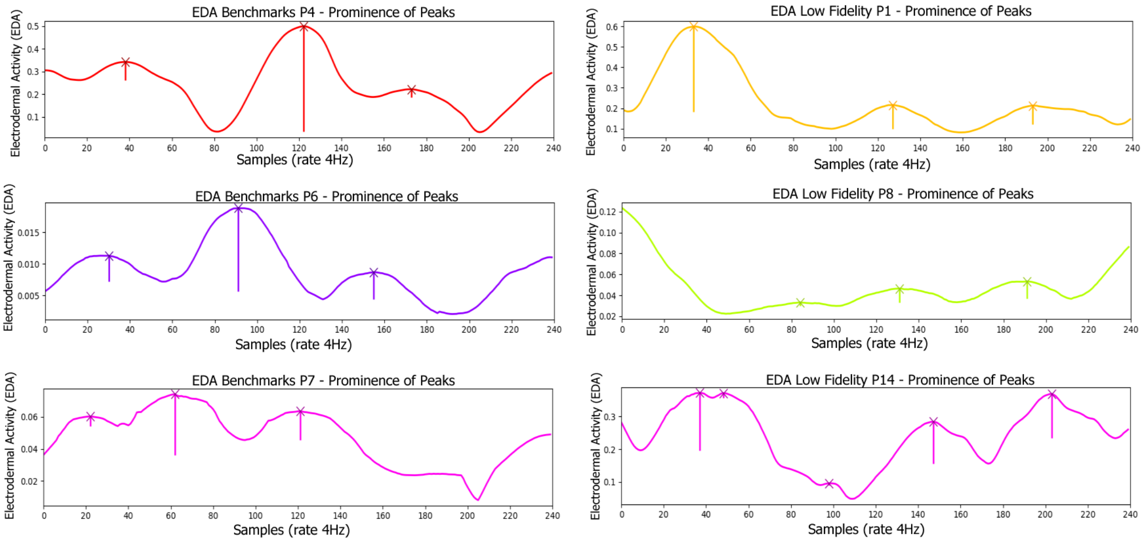

Figure 6.2: Left: Filtered phasic EDA data from the real life walk with similar behaviour. Right: Filtered phasic EDA data from the Low Fidelity Version with similar behaviour

It can see seen that the results are similar when it comes to the medians and data point groupings amongst the three groups, which suggests that it is possible to recreate similar stress levels in VR. However, our $EDA - H_0$ and $EDA - H_1$ hypotheses must remain inconclusive as confounding variables has had too much of an impact on the experiment.

6.3 Hardware Limitations

Although the Oculus Quest 2 had its uses during development, it sometimes became an issue when performing stress tests of the system. Sometimes the Oculus would heat up to the point where it was unusable from minutes up to hours which halted development time.
Using the air link, the Oculus was coupled with a desktop during the VR tests, but sometimes the connection appeared unstable. The connection ran through a smartphone's hotspot on 4G+, which resulted in the audio in the simulation cutting out a few times and stuttering in the image occurring. This could have impacted the tests during final evaluation, and created a distraction from the desired experience, resulting in mixed answers for the IPQ.

The Oculus had its limitations, not only regarding the heat issue, but also its ability to run built versions of the prototypes. Following the Oculus Quest 2 developer documentation [Facebook Technologies, LLC., 2022a] and building directly, as an android build, onto the Oculus caused the framerate to drop to 1-2 frames per second, which led to building it for PC instead.

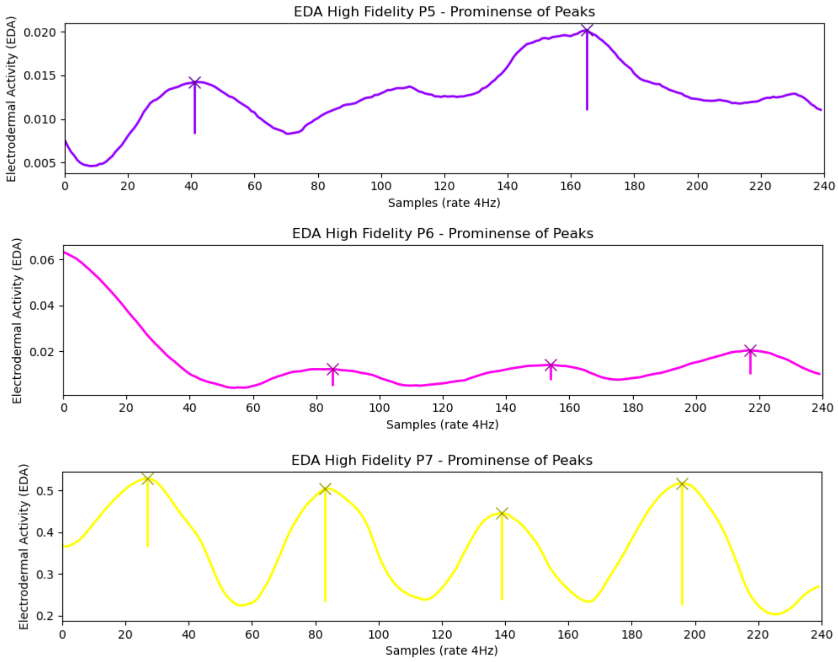

Figure 6.3: Filtered phasic EDA data from the High Fidelity Version with similar behaviour

6.4 Future Experiments

During our experiment we always had the same starting location in VR. This could accidentally have led to slightly skewed results in the beginning as the novelty of the VE was likely still present prior to the participants encountering the crosswalks in focus. Therefore it would have been interesting to see if different starting locations had an effect on the experience for the participants.
As discussed above in section 6.1 the graphical realism gap between the two prototype was seen by the participants as being small, in the future it would be interesting to explore a bigger graphical gap in the prototypes by creating smaller polygon count buildings and vehicles. Perhaps even looking into reducing the fidelity of the sound as well and exploring the effects of this.
Another key takeaway from this project is for possible future experiments to ensure that proper logging of data is done when people are doing certain elements within the prototype, i.e. crossing a road, entering traffic dense areas etc. One of the shortcomings of this experiment was that it was difficult to cross-analyze different EDA data as our measures in logging the participants actions fell short of what was required.

6.5 Implementation

In section 3.1.1 we described how the prototypes were implemented to simulate realistic car behaviour and that staying true to the real-life counterpart was an important design decision. One of these designs were the speed at which the cars travelled across the map, however the final version of the prototype had to be limited to only 20 km/h. As the traffic would otherwise cause accidents. This was due to the traffic system being developed and optimized separate from the map (as stated in section 3.2) and therefore did not adhere to the spatial limitations of the map when later having to turn or stop.

Vesterbro in Aalborg has multiple lanes when driving from south to north and we wanted to implement this into the prototype. This was a decisions made late in the pipeline which meant altering the collider based detection system (mentioned in section 3.4.1) a significant amount. This was then deemed to be a nice-to-have solution rather than a need-to-have solution seeing as the participants would always be on the sidewalks and never really interact with the middle lane of cars. A few participants however did mention that they lived either on or near Vesterbro which could affect there perception of the realistic nature of the chosen area, as it did not resemble what they knew from the real world one to one.

A big part of the simulated world were the inclusion of pedestrians. A lot of research went into learning more about pedestrian behaviour (see section 2.1) and how to use other pedestrians to perhaps manipulate the participants into certain behaviours of their own. A fully functional node based AI pedestrian system was also implemented but due to fps issue it was left out of the simulation all together. In the real-world benchmark test it was observed just how much other pedestrians impact and obtrude the participants actions and behaviour, so it serves as a large confounding variable for the comparison between VR and the benchmarks.
All research and mentions of pedestrians is kept in this report as AI pedestrians serves as the first priority of future work. were there to be implemented further on the project.

When it comes to the implementation of the arm swing method, it did serve its function of being used as a method for locomotion inside a VE, however, it became apparent from observing the experiment that some of the users eventually resorted to arm swinging motions that were less natural in terms of a standard human gait, by swinging their arms in front of them. This happened as a result of an oversight in the testing of the implementation, which allowed this to be as or more effective at moving the participant virtually through the scene than the intended arm swinging motion. The implementation itself and the testing of it should have better conformed to the implementation of the arm swinging method, made by Keio Univerisity [Pai and Kunze, 2017] and followed a similar gait pattern to one introduced in their paper. This deviation could have had impact on the participants perceived realism of the test and perhaps further supported some of their beliefs of it being a "game" they had to complete.

Chapter 7

Conclusion

The report set out to test whether graphical realism would have an impact on users stress levels in a virtual urban environment.
We developed two prototypes that incorporated graphical elements that according to our research had a significant impact on graphical realism. To facilitate high level of presence amongst the participants we implemented an arm swinging locomotion method that allowed the user to navigate endlessly, by never encountering real-world boundaries.

According to our analysis of the results, we conclude that we were able to develop a system with above average presence for the user, with a significant difference in the perceived realism and involvement between the two fidelity versions. Similar stress levels were present in the benchmark data collection group and between the low- and high fidelity versions, however we can not conclude on any definitive cause and effect between our prototypes and the stress levels due to confounding variables.

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Appendix A

Project Source Code

Version control was done using Plastic SCM and is therefore unable to be shared openly without invite. However a .zip file containing the entire project with source code and assets have been uploaded to Google Drive at the following link and will also be uploaded alongside the report: https://bit.ly/3yNuxsR

Appendix B

Graphs of Filtered Phasic EDA Signal with Peaks and Prominence

Data Collection (Benchmarks)

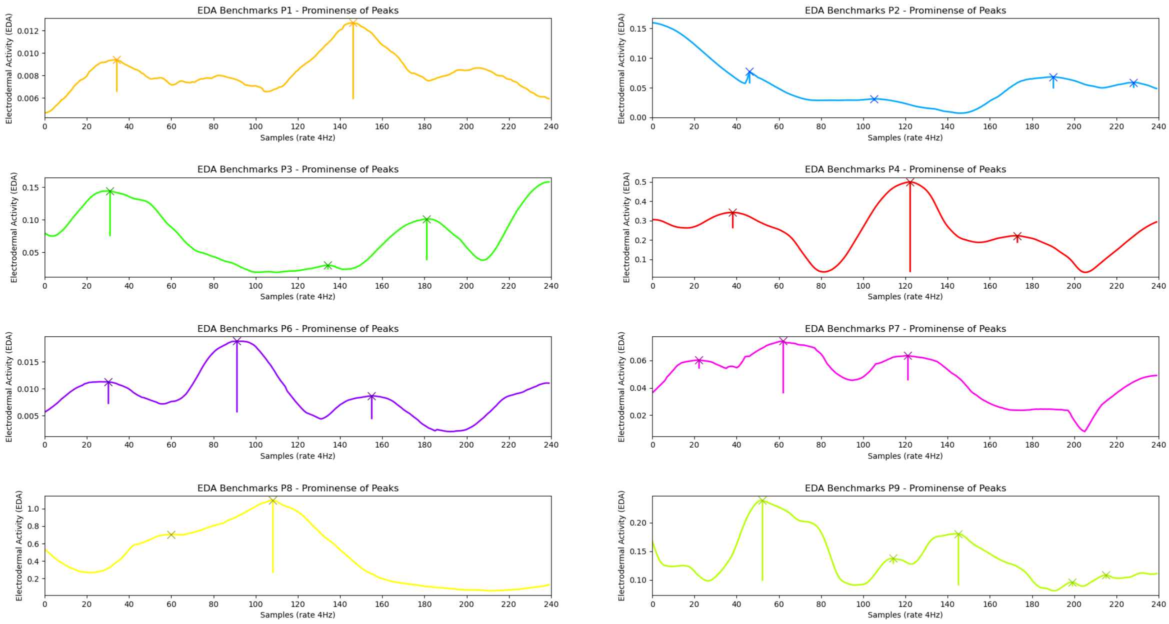

Figure B.1: The peaks and prominences for all participants except P5 for the benchmarks gathered in the real-world data collection. The peaks are found on a filtered version of the phasic EDA data.

Low Fidelity Version

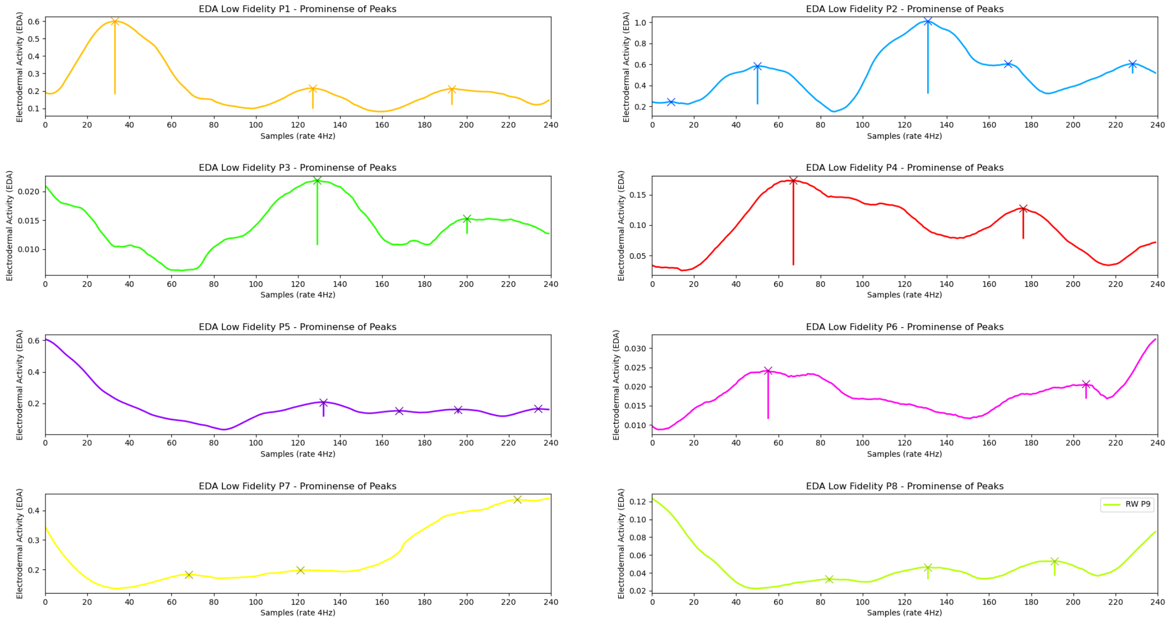

Figure B.2: The peaks and prominences for the first half of participants for the low fidelity version, gathered in the final virtual reality evaluation. The peaks are found on a filtered version of the phasic EDA data.

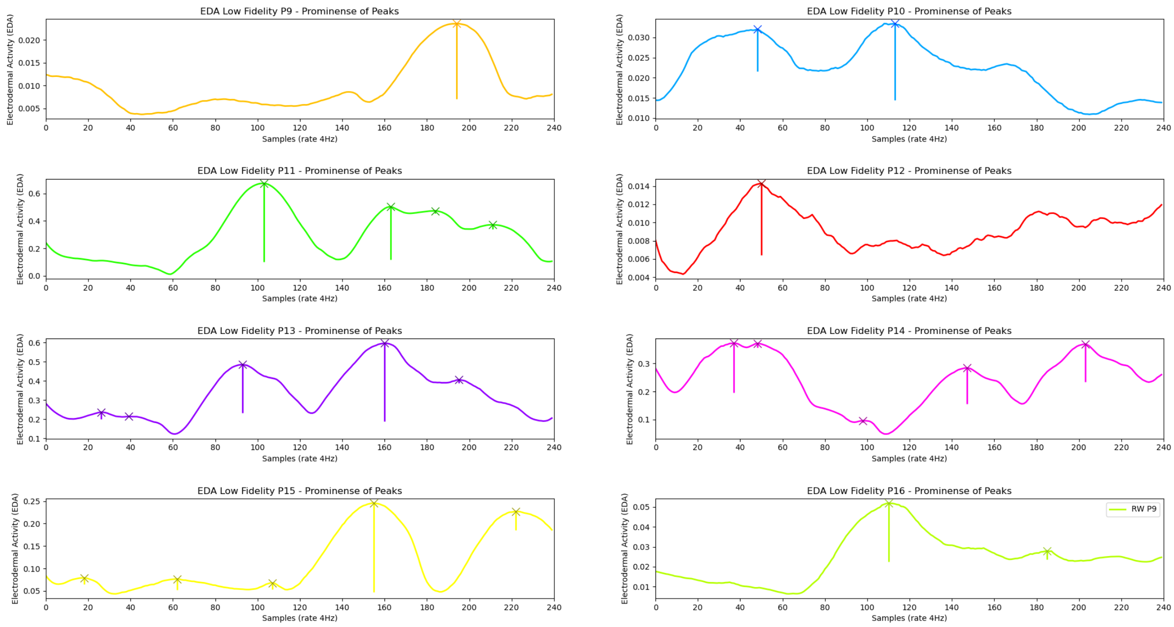

Figure B.3: The peaks and prominences for the second half of participants for the low fidelity version, gathered in the final virtual reality evaluation. The peaks are found on a filtered version of the phasic EDA data.

High Fidelity Version

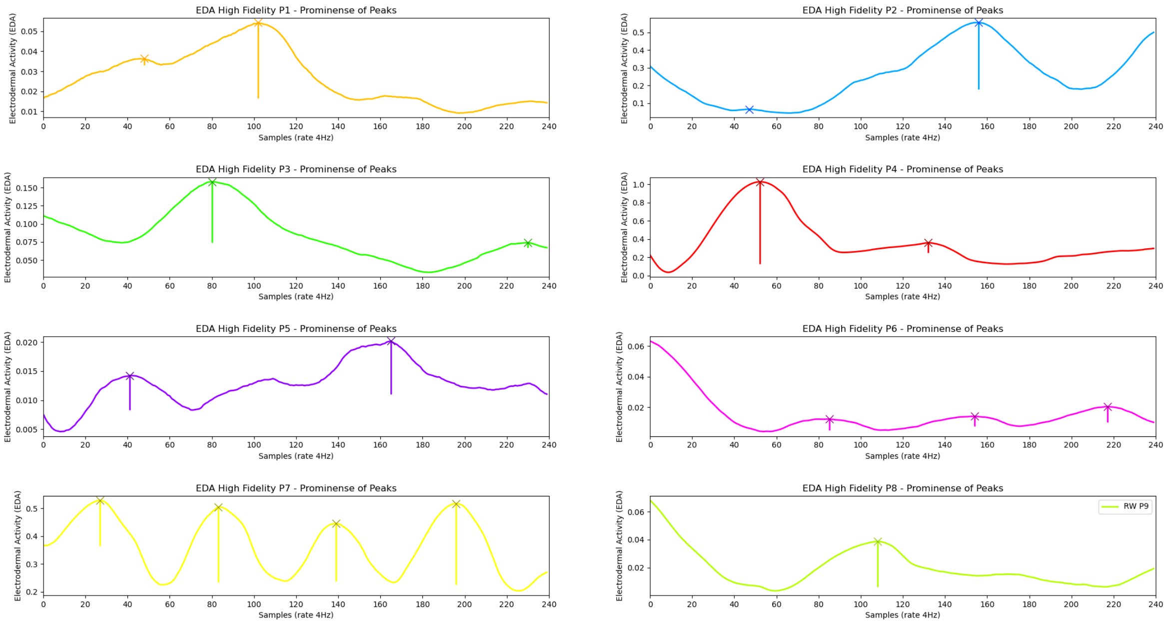

Figure B.4: The peaks and prominences for the first half of participants for the high fidelity version, gathered in the final virtual reality evaluation. The peaks are found on a filtered version of the phasic EDA data.

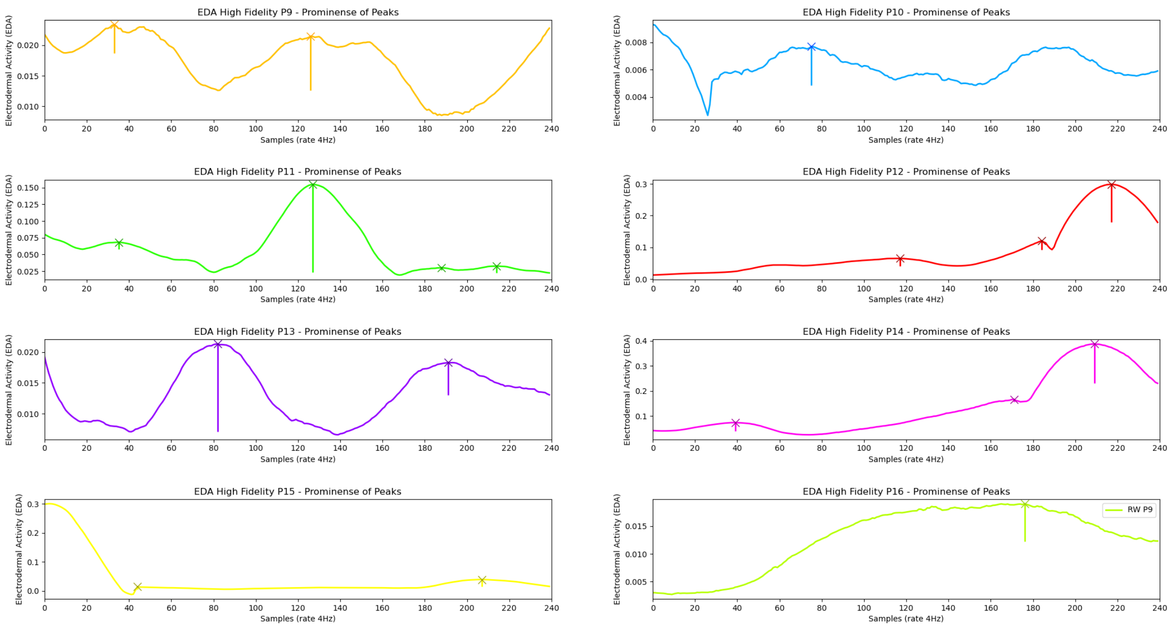

Figure B.5: The peaks and prominences for the second half of participants for the high fidelity version, gathered in the final virtual reality evaluation. The peaks are found on a filtered version of the phasic EDA data.