



# **Procedural City Generator for Research in the Field of Restorative Environmental Design**

Hörður Már Hafsteinsson

Thesis of 60 ECTS credits  
**Master of Science (M.Sc.) in Computer Science**

June 2019





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by

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Thesis of 60 ECTS credits submitted to the Department of Computer Science  
at Reykjavík University in partial fulfillment  
of the requirements for the degree of  
**Master of Science (M.Sc.) in Computer Science**

June 2019

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## **Abstract**

Imagine a future where the urban city environment has been designed and planned to sustain its inhabitants on a psychological level and thus promoting their health and well being. The emerging data-driven methodology of Restorative Environmental Design (RED) has been proposed as a promising answer to bringing in the social and psychological factors that may have been neglected in the planning of compact urban areas in the past. A restorative environment is an environment that helps us renew the physical, psychological and social resources that diminish in meeting everyday demands. If we are unable to restore those lost resources over a prolonged period of time, there can be negative consequences to our health and well being. RED attempts to measure how different environments affect people using controlled studies, where participants are exposed to environmental stimuli. In the past, the stimuli in these studies has mainly consisted of static images and computer generated 3D worlds on a display. However, with recent innovations in virtual reality (VR) these studies can now immerse participants to a much greater degree than previously possible. This raises the need for a specialized tool for creating a variety of urban city environments, compatible with VR presentation, as well as a method for collecting survey data on restoration from study participants. The Cities that Sustain Us research project, dedicated to advancing RED through the use of VR, started developing such tools, but early versions relied too heavily on manual construction. This thesis presents a new application where a new procedural approach automates the construction of large VR-ready cities, where a number of attributes can be controlled, as simple as editing a few layout bitmaps. Data gathering locations can be added to these cities, where study participants interact with restoration data surveys using a VR interface. The application also includes an interactive tutorial environment where participants are instructed on how to move through the cities and interact with the survey interface. Even if these VR environments are both large and complex, they perform very well, and user testing results indicate that reliable restoration data can be gathered from study participants.

# Borgarsmiðjun fyrir rannsóknir á sálfræðilegri endurheimt í hönnun umhverfa.

Hörður Már Hafsteinsson

June 2019

## Útdráttur

Ímyndum okkar framtíð þar sem borgarumhverfi hefur verið hannað með það að leiðarljósi að styðja sjálfbærni íbúa þess útfrá sálfræðilegu sjónarmiði og styðja þar með aukna vellíðan og heilsu. Gagnadrifin aðferðarfræði "Restorative Environmental Design"(RED) hefur verið lögð fram sem svar við þessum félagslegu og sálfræðilegu þáttum sem ekki hefur verið tekið nægilegt tillit til í skipulagi og hönnun borgarumhverfa fram að þessu. Umhverfi sem styður sálfræðilega endurheimt hjálpar okkur að endurnýja líkamlega, sálræna og félagslega hæfni sem getur tapast í amstri dagsins. Ef við getum ekki endurnýjað þessa hæfni okkar til lengri tíma þá geta afleiðingarnar verið neikvæðar fyrir heilsu okkar og vellíðan. RED reynir að mæla hvernig áhrif mismunandi umhverfis hefur á okkur með kerfisbundinni rannsókn, þar sem þátttakendur upplifa mismunandi umhverfislegt áreiti. Þetta áreiti hefur á árum áður yfirleitt verið í formi ljósmynda og þrívíddarheima á skjám. Vegna örrar þróunar á sýndarveruleikatekni (VR) þá geta þátttakendur nú upplifað þessi umhverfi á mun djúpstæðari máta en var áður mögulegt. Þetta kallar eftir tækni sem gerir rannsakendum kleift að hanna margskonar borgarumhverfi sem er sérsníðið fyrir upplifun í sýndarveruleika, ásamt því að geta safnað gögnum frá þátttakendum um sálfræðilega endurheimt inni í umhverfunum. Í verkefninu "Cities That Sustain Us", sem er tileinkað frekari þróun RED með sýndarveruleikatekni, hefur slík tækni verið þróuð, en smíði umhverfa í eldri útgáfum þeirrar tækni hefur krafist mikillar handavinnu. Í þessari ritgerð er settur fram hugbúnaður þar sem hönnun þessara borgarumhverfa hefur verið sjálfvirknisvædd. Þessi borgarumhverfi eru hönnuð sérstaklega fyrir sýndarveruleika, og þessi tækni býður auk þess upp á þann möguleika að geta stjórnað ákveðnum eiginleikum borganna. Einnig er hægt er að velja ákveðnar staðsetningar inni í þessum sýndarborgarumhverfum þar sem gögnum er safnað frá þátttakendum í gegnum sýndarveruleikaviðmót. Loks inniheldur hugbúnaðurinn líka Þjálfunarumhverfi þar sem þátttakendum er kennt að ferðast gegnum umhverfin og að nota sýndarveruleikaviðmótið. Jafnvel þó þessi borgarumhverfi séu bæði stór og flókin að gerð, þá er samt hægt að birta þau í gagnvirkum sýndarveruleika án nokkurra vandkvæða. Niðurstöður notendaprófana sýna jafnframt fram á að með þessu nýja verkfæri sé mögulegt að safna áreiðanlegum gögnum um sálfræðilega endurheimt.

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# Contents

<b>Acknowledgements</b>	<b>xi</b>
<b>Contents</b>	<b>xiii</b>
<b>List of Figures</b>	<b>xv</b>
<b>List of Tables</b>	<b>xix</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Vision . . . . .	1
1.2 Cities That Sustain Us . . . . .	1
1.3 Problem Statement . . . . .	2
1.4 Contribution of this Thesis . . . . .	2
1.5 Structure of Thesis . . . . .	2
<b>2 Related Work</b>	<b>3</b>
2.1 Software Solutions . . . . .	3
2.1.1 Data Gathering . . . . .	3
2.1.2 City Generation . . . . .	4
2.2 VR Architecture / Interfaces . . . . .	9
2.3 Cities that Sustain Us . . . . .	10
<b>3 Approach</b>	<b>13</b>
3.1 Architecture . . . . .	13
3.2 Challenges . . . . .	14
3.2.1 Performance . . . . .	14
3.2.2 Tutorial Environment . . . . .	15
3.2.3 Procedural Generator . . . . .	15
3.2.4 Data Gathering . . . . .	15
3.3 User Testing . . . . .	15
<b>4 Implementation</b>	<b>17</b>
4.1 Resources . . . . .	17
4.1.1 Unity3D . . . . .	17
4.1.2 Blender . . . . .	18
4.2 Survey Interface . . . . .	18
4.2.1 Questionnaire . . . . .	20
4.2.2 Teleport Markers . . . . .	20
4.2.3 Tutorial Environment . . . . .	21
4.3 Procedural City . . . . .	22

4.3.1	The City Generator . . . . .	22
4.3.1.1	Layers . . . . .	24
4.3.1.2	Tiles . . . . .	26
4.3.1.3	Textures . . . . .	30
<b>5</b>	<b>Results and Evaluation</b>	<b>33</b>
5.1	Resulting System . . . . .	33
5.2	User Testing with Study Participants . . . . .	34
5.2.1	The Question . . . . .	34
5.2.2	Method . . . . .	34
5.2.2.1	Participants . . . . .	34
5.2.2.2	Environment/Task . . . . .	35
5.2.2.3	Measurements . . . . .	35
5.2.2.4	Procedure . . . . .	36
5.2.3	Results . . . . .	37
5.2.3.1	Restoration Data . . . . .	37
5.2.3.2	Interface Difficulty . . . . .	37
5.2.3.3	Simulator Sickness . . . . .	38
5.2.3.4	Association Towards VR . . . . .	39
5.2.4	Discussion . . . . .	39
5.3	Summary . . . . .	40
<b>6</b>	<b>Conclusion and Future Work</b>	<b>41</b>
6.1	Summary of Contributions . . . . .	41
6.2	Future Work . . . . .	42
6.3	Conclusions . . . . .	43
	<b>Bibliography</b>	<b>45</b>
<b>A</b>	<b>Credits</b>	<b>47</b>
A.1	Textures . . . . .	47
A.2	Sounds . . . . .	47
A.3	Models . . . . .	47
<b>B</b>	<b>Participant Questions</b>	<b>49</b>
<b>C</b>	<b>Restoration Data</b>	<b>53</b>
<b>D</b>	<b>Participant Statements</b>	<b>55</b>
<b>E</b>	<b>Participant Comments</b>	<b>57</b>

# List of Figures

2.1	An example of a new environment created from a previously existing environment using layers. (source: [7]) . . . . .	4
2.2	An example of a generated environment using the tool presented by Lipp et al. (source: [7]) . . . . .	5
2.3	An example of a main road being generated from specified points with the CityGen tool. (source: [8]) . . . . .	5
2.4	An example of different secondary roads that can be generated by the tweaking of parameter with the CityGen tool. (source: [8]) . . . . .	6
2.5	An example of a procedural city generated with the CityGen tool. (source: [8])	6
2.6	CityEngine. An example of the creation of roads from street lines, and the subsequent creation of lots enclosed within the roads. (source: [9]) . . . . .	6
2.7	An example of an environment created with the CityEngine tool. (source: [9]) .	7
2.8	Example of view frustum filling as presented by Greuter et al. (source: [10]) . .	7
2.9	Grid based procedural city as presented by Greuter et al. (source: [10]) . . . . .	8
2.10	Procedural building generation as presented by Greuter et al. Shows how polygons are merged to create more complex shapes, these shapes can then be extruded downwards. This process can then be repeated to create complex and diverse buildings. (source: [10]) . . . . .	8
2.11	An example of a finished building using the tool presented by Greuter et al. (source: [10]) . . . . .	8
2.12	First view perspective when viewing a procedural city generated with the tool presented by Greuter et al. (source: [10]) . . . . .	9
2.13	A first person perspective of a part of the environment created in the third study of Páll Jakob Línðal dissertation [15]. . . . .	10
2.14	A first person perspective form a part of the environment created with VRPsychLab 1.0. (source: [14].) . . . . .	11
2.15	An early version of the city builder interface from VRPsychLab 1.0. (source: [14].	12
3.1	Overview of the application. . . . .	13
4.1	The survey interface presented to study participants in the application. This shows the survey interface with the slider, e.g. this is a question slide. The survey interface is also sometimes referred to as a podium. . . . .	19
4.2	Study participant interacting with the button (left) and the slider (right) on the podium. The button and the slider highlight a yellow color when the controller is in range, indicating that they can be interacted with. . . . .	19
4.3	The HTC Vive hand held controller. The right image shows the yellow outline that surrounds the TRIGGER button. . . . .	20

4.4	Example of an instruction and a questionnaire created with the Questionnaire asset. Left is an instruction slide, right is a question slide. . . . .	21
4.5	The teleport markers. Left is a marker that does not contain any slides at the new location, the right marker does contains one or more slides. . . . .	21
4.6	The teleport marker, with an outline, making it stand out a bit more from the background. . . . .	21
4.7	The tutorial environment, where study participants were guided through different tasks in order to learn how to interact in the environment. . . . .	22
4.8	In the left image are the red balls the study participant is asked to touch in the environment and the virtual space for them to move around in is shown with the white cube. In the right image you can see the corresponding physical space, the physical space closely matches the virtual space except for being a bit larger. The physical space has been cleared for any obstacles as can be seen. . . . .	23
4.9	An overview of the Procedural City Generator. The main inputs into the generator are the layers and tiles. Rules within the generator handle the correct placement of tiles in regards to the layers to such that the resulting city environment is correct. . . . .	23
4.10	Procedural city environments created with the application. . . . .	23
4.11	Example of Main Layer. White pixels are roads, blue pixels are houses and green pixels are parks. . . . .	24
4.12	Example of Decoration Layer. Red pixels are low decoration, blue pixels are medium decoration and orange pixels are high decoration. Green pixels are high decoration parks, where as grey pixels would be low decoration parks however there are none in this layer. . . . .	25
4.13	Example of Roof Layer. Blue pixels are roofs with 4 turns, pink pixels are roofs with 5 turns, green pixels are roofs with 9 turns and orange pixels are roofs with 11 turns. . . . .	25
4.14	Example of Floor Layer. Blue pixels define buildings with 1 floors, red pixels define 2 floors, orange pixels define 3 floors and purple pixels define 4 floors. . . . .	26
4.15	Example of Color Layer. . . . .	26
4.16	Example of Flower Bed Layer. . . . .	26
4.17	These are the road tiles that are used to create the streets in the city environment. First one from left is a straight road tile, the second one is an outer road tile and the last one is an inner road tile. . . . .	27
4.18	Constraints satisfied for an inner road tile. Building above the tile and a park to the right of it. . . . .	27
4.19	Constraints satisfied for the outer road tile. Building tile in the tile above and to the left, as well as a road tile in the tile above and the tile to the left. . . . .	28
4.20	Constraints satisfied for the placement of a straight road tile, as seen in the middle straight road tile. It has a road tile to the left as well as a road tile to the right. It's curb also faces the house, instead of the park. . . . .	28
4.21	Left image is a top down view of the right image. As can be seen in the left image there is a road tile above the park tile, and thus the fence is instantiated at the top side of the park. There is not a road tile to the left or to the right of the park tile and as such the fence contains an opening as can be seen in the right image. . . . .	29
4.22	These are the park tiles. Left is the high restorative one, and the right is the low restorative one. . . . .	29

4.23	A dirtbed tile that can be placed in front of buildings left. A dirtbed in front of a building on the right. . . . .	29
4.24	The front side of the house on the building tile faces to the right instead of above. That is because the right check is sooner in the rule sequence. . . . .	30
4.25	These are the texture assets used for the buildings. The first one is the texture for the walls, second is the texture for the roofs and the third one is the texture for the stairs. These can easily be replaced, or add more to a pool to create even more variations in the generated environments. . . . .	30
4.26	These are the textures used for the doors and the windows in every environment created. As with the building textures, these can also be replaced or more can be added to a pool to create even more variations. . . . .	31
5.1	An overview of a city generated with the application. . . . .	34
5.2	First person perspective of two very different environments generated with the procedural generator, and the participant is presented with the survey interface. . . . .	34
5.3	The blackhole room at Reykjavik University. . . . .	35
5.4	Restoration survey points 1, 2 and 3 (from left to right) . . . . .	36
5.5	Restoration survey points 4, 5 and 6 (from left to right). . . . .	36
5.6	The User Testing procedure. . . . .	37



# List of Tables

4.1	Events that the podium logs. . . . .	20
5.1	Results from Simulator Sickness Questionnaire. Higher number mean increased measured simulator sickness. The highest possible score that can be achieved in the SSQ questionnaire is 235. . . . .	38
5.2	Results from the Associations Towards Virtual Reality questionnaire. These results are averages of participant answers for each word. . . . .	39
C.1	Results from the restoration likelihood questions. Higher numbers mean the potential for restoration is higher. . . . .	53
D.1	Results from statements related to the participants experience to the virtual survey interface and teleportation. Answers are numbered from 1 - 5, where 1 is Very Confusing and 5 is Not at all Confusing. . . . .	55
D.2	Results from statements related to the participants general experience to the virtual reality experience. Answers are numbered from 1 - 5, where 1 is Completely Disagree and 5 is Completely Agree. . . . .	55





# Chapter 1

## Introduction

### 1.1 Vision

Imagine a future where the urban city environment has been designed and planned to sustain its inhabitants on a psychological level and thus promoting their health and well being. But, so far, it has been difficult to incorporate psychological factors into the planning stages of city development, for lack of a solid methodology.

The emerging data-driven methodology of Restorative Environmental Design (RED) has been proposed as a promising answer to bringing in the social and psychological factors that may have been neglected in the planning of compact urban areas in the past [1].

Restoration is a term widely used in psychology and relates directly to our health and well being. It refers to the renewal of our physical, psychological and/or social resources and capabilities that can become diminished, or even depleted, in meeting day to day demands, and as such a restorative environment is an environment that enables and promotes the restoration of those lost resources [2]. If we are unable to restore those lost resources over a prolonged period of time, there can be negative consequences to our health and well being [3].

In previous research it has been shown that certain physical attributes of buildings can affect the restorative possibilities of urban city environments, such as the number of floors, ornamentation and roof silhouette [4]. Results therefore indicate that restoration can be promoted in urban city environments if properly designed and planned [4].

RED attempts to use data on the restorative qualities of various designs to design environments that maximize the potential for psychological restoration and thus well-being and health. This data driven approach is key to sustaining quality human life in urban cities.

### 1.2 Cities That Sustain Us

Cities that Sustain Us (CiSuUs) is a research project at Reykjavik University, Iceland. The focus of CiSuUs has been on urban environments and how they affect people. The CiSuUs research project is a continuation of the dissertation of Páll Jakob Línal which involved a number of studies on the restorative potential of urban environments that were created using 3D graphics and displayed in an interactive environment.

How different environments affect people can be measured in controlled studies, where participants are exposed to environmental stimuli. So far, the stimuli in these studies has consisted of static images and computer generated 3D worlds on a display. With the recent innovations in virtual reality (VR) technology the studies can now incorporate environments

with a much greater sense of presence and immersion than previously possible. This raises the need for a specialized tool for creating a variety of urban city environments, compatible with VR presentation, as well as a method for collecting survey data on restoration from study participants.

### 1.3 Problem Statement

Research into the design on the restorative possibilities of different urban environments requires us to be able to easily create different environments for testing. *Is it possible to create an application that can be used to quickly generate endless variations of urban city environments and present them to study participants in VR?* A tool like that would have to support the placement of buildings, parks, roads and vegetation by designers, as well as other attributes related to the buildings, such as their height, ornamentation, roof silhouette and color. The application must also be able to collect survey data from participants about the restorative possibilities of the environment while they navigate it. Finally, the performance characteristics and usability of the application, should not interfere adversely with the quality of the collected restoration data.

### 1.4 Contribution of this Thesis

The contribution of this thesis work is an application that can be used to carry out studies in the field of restorative environmental design. The application includes a procedural city generator. This procedural city generator is capable of creating large urban city environments with the click of a button. These cities can then be explored in virtual reality through virtual reality hardware, such as the HTC VIVE. The complete layout of a city can be designed as a template for a city environment. Through this layout the location of houses, roads and parks can be decided. A number of more detailed variables can also be controlled in the creation of the city, such as the color of each building, its ornamentation as well as the roof silhouette and the height of each building among others. The application also includes a VR survey interface through which data can be collected from study participants about the restorative potential of the environments they are experiencing. Lastly, a VR tutorial environment was created to teach study participants how to navigate the virtual environment and how to interact with the virtual survey interface. The application was tested on study participants to ensure that there were no major issues that could possibly ruin the data collection.

### 1.5 Structure of Thesis

The structure of this thesis will be as follows, in chapter 2 we will begin by exploring existing software solutions that can be used to gather data from users, such as with questionnaires, as well as look at existing solutions for creating procedurally generated environments, as well as the work this application is based on. In chapter 3 we will discuss the requirements and challenges faced in the design of the application presented in this thesis work. In chapter 4 we will look at the implementation in detail. In chapter 5 we will evaluate the resulting application as well as discuss user testing. In chapter 6 we will conclude this thesis with a summary of the contribution in this thesis work as well as discuss future work.

# Chapter 2

## Related Work

In this chapter we will discuss existing technologies and software used in data gathering and procedural city generation. We will also look at some principles of virtual reality interface designs. The chapter will conclude with discussion on previous work that has been done in the field of restorative environmental design.

### 2.1 Software Solutions

#### 2.1.1 Data Gathering

Multiple solutions exist today that allow people to easily create surveys that are used to gather data from users. Most of these are online solutions, where people can create surveys and send to participants via an email.

SurveyMonkey [5] is a cloud based online solution that offers people the ability to easily create surveys. This solution offers people the ability to design professionally looking surveys with ease. These surveys can contain multiple questions and can be sent via a web link to participants to their emails. There are a number of additional items that they can provide for a fee, such as data analysis.

LimeSurvey [6] is another very popular survey tool. Very similar to SurveyMonkey, LimeSurvey allows it's users to easily create and customize their created surveys in many ways through it's web based interface. These surveys can then be shared via a web link that can be sent to participants very similarly to SurveyMonkey. Unlike SurveyMonkey, LimeSurvey is open source which gives users the ability to easily setup and host their surveys on their own server.

These are just two of the available survey tools that are available today. What these survey tools usually have in common is the easy and quick creation of a survey that can then be sent to participants through email for example in the form a URL link that links to the survey. These survey solutions can differ in some aspects such as they can be used for free, in which case there can be some limitations to it's usage. These limitation can for example be a hard limit on the number of participant responses you can receive from a single survey.

In the application developed in this thesis work study participants travel through a virtual environment in VR and while traveling through this environment they are asked questions about their surrounding virtual environment. In this case it was required that the they can be

able to answer these questions while inside the VR environments. There are two main reasons for this, if a participant is required to exit the VR at each place he is required to answer a question, e.g. through a web interface, it would immensely affect his/her immersion and presence within the VR environment. Additionally the participants are required to answer questions about their surrounding virtual environment at multiple specific points and therefore it is not an option to let participants finish going through the whole virtual environment and then asking them to answer all the questions after exiting the VR. The reason for that, is that the questions are in essence relating to their personal preference at particular points within the VR environment, and if the participants are unable to answer these questions at those particular points, their answers would not be as accurate as they might otherwise be.

For these reasons a special method for creating a survey and gather data needed to be developed within the virtual reality. This will be further described in Chapter 3 and Chapter 4.

### 2.1.2 City Generation

A number of tools that allow people to generate complex city environments exist, however the use for which these tools have been developed differs greatly. For example there are a number of video games that allow it's users to create complex and visually stunning cities, and then there can be other tools that are more suited for real life scenarios for visualization or perhaps simulation, in the context of city planning to name one.

Lipp et al. created a tool that allows the manipulation and somewhat the generation of new valid procedurally generated urban city neighborhoods from an existing generated environment [7]. They employ a similar idea of a layered generated environment as is done in the application presented in this thesis work. Their tool supports the generation of new urban city layouts by editing previously existing layouts through the use of specific operators, such as deletion, merging and affine transformations like rotation, scaling and translation. Their tool allows users to perform these operators on an existing layout from which a new valid layout will be generated.

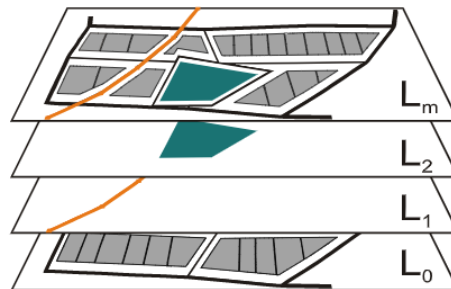


Figure 2.1: An example of a new environment created from a previously existing environment using layers. (source: [7])

In Figure 2.1 we can see a new urban city image layout marked as  $L_m$  that has been created from a previously existing urban city layout,  $L_0$ , by adding two layers on top of it, i.e.  $L_1$  and  $L_2$ . These middle layers between the previously existing urban layout and the generated new urban layout serve the purpose of adding a new road into the layout as well as a park. In Figure 2.2 we can see an example of a generated environment using the tool

proposed by [7].

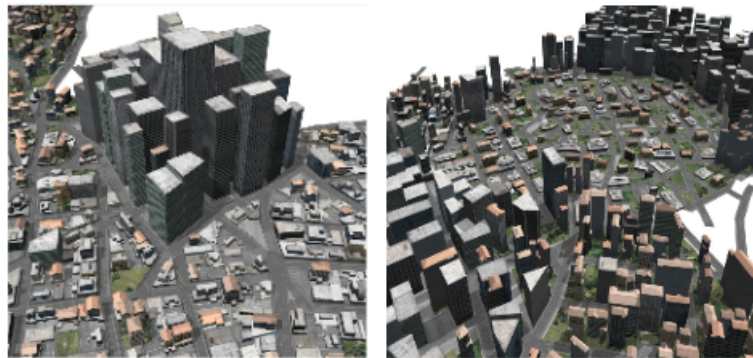


Figure 2.2: An example of a generated environment using the tool presented by Lipp et al. (source: [7])

CityGen [8] is an interactive system that allows users to create procedurally generated cities. Users are able to specify points for which a main road should be laid out in the environment, a secondary road is then generated within that main road. The secondary road can be tweaked by adjusting certain parameters through a user interface.

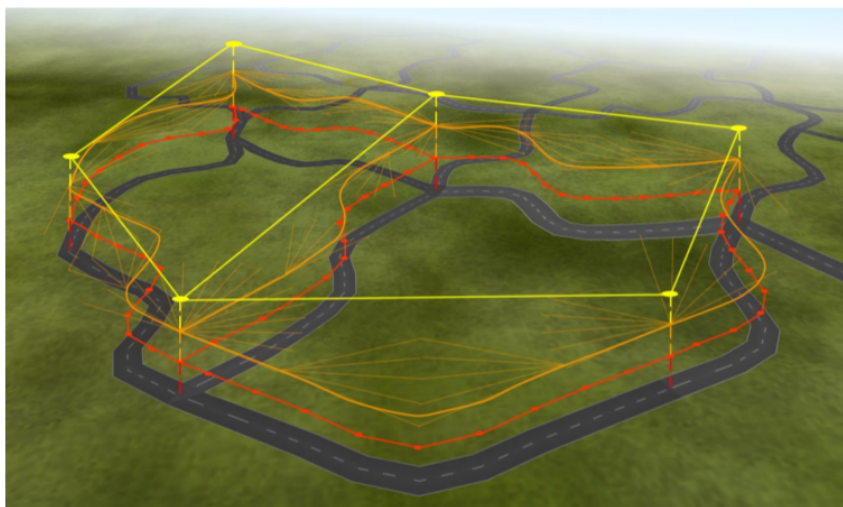


Figure 2.3: An example of a main road being generated from specified points with the CityGen tool. (source: [8])

Figure 2.3 shows the generation of main roads, and then within these main roads, secondary roads are procedurally generated from parameters that can be tweaked.

As can be seen in Figure 2.4 secondary roads are generated within the enclosed main roads. After the secondary roads have been generated the spaces that are enclosed within are subdivided to create smaller areas referred to as lots. An example of the generated lots can also be seen in Figure 2.4. These lots are areas on which you can place buildings, buildings are only placed on lots that are next to a road, whereas lots that are not next to a road are transformed into green areas. In Figure 2.5 we can see a city that has been generated with the CityGen tool.

CityEngine [9] is a tool that allows the creation of large environments through a number of input data, such as statistical and geographical data. As with the CityGen tool, which was

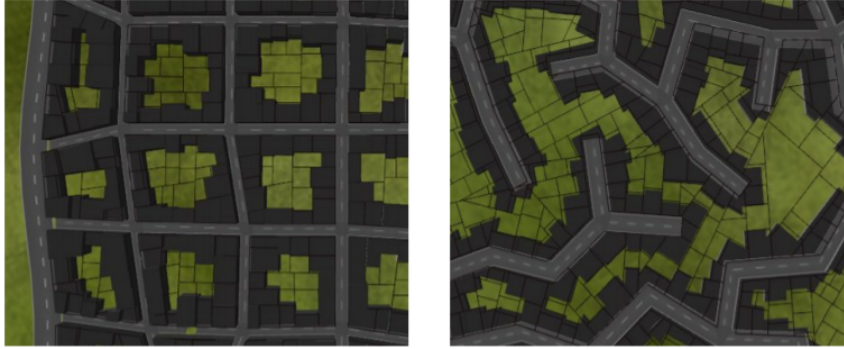


Figure 2.4: An example of different secondary roads that can be generated by the tweaking of parameter with the CityGen tool. (source: [8])

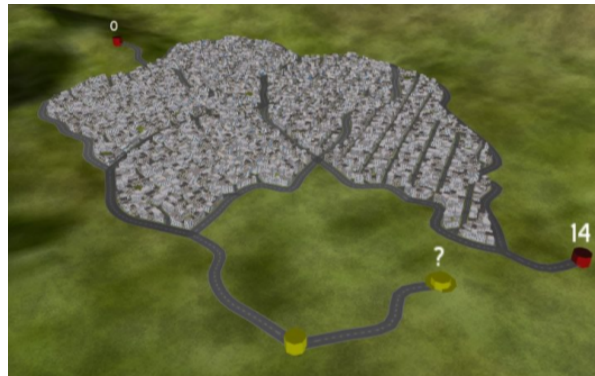


Figure 2.5: An example of a procedural city generated with the CityGen tool. (source: [8])

very much influenced by the CityEngine tool, roads are generated first. In the CityEngine tool, roads are generated from string grammars and image maps, where string grammars are the underlying rule system and commands for creating the road network. In Figure 2.6 an abstract view of the environment road creation pipeline can be viewed, i.e. it starts by the creation of road lines (left most image), following next is the creation of roads and the spaces enclosed by the roads (middle image). Lastly these spaces are subdivided into smaller lots, for which houses can be placed upon (right most image). These houses can then be textured automatically by the system to give additional detail to the environment.

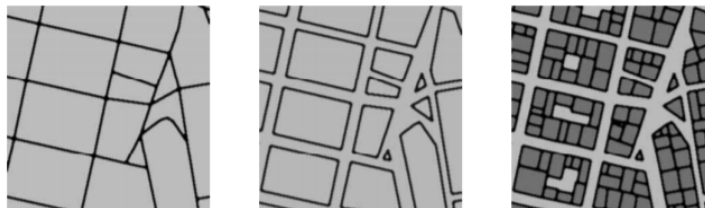


Figure 2.6: CityEngine. An example of the creation of roads from street lines, and the subsequent creation of lots enclosed within the roads. (source: [9])

In Figure 2.7 we can see an example of an environment that is created with the CityEngine tool. Today CityEngine is a widely used commercial tool for the generation of urban city environments. It is owned and developed by ESRI R&D Center Zurich (formerly Procedural Inc.)





Figure 2.7: An example of an environment created with the CityEngine tool. (source: [9])

Greuter et al. presented an approach to generate pseudo infinite procedurally generated cities [10]. In this proposed approach a procedural city is generated on the fly this has some limitations to performance pre-processing that can otherwise be done when dealing with static geometry. In this approach the authors propose view frustum filling, i.e. to only draw geometry that should be visible to the user at each place in the environment. In Figure 2.8 it can be seen how view frustum filling only draws geometry visible to the user, i.e. if the user is placed at the bottom of the image in the middle, looking upwards.

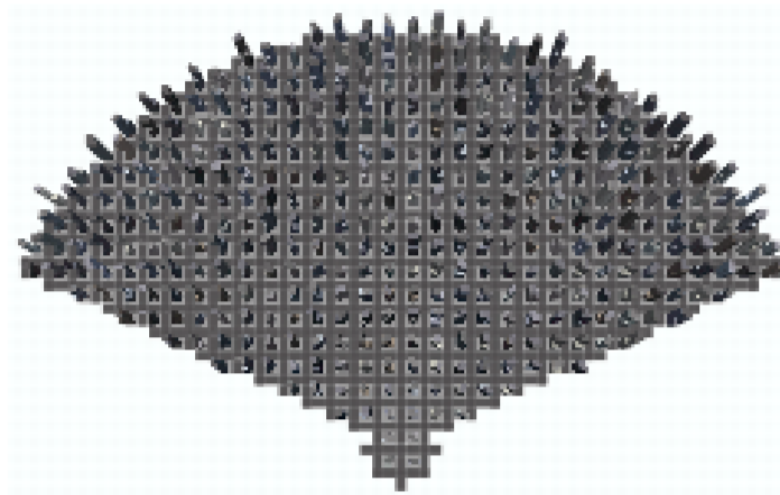


Figure 2.8: Example of view frustum filling as presented by Greuter et al. (source: [10])

The environment created is a grid based environment, where the grid is divided into small lots where buildings can be placed. Each lot is assigned a random number, which is fed into an algorithm that generates procedural buildings. In Figure 2.9 an example image can be seen where the grid has been divided into lots and random numbers assigned to each lot.

Figure 2.10 shows an example of the creation of a building. Buildings start as a primitive 2D polygon, another primitive polygon can then be merged into the original primitive

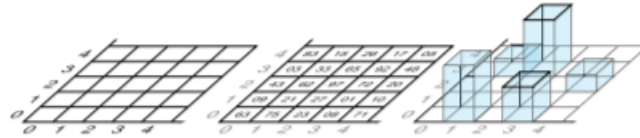


Figure 2.9: Grid based procedural city as presented by Greuter et al. (source: [10])

polygon to create a more complex shape. In the merge process a vertex is randomly selected from the original polygon which serves as a center point for the other new primitive polygon that will be merged with the original.

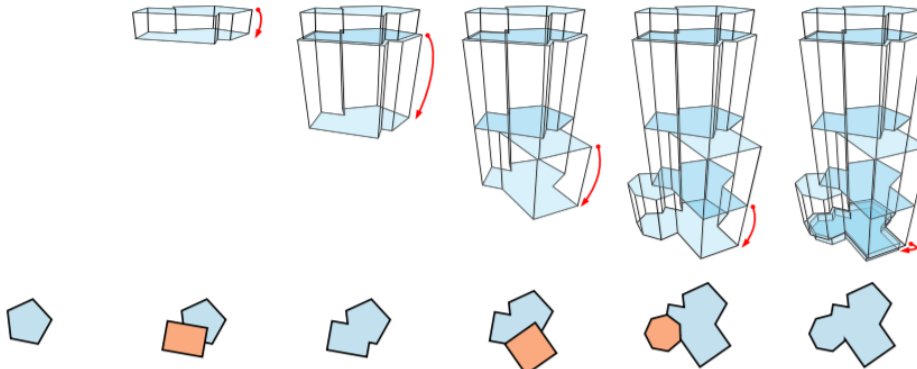


Figure 2.10: Procedural building generation as presented by Greuter et al. Shows how polygons are merged to create more complex shapes, these shapes can then be extruded downwards. This process can then be repeated to create complex and diverse buildings. (source: [10])

Buildings created with this approach can be seen in Figure 2.11.

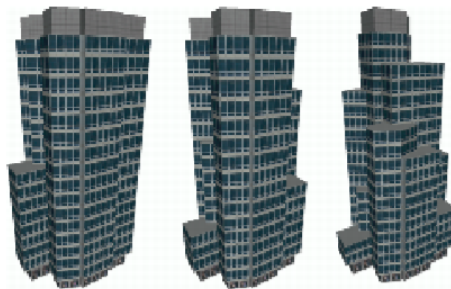


Figure 2.11: An example of a finished building using the tool presented by Greuter et al. (source: [10])

In Figure 2.12 a city generated with the tool presented by [10] can be seen in first person perspective view.

The tools mentioned above are all good for its given purpose, i.e. to create a procedurally generated urban city environment. Whether it is to be used for visualization or as an environment in a computer game. These tools have that in common that the cities generated with them look perhaps quite detailed when viewed from a distance, however they do not look as detailed the closer you get.

Creating a VR environment requires a bit more detail than these tools offer, the requirements being that the environments need to look very detailed when viewed from a first person perspective. But that is not the most important part, in designing VR environments



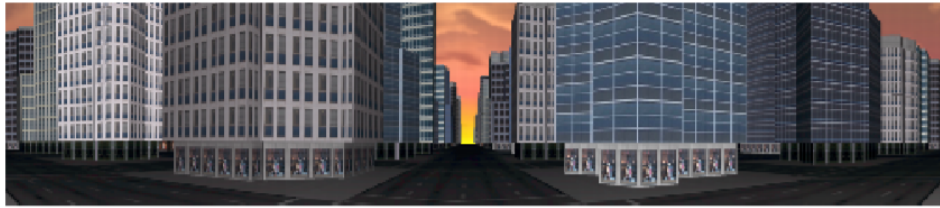


Figure 2.12: First view perspective when viewing a procedural city generated with the tool presented by Greuter et al. (source: [10])

the key factor is that the performance of the environment needs to be good. Therefore these VR environments need to be designed with good performance in mind.

In RED the effects that different architectural features in urban city environments have on people are measured. To achieve this designers need to have very fine grained control over how the generated environment will look like, such as the decoration style of buildings, the type of roofs they have, the number of floors etc. The final look of a urban city environment by modification of these controls needs to be very easy to achieve. For these reasons a special tool needed to be created for the generation of urban city environments where fine grained details could be modified by designers in an easy manner, and it needed to perform very well for it's use in virtual reality.

## 2.2 VR Architecture / Interfaces

Virtual reality (VR) is not a new concept. It has however just recently gained some traction with the release of modern virtual reality capable hardware, such as the Oculus Rift and the HTC Vive. One of, if not, the greatest challenge of virtual reality is that many users often report feeling sick after experiencing the virtual reality.

In full VR a person can be tracked within a small physical space. This allows people to physically move and walk around a virtual environment within the confines of the tracked space and their movements are then reflected in what they experience in the virtual reality.

One of the greatest challenges of creating virtual environments is to reduce the chance of sickness some study participants experience while inside a VR environment. One of the main causes for participants experiencing sickness in VR is the way in which locomotion is handled by the VR application. A locomotion system needs to be in place for cases where a participant might need to travel long distances in the VR environment, further than the physical space allows. An example of a poor locomotion system design would be to continuously move the participant in the VR environment, while he is being physically stationary, until he would reach a desired long distance location. This example of a locomotion system design is very likely to cause a feeling of sickness in users [11].

Therefore it is incredibly important that the locomotion system inside the VR will be carefully designed with that in mind to minimize the negative effects that some participants experience. There are a number of modes a participant could use to travel a virtual environment, i.e. the classic controller, teleportation or they could literally physically walk to travel. By using the classic controller as a mode of travel inside the virtual reality participants would experience movement as a continuous motion in some chosen direction by using the controller. However by using teleportation to travel a virtual environment they are instead instantly moved within the virtual environment to a specific location that they are able to travel to, this eliminates the continuous movement that would otherwise be experienced

through the use of a controller. Physically walking is the travel mode that most matches our natural mode of travel, which in turn can cause the least amount of sickness [12]. However there are limitations to that mode of travel, i.e. the physical space that is available and possible to walk around in. By having a limitation on the physical area that in turn puts a somewhat limitation on the size of the area in the VR that you are able to travel through. Research has shown that the teleportation technique of locomotion causes less sickness in participants experiencing the VR than continuous locomotion movement (e.g. [11], [13]).

## 2.3 Cities that Sustain Us

The application created in this thesis work is a part of the Cities that Sustain Us (CiSuUs) research project [14] at Reykjavik University, that builds on the results of three studies that were carried out by Páll Jakob Línal in his dissertation thesis on Restorative Environmental Design [15]. CiSuUs focuses on utilizing VR in the design and planning of sustainable urban city environments through the foundation of RED.

In Lindal's first study, the effects that specific architectural attributes in buildings in urban city environments can have on restoration were being examined. In his second study the effect that vegetation can have on restoration in urban city environments was examined. These two studies will now quickly be reviewed.

In [4] specific architectural attributes on buildings as well as building height were being examined with the potential of restoration. 147 street scape images, created with Google Sketchup, were created that contained the systematic manipulations of the variables, i.e. building ornamentation, roof silhouette and building height. These images were then rated by study participants on their restorative potential through an online web survey. Results show that these attributes can affect the possibility for restoration in urban city environments.

In [16] five vegetation variables were systematically manipulated and added to images from the previous study that had scored low to moderately on ratings for restorative potential. These five vegetation variables were the number, size and arrangement of trees along the street, grass or no grass and finally flowers or no flowers. These manipulations resulted in an image pool of 104 street scape images. Study participants were asked to rate these images on their restorative potential through an online web survey. Results show that the addition of, and increasing amount of trees along the street scape as well as the presence of flower beds increase the potential for restoration in urban city environments.



Figure 2.13: A first person perspective of a part of the environment created in the third study of Páll Jakob Línal dissertation [15].

In Lindal's third study [15] elements that contributed to different ratings of restoration likelihood were combined and further compared in full neighborhoods. In this study interactive virtual display technology was used to let study participants travel through and experience the environments. Two interactive 3D urban residential environments were created from images based on the results from a previous study [4]. The two created environments were assumed to differ in restoration likelihood, where one of the environments was assumed to have a low restoration likelihood and the other was assumed to have a high restoration likelihood. The elements that were used to create the low restoration environment were based on five images that had in the previous study [4] got the lowest mean rating on restoration likelihood, where as the elements used to create the high restoration environment were based on five images that had in the previous study [4] got the highest mean rating on restoration likelihood. The environments were created in Google Sketchup and the environments were rendered and presented in Unity3D. In Figure 2.13 we can see an image of a part of the environment created for the study.

The results of the third study provided a correspondence between restoration likelihood ratings of images and the measured restoration in virtual environments based on those. Study participants who traveled through the low restoration environment showed a negative shift in affective balance, where as participants that traveled through the high restoration environment showed a positive shift in affective balance. The results were also very promising for the use of virtual display technology as the predicted change in affective state seemed even greater than by previously used digital images.

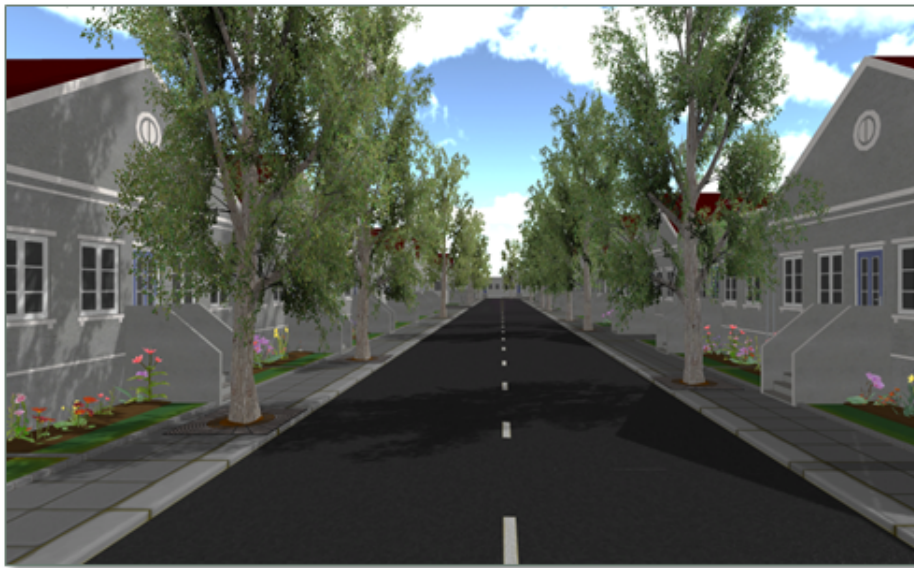


Figure 2.14: A first person perspective from a part of the environment created with VRPsychLab 1.0. (source: [14].)

The first study of the CiSuUs project was a continuation of the third study performed by Lindal in his dissertation [15]. In this study VR was used to measure the restorative potential of different urban environments, instead of presenting the virtual environment on a computer display. In Figure 2.14 we can see a part of the environment that was created for the study. For this study an application was created, called VRPsychLab 1.0, which is the forerunner of the application presented in this thesis. This application allowed designers to change the attributes of buildings through an interface within the application itself, this was already an improvement because it was no longer required to manually construct the



Figure 2.15: An early version of the city builder interface from VRPsychLab 1.0. (source: [14].

buildings by hand, and then insert them into the application. In Figure 2.15 we can see an example of this interface. The results of this study have not been published yet, but the great potential of VR for this kind of study was confirmed.

The application created in this thesis work builds on all of this prior work and addresses some of the shortcomings of the tools and methods used so far. The creation of these city environments by hand is extremely time consuming, i.e. to create all these variations of buildings with different architectural features, such as the buildings need to differ in height, ornamentation and roof silhouette as well as the placement of vegetation and green areas [15]. This requires a lot of time, effort and work. VRPsychLab 1.0 [14], developed in CiSuUs, was a step in the right direction, however it still required a lot of manual work to create individual tiles and different combinations.

By automating many of the steps in a procedural approach, the application in this thesis presents a solution to this time consuming, manual work that has previously been required in the construction of these virtual cities. This application offers designers the ability to create large urban city environments where all of these variables can be easily controlled. With this application these virtual city environments can be created with the click of a button. They can then be experienced by study participants in VR, while data from them is gathered about the restorative potential of the environments.

# Chapter 3

## Approach

In this chapter we will give a brief overview of the application created for this thesis work. We will discuss some of the challenges faced, as well as the requirements that need to be fulfilled.

There were a number of requirements this application needed to support. It needed to support the generation of an urban city environment where a number of variables can be controlled that can drastically affect the outlook of the generated environment. The possibility of getting real time feedback from study participants about the restorative potential of the environment while traveling through it in VR was also required. This was achieved by the creation of a VR survey interface, through this interface questions and/or instructions can be presented to the study participant while inside the VR city environment.

### 3.1 Architecture

As can be seen in Figure 3.1 the study participant travels through two VR environments. The first environment is a tutorial environment, and the second environment is the procedural city environment.

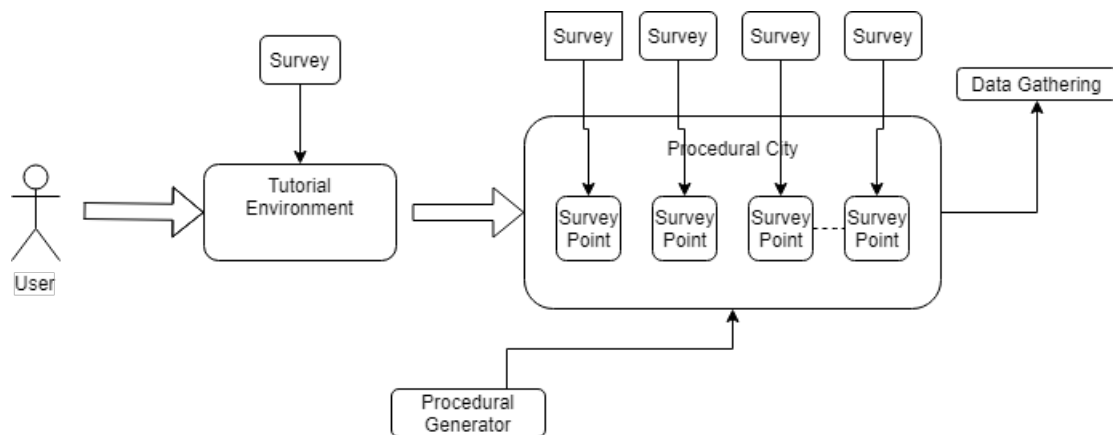


Figure 3.1: Overview of the application.

**Tutorial Environment.** Teaches study participants how to interact with the VR survey interface that will be presented to them in the procedural city environment. This is important so that we are able to collect reliable restoration data from study participants.

**Survey.** The survey is the VR interface that can be presented to users while inside the VR city environment. This survey interface can be used to convey instructions to them as well



as questions. A single survey can contain multiple questions and/or multiple instructions, these will be referred to as slides, e.g. a single slide contains one question or instruction. The survey interface consists of two main elements, a button and a slider handle. The button is used to finish a single slide in the survey, where as the slider handle is used to select numbers from a likert scale that act as answers to questions presented by the survey interface.

**Survey points.** These are locations within the VR environments where a survey interface will appear. At each survey point it is specified which slides should appear there, it can also be none. When a study participant finishes going through all the slides at a survey point the survey interface fades out from the environment, at which point a triangle marker will appear in the environment. This marker is an indication of where the next survey point is located. Study participants travel to this new location by way of teleportation. Studies have shown that teleportation is a better locomotion technique than being moved to the new location, e.g. on a wagon like platform ([13], [11]).

**Procedural City Generator.** Allows designers to control a number of variables for the design of the procedural city environment that it creates. It allows designers to control the complete layout of the city, i.e. where roads, buildings and parks are placed within the environment. It also allows designers to control more detailed variables, such as the color of each building, height of buildings, amount of ornamentation and the roof silhouette of each building. Designers can also control where trees should be placed in the environment, as well as whether buildings should contain a flower bed in front of them.

**Procedural City.** The procedural city environment is an urban city environment that can be experienced in VR using the HTC Vive. This environment is created by the procedural city generator.

**Data Gathering.** Data is gathered from study participants while they are navigating through the virtual city environment. This data comes from the questions that can be presented to them within the virtual city environment through the survey interface. Additionally physiological data can be gathered from the study participants as well by attaching electronic physiological measurement devices to them.

## 3.2 Challenges

In this section we will briefly discuss the main challenges that needed to be addressed in designing the application in this thesis work. This relates to the performance of the application as well as the capabilities required of the application, in terms of flexibility and functionality. The greatest challenge in designing an application for VR is that many users report feeling sick after experiencing it [17]. This relates strongly to the performance of the application and the method used to travel through the virtual environments.

### 3.2.1 Performance

It is very important for a VR environment to run smoothly, e.g. that it contains no visual stuttering as can happen when the frame rate drops. For a VR application it is very important to try to keep the frame rate above 90 frames per second. Frame rates below 90 frames per second are more likely to induce the effects of nausea, disorientation and other negative effects on the study participant [18]. A number of changes have been made to the application in the past to meet this requirement, as well as some specific configurations that need to be applied, within Unity3D, to increase performance. We will go over these in more detail in Chapter 4.

### **3.2.2 Tutorial Environment**

Considering that not many people are yet familiar with VR and have not tried it before it was important to design a special VR environment that would teach study participants how to interact with the VR survey interface using the hand held controllers from the HTC Vive.

### **3.2.3 Procedural Generator**

The main challenges in the design of the procedural city generator were regarding the rotational placement of buildings, parks and roads in the generated environment. Specific rules need to be generated that the generator can follow when it places these elements in the environment. For example a single straight road tile contains the road part as well as the sidewalk part. This cannot be placed blindly in the environment, i.e. it needs to take into account the direction of the road specified in the layout. These same rules can apply for buildings, i.e. we would want a building's entrance to face the road's sidewalk. As a final example we can think of the park tile that can be placed in the environment, imagine that we want to be able to place a fence around the park, but only at the side of the park that is next to a road tile. If a park tile is next to a house tile we would not want a fence. There are endless possibilities for these placements and general rules need to be designed so that the generated environment looks good as a whole.

### **3.2.4 Data Gathering**

There are numerous data that need to be collected and stored, such as certain events that relate to the virtual survey interface such as when a study participant answers a question. These data can then be further analyzed and used to answer specific research questions, such as how much time does a study participant spend at each survey point.

## **3.3 User Testing**

VR is a concept not many are familiar with and even less have perhaps experienced being inside a virtual reality environment. It is hard to speculate how study participants might interact inside a virtual reality environment. In this application restoration data is being collected from study participants about the various designs of urban city environments and it is important to know that they are comfortable inside the VR environments and that they are familiar with the interactions required of them. This is important such that we can collect reliable restoration data from study participants. A tutorial environment was created to help study participants with this transition into VR as well as getting them familiar with the VR survey interface. But the question still remains, how well does the tutorial environment do in achieving that. For this reason a user test was conducted to discover any problems study participants might experience within the VR that could hinder the collection of reliable restoration data.





# Chapter 4

## Implementation

In this chapter we will describe the implementation of the application in detail. Before we go into the implementation I will begin by describing the various tools and resources used to create this application. The main tool used was Unity3D, which is a game engine. Another tool used to make some of the content in the application was Blender. Blender is a 3D modeling tool that can be used to create 3D models that can then be imported into Unity3D. Various 3rd party resources were also used, such as textures from *textures.com* and sound effects from *freesound.org*.

### 4.1 Resources

#### 4.1.1 Unity3D

Unity is a game engine that can be used to create 3D or 2D games or applications. In Unity, environments are created within a Scene, and each object in a Scene is referred to in Unity as a GameObject. Components are a key element within Unity, they can be attached onto GameObjects and allow you to change their behavior and / or look in various ways.

There are two very important features built into Unity that were essential for the design of this application, *Baked Lighting* and *Baked Occlusion Culling*. These features are strongly correlated to the performance that can be achieved with the application, e.g. the frame rate.

- *Baked Lighting* allows you to bake the lighting calculations for the entire environment into textures, that are then read from memory and projected into the environment giving very realistic lighting and shadows. The drawback of using baked lighting is that you can not change the lighting dynamically, in essence baked lighting is static lighting that does not change. That works well for this application since it is not a requirement for the lighting to change during runtime. To give an example, image the sun moving gradually in the sky of a virtual environment. As the sun moves the shadows in the environment change, requiring dynamic lighting, but if the sun is in a fixed position the shadows will not change, in which case static lighting is possible. Real time lighting calculations are very performance expensive and therefore by baking the lighting into these textures performance can be increased drastically.
- *Per Model Baked Lighting* is a custom method that was implemented. This method utilizes the Baked Lighting feature of Unity. In this method all the 3D models within an environment are grouped together based on a certain criteria. For example all buildings that share the same architectural features, scale and rotation are grouped

together. The lighting is then baked once for a single model in each of these groups. The lighting that was baked for a single model in these groups is then shared with all the other models in the same group. By using this method we can quickly apply baked lighting to 3D models in an environment without the need to bake the lighting every time, because we will eventually have the baked lighting information for all possible variations of 3D models in the environment. This method requires partial real time lighting, because the lighting calculations are done separately for a single model and are not performed for the whole environment. For this reason the baked lighting does not affect the surroundings of the models, i.e. a buildings shadow does not appear on the street.

- *Baked Occlusion Culling* is a very powerful yet a very simple tool to use that Unity features. It ensures that what is not being rendered on the screen is not being loaded into memory. This has a direct relationship to the performance of the application.-

### 4.1.2 Blender

Blender is a 3D modeling tool. It allows you to create complex 3D shapes that can then be transferred to Unity and placed within a scene. Blender was used to create various models within the application. It was used to create the individual parts that make up a building. It was also used to create parts of the survey interface as well as the roads in the environment among others. Blender was also used to simplify the 3D models used as much as possible in order to increase the performance of the application.

## 4.2 Survey Interface

It was required in this application to be able to gather data from participants about the restorative potential of the environments they experience. For that purpose a virtual survey interface was designed, also referred to as a podium. Study participants could interact with this interface by using the hand held controllers provided with the HTC Vive. The VR survey interface is capable of conveying questions and/or instructions to study participants. It allows them to answer the questions on a numbered likert scale by moving a virtual slider on the survey interface. Then they can confirm their answer by pressing a button which is a part of the survey interface. The button and the slider are the only possible interactable elements on the survey interface.

The survey can be placed at various locations within the environment where it is desired that the study participant will pass through. Each survey location can contain zero or more slides, a slide is a single question or a single instruction that will appear in the survey interface. An example of the survey interface with a question slide presented can be seen in Figure 4.1. This collection of slides is created with a Questionnaire asset. The study participant advances to the next slide by pressing the button on the VR survey interface. When he has gone through all the questions / instructions at the current survey location a marker will appear in the environment indicating the next survey location in the environment that he will then be teleported to. And thus this process will repeat until there are no survey points remaining.

The interactable parts of the survey interface in the virtual environment are the button and the slider, as can be seen in Figure 4.2. To interact with the button the study participant must move the hand held HTC Vive controller into range of the button, and press the TRIGGER

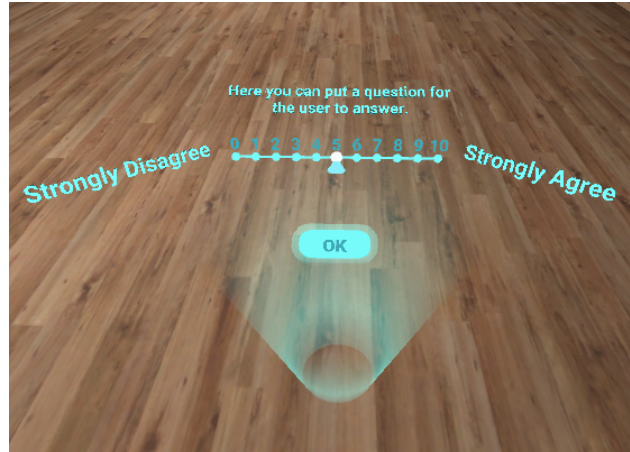


Figure 4.1: The survey interface presented to study participants in the application. This shows the survey interface with the slider, e.g. this is a question slide. The survey interface is also sometimes referred to as a podium.

on the controller, while being in range of the button. The TRIGGER is marked with a yellow outline in the virtual environments to easily recognizing the TRIGGER. Figure 4.3 shows the HTC Vive controller, as well as the indicated TRIGGER button.

Interacting with the slider handle follows the same principle, as the study participant needs to have the HTC Vive controller in range and press the TRIGGER. However the slider is movable, and the study participant can move the slider as he moves the controller. The controller is in range of the button and/or the slider handle when the controller is touching the Collider component that is attached to the button and the slider handle. The Collider component is a Unity built-in feature that you can attach onto GameObjects. When a GameObject has an attached Collider it can sense when other objects, such as the HTC Vive controller are touching it.

There are a number of events that are logged from the survey interface when the study participant is interacting with it. This log file is saved and can be reviewed after a participant has finished going through the city environment. To name a few of the events that are logged, are the start and the end time of the application, the time when a participant lands at a location after a teleport is logged and as well is the time when the participant teleports from said location logged, with this information you can for example see exactly how long each participant spends at each point. Table 4.1 shows the events logged from the survey.



Figure 4.2: Study participant interacting with the button (left) and the slider (right) on the podium. The button and the slider highlight a yellow color when the controller is in range, indicating that they can be interacted with.

Logged Podium Events	Description
Question Confirmed	Logs the value the study participant has chosen when interacting with the likert scale.
Question Marker	Specifies in the log when the study participant enters a location that contains a slide.
Survey Fade	Logs when the podium fades in to the environment, as well as when it fades out of the environment.
Teleport	Logged when the study participant presses the trigger when the teleport marker is visible.
Screen Fade	Not implemented.
Current Stop	Logs the current location that the study participant has just been teleported to.

Table 4.1: Events that the podium logs.



Figure 4.3: The HTC Vive hand held controller. The right image shows the yellow outline that surrounds the TRIGGER button.

### 4.2.1 Questionnaire

The Questionnaire is a Unity3D ScriptableObject asset. This asset contains a list that can be populated with questions / instructions. Questions are those that contain the slider, instructions are those that do not. When creating an element in this list you can specify if it should contain a slider. If it does not contain a slider, then you can only write the message the survey interface should display, and what the button should display. If it contains a slider, you are required to fill the min and max options on the survey interface, and the possible likert scale numbered values. As in 4.1 the left option has been set to "Strongly Disagree" and the right value has been set to "Strongly Agree", and the likert scale contains values from 0 to 10. An example of an instruction and a question created with the Questionnaire asset can be seen in Figure 4.4.

### 4.2.2 Teleport Markers

A teleport marker is a green triangle that appears in the environment that indicates the next survey location in the virtual environment that the study participants will be teleported to next. There are two different visual looks for the teleport markers which indicate different types of survey locations, there are two types of survey locations, i.e. there are location that contain slides and there are locations that contain no slides. The two different visual looks for the teleport marker can be seen in Figure 4.5. The teleport marker emits a yellow outline at regular intervals to be more noticeable to the participant. The marker also emits

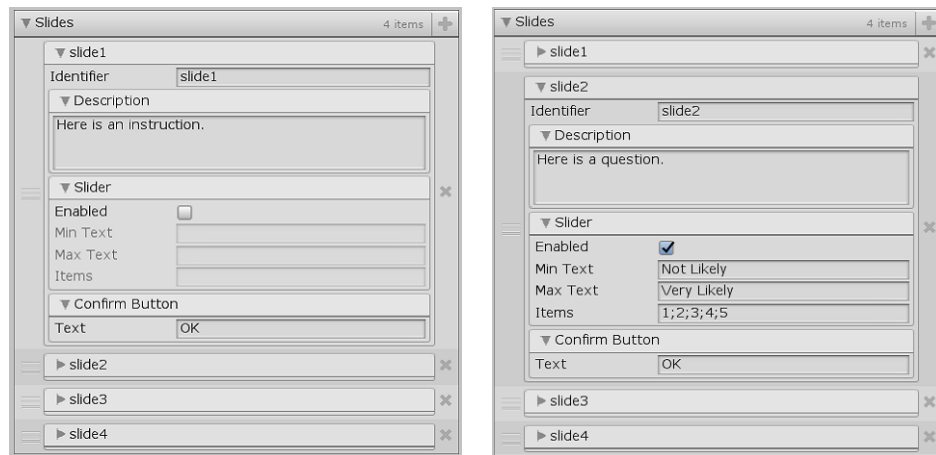


Figure 4.4: Example of an instruction and a questionnaire created with the Questionnaire asset. Left is an instruction slide, right is a question slide.

the yellow outline whenever the participant points the front of the hand held controller at the marker, as can be seen in Figure 4.6.

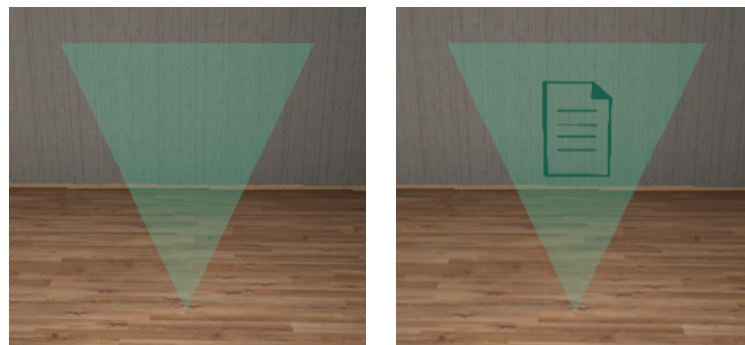


Figure 4.5: The teleport markers. Left is a marker that does not contain any slides at the new location, the right marker does contains one or more slides.

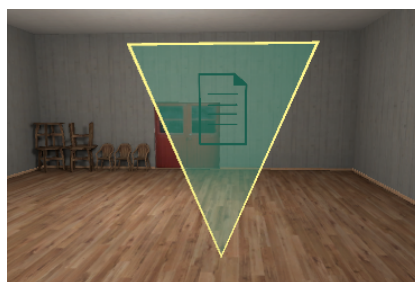


Figure 4.6: The teleport marker, with an outline, making it stand out a bit more from the background.

### 4.2.3 Tutorial Environment

The tutorial environment, as can be see in Figure 4.7, was designed to teach study participants how to interact with the VR survey interface, as well as learning about the teleport

markers. In the tutorial environment a special Questionnaire was designed that took them through different interactions in the environment.

In the tutorial environment participants followed simple instructions that appeared on the survey interface. These instructions explained various things relating to the interface, the markers and the HTC Vive hand held controllers. To begin with, it was explained to the participants where the TRIGGER button on the HTC Vive controller is located. The TRIGGER button is outlined yellow to make it easier to spot. The TRIGGER button on the controller is the only required interaction with the controller in this application. There are multiple buttons on the controller but to make things easier only one is used. The next step was to teach the participants how to interact with the button on the survey interface, as well as to interact with the slider handle. It was also explained to them what the green triangle markers mean, that they are an indicator to a new survey location they will be teleported to. It was explained to them that whenever they see a marker in the environment, they can press the TRIGGER on the controller and are then teleported to that new survey location. Before being moved to the new location, the screen fades to black and while the screen is black they are moved to the new location, and when at the new location the screen fades back from black.

There is one task that is asked of the participants while in the tutorial environment that did not relate to the interface. This task was put in there to encourage them to physically move in the virtual environment. Sometimes participants that are not familiar with VR are not very keen on physically moving around while inside the virtual environment.

The task was to touch four red balls that were placed on two tables close to the participants as can be seen in Figure 4.8. The balls changed their color to green upon being touched by the controller, and when all the balls were green it was then only possible to interact with the button on the survey interface to advance to the next slide. By asking the participants to touch these balls they were required to physically move to the table in order to touch the balls.



Figure 4.7: The tutorial environment, where study participants were guided through different tasks in order to learn how to interact in the environment.

## 4.3 Procedural City

### 4.3.1 The City Generator

The procedural city generator is a tile based generator. This means that the environment is made out of tiles, in which each building, road segment and park is placed into a single tile. The generator is a script that is placed on a GameObject within a scene in Unity. The input into the generator is a ScriptableObject and this ScriptableObject is regarded as a template



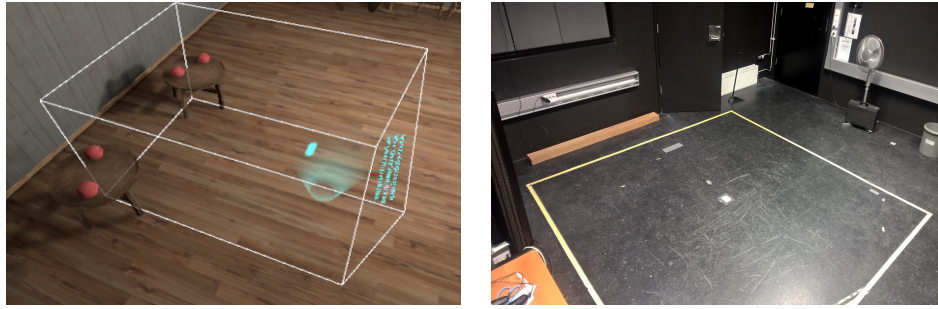


Figure 4.8: In the left image are the red balls the study participant is asked to touch in the environment and the virtual space for them to move around in is shown with the white cube. In the right image you can see the corresponding physical space, the physical space closely matches the virtual space except for being a bit larger. The physical space has been cleared for any obstacles as can be seen.

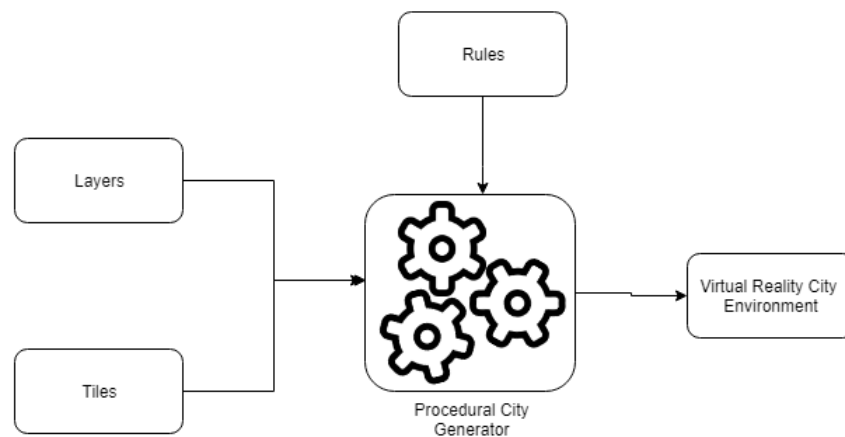


Figure 4.9: An overview of the Procedural City Generator. The main inputs into the generator are the layers and tiles. Rules within the generator handle the correct placement of tiles in regards to the layers to such that the resulting city environment is correct.

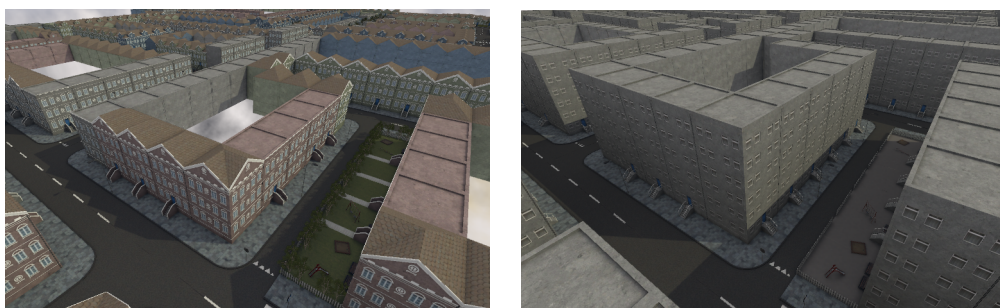


Figure 4.10: Procedural city environments created with the application.

for a city environment. The ScriptableObject contains three categories for data that can be manipulated to change the look of the environment. The categories are layers, tiles and textures. In Figure 4.9 an overview image of the generator can be seen. In Figure 4.10, two environments created with the city generator can be seen.

### 4.3.1.1 Layers

A single procedural city can consist of multiple layers, where each layer can be defined as a controllable variable in the design of the environment. These layers are essentially textures that can be created with various paint programs, such as MS Paint. In these layer textures a single pixel defines a single tile in the generated environment. There must always be a main layer, which defines the complete layout of the city.

In each layer texture there are pixels encoded in the top left corner. These pixels are referred to as the legend of the layer texture. They specify to the generator which color of pixels represents which attribute of the layer. For example in the floor layer, there are 4 pixels in the legend. The generator has been designed to read these pixels in order, where the first pixel indicates the color code for buildings with 1 floor, the color of the second pixel represents buildings with 2 floors, third pixel the code of 3 floors and the fourth pixel is the code of 4 floors.

The core layers in the generator are the layers that affect the generated environment the most in it's visual appearance. Those layers are the following:

- Main Layer.
- Decoration Layer.
- Roof Layer.
- Floor Layer.
- Color Layer.
- Flower Bed Layer.

The **Main Layer** tells the generator where buildings, roads or parks should be placed. An example of the Main Layer can be seen in Figure 4.11.

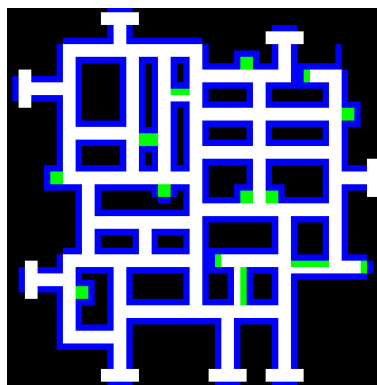


Figure 4.11: Example of Main Layer. White pixels are roads, blue pixels are houses and green pixels are parks.

The **Decoration Layer** tells the generator how the ornamentation/decoration should be on the building. These decorations have been pre generated and as of now the generator supports three different decoration styles. The styles are low, medium and high decoration styles. There are two types of parks that can be created, these are low decoration and high decoration and these can be decided in the decoration layer. In Figure 4.12 an example of the Decoration Layer can be seen.



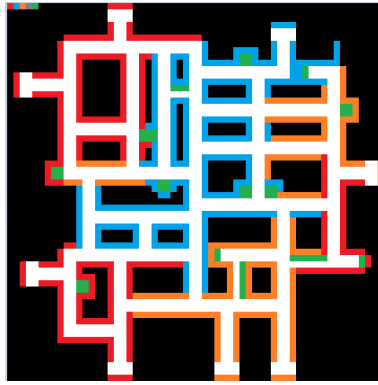


Figure 4.12: Example of Decoration Layer. Red pixels are low decoration, blue pixels are medium decoration and orange pixels are high decoration. Green pixels are high decoration parks, whereas grey pixels would be low decoration parks however there are none in this layer.

The **Roof Layer** tells the generator which type of roof silhouette it should place on each building. Currently the generator supports four types of roof silhouettes, with 4, 5, 9 or 11 turns in the roof silhouette. In Figure 4.13 an example of the Roof Layer can be seen.

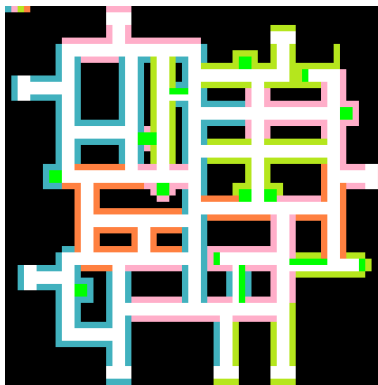


Figure 4.13: Example of Roof Layer. Blue pixels are roofs with 4 turns, pink pixels are roofs with 5 turns, green pixels are roofs with 9 turns and orange pixels are roofs with 11 turns.

The **Floor Layer** tells the generator how many floors a building should be. The generator supports buildings with a maximum of 4 floors. In Figure 4.14 an example of the Floor Layer can be seen.

The **Color Layer** tells the generator in what color the buildings should be in. The generator currently supports 4 colors, which can be defined in the legend of the Color Layer. In Figure 4.15 an example of the Color Layer can be seen.

The **Flower Bed Layer** tells the generator where to place dirtbeds in front of houses. An example of the Flower Bed Layer can be seen in Figure 4.16.

As can be seen these layers all match the main layer, and as such the main layer needs to be created first and then additional detail layers can be added at will. The layers shown in the examples above were used to create the first image in Figure 4.10.

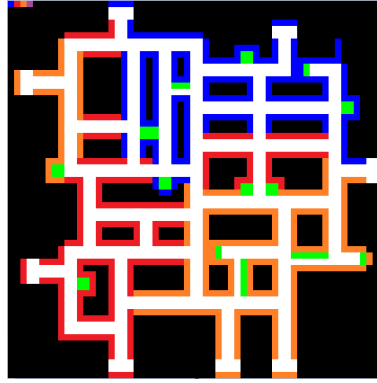


Figure 4.14: Example of Floor Layer. Blue pixels define buildings with 1 floors, red pixels define 2 floors, orange pixels define 3 floors and purple pixels define 4 floors.



Figure 4.15: Example of Color Layer.

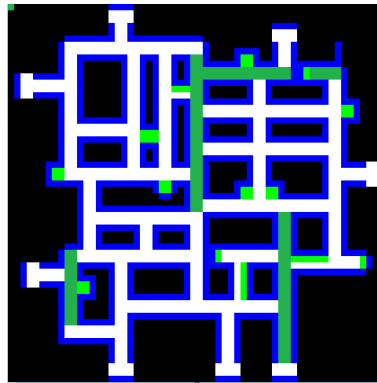


Figure 4.16: Example of Flower Bed Layer.

#### 4.3.1.2 Tiles

The tiles section contains the items that the generator places in the environment from reading the main layer. These contain three road tiles, two park tiles, a flower bed tile and building tile. The generator knows where to place tiles in the environment by looking at the main layer. The main layer contains the locations of roads, houses and parks. These locations are marked into the layer texture as colored pixels, three different colors for three different categories of tiles. There are certain rules the generator must follow in order for the placement of tiles to be correct. Below I will go over the three categories of tiles that the generator can

place in the environment, as well as go over certain placement rules when it applies.

The **road tiles** are saved 3D models within Unity that have been converted into prefabs. Prefabs are objects in Unity that do not need to be placed manually into a scene, but can be instantiated into the scene through scripts. The road tiles used can be seen in Figure 4.17.

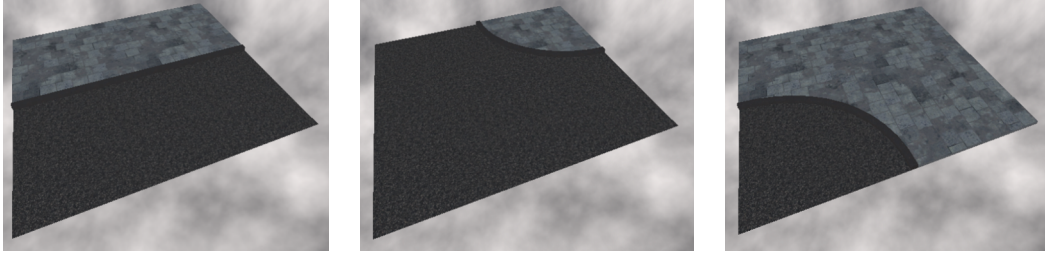


Figure 4.17: These are the road tiles that are used to create the streets in the city environment. First one from left is a straight road tile, the second one is an outer road tile and the last one is an inner road tile.

There are a number of rules that are gone through when the generator is placing road tiles in order to place the tiles correctly. When placing a road tile in the environment, the generator must go through the nearest (adjacent) tiles, in some cases it is required that the generator must look two tiles ahead.

If we begin by looking at the constraints that need to be satisfied for the inner road tile. The constraints for placing down an inner road tile is that there must be a building or a park on the tile to the right of it and above it, if we look at the right most image in 4.17 for reference. This same rule applies to three other variations, i.e. if the building/park was to the left instead of the right as in the example above, the inner road tile will be rotated by 270 degrees to the right before being instantiated into the environment. In Figure 4.18 we can see an example for the constraints needing to be satisfied for the placement of an inner road tile.



Figure 4.18: Constraints satisfied for an inner road tile. Building above the tile and a park to the right of it.

Next we will look at the constraints that need to be satisfied for the outer road tile, which is the middle image as seen in Figure 4.17. We will use this image for reference. If there is a building tile in the tile above and to the right, as well as there is a road tile in the tile above and in the tile to the right the constraint for placing the outer road tile are satisfied. An example of this can be seen in Figure 4.19.

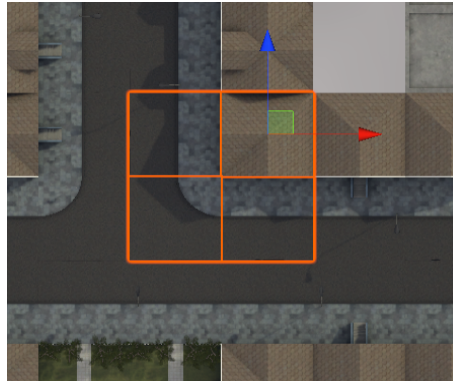


Figure 4.19: Constraints satisfied for the outer road tile. Building tile in the tile above and to the left, as well as a road tile in the tile above and the tile to the left.

The last road tile is the straight road tile. If we use the first image in Figure 4.17 as a reference for a straight road tile then the requirements for placing down this straight road tile would be that there is a road tile in the tile to left and a road tile in the tile to the right. Straight road tiles have their curb faced to a house first, and to a park second. An example of this can be seen in Figure 4.20.



Figure 4.20: Constraints satisfied for the placement of a straight road tile, as seen in the middle straight road tile. It has a road tile to the left as well as a road tile to the right. It's curb also faces the house, instead of the park.

The **park tiles** are just a simple 3D plane. And as with the road tiles, the park tiles have been converted into prefabs as well so that they can be instantiated into the scene. There are two different types of park tiles, a high restoration park tile and a low restoration park tile as can be seen in Figure 4.22. The different between these tiles is that the low restoration park tile contains no vegetation but they both contain a fence. The park tile prefab consists of four separate fences that are on each side of the park tile, these separate fences have the possibility to have an opening as can be seen on the park tile in Figure 4.22. As well as containing some vegetation, trees and small weed plants, on each of the four sides. Larger trees can also be instantiated in the four corners of the park tile.

There is a certain rule when placing and instantiating a park tile in the virtual environment. The rule is that the fences are placed on the sides of the park if the adjacent tile to the side of the park is a road tile. There is also a certain rule for the opening of a fence, i.e. if a fence is instantiated it will not contain an opening if the tile to the left or the right contains a road tile. An example of a park tile in a generated city can be seen in Figure 4.21.

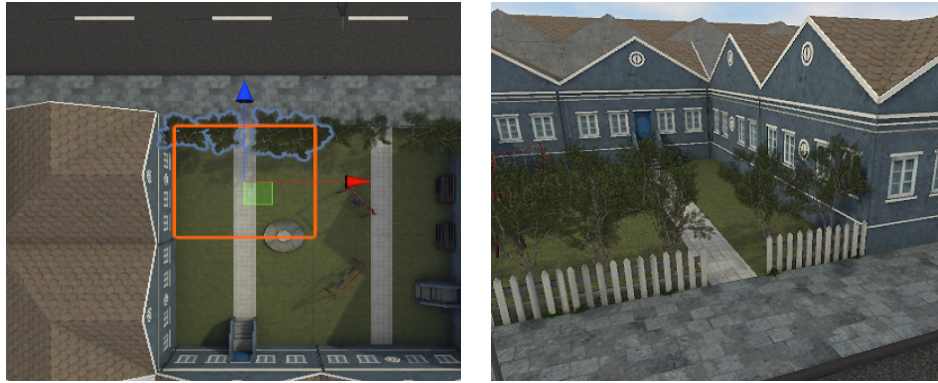


Figure 4.21: Left image is a top down view of the right image. As can be seen in the left image there is a road tile above the park tile, and thus the fence is instantiated at the top side of the park. There is not a road tile to the left or to the right of the park tile and as such the fence contains an opening as can be seen in the right image.

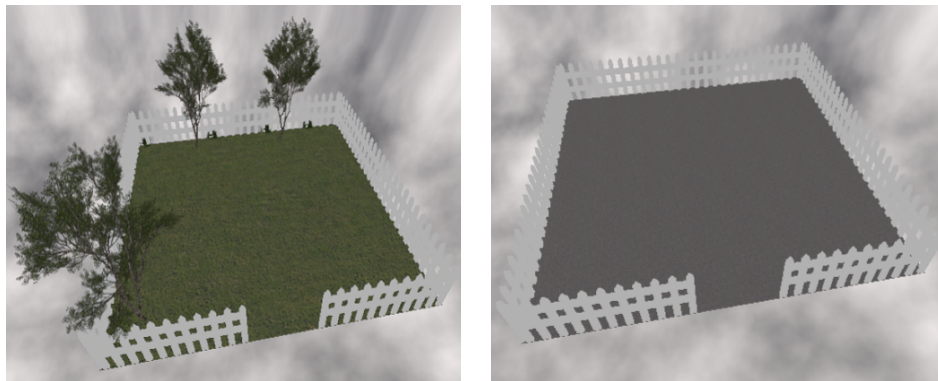


Figure 4.22: These are the park tiles. Left is the high restorative one, and the right is the low restorative one.

The **dirtbed tile** is a prefab created from multiple 3D models. The models include a small fence and various vegetation. The dirtbed tiles are placed in front of houses according to the dirtbed layer. An example of a dirtbed tile can be seen in Figure 4.23.



Figure 4.23: A dirtbed tile that can be placed in front of buildings left. A dirtbed in front of a building on the right.

The **building tile** is an asset that was created by Unnar Kristjánsson [19] who has worked with the Cities that Sustain Us project as well. The building tile asset takes as input certain parameters, which are given by the core layers. In essence a single building is a collection



of multiple models, for an example a simple square house contains four 3D planes that are comprised of it's walls. These reusable small models are then combined to create a single building mesh.

There is a simple rule that is executed when a building tile is placed in the environment by the generator. The rule is that if an adjacent tile of the building tile is a road tile, then the front side of the building faces the road tile. The front side of a building is the side that contains the main entrance. The sequence the generator goes through when checking the adjacent tiles is left, right, below and then above. An example of this can be seen in Figure 4.24.

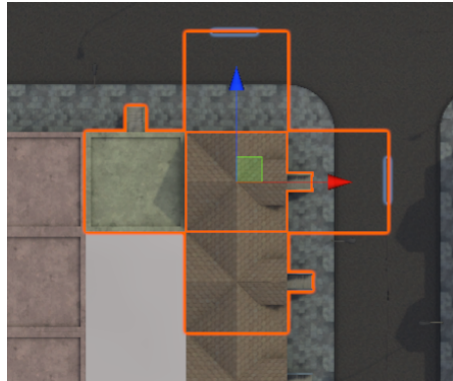


Figure 4.24: The front side of the house on the building tile faces to the right instead of above. That is because the right check is sooner in the rule sequence.

#### 4.3.1.3 Textures

The texture category of the ScriptableObject template that is fed into the generator contains the various textures used by the buildings, as well as containing an additional color for each texture element which can be used to affect the color on the texture mildly depending on how dark the color on the texture is. The template contains a texture asset for the walls, roofs, stairs, doors and windows of the buildings generated. When the generator creates the houses it assigns these textures to a building's wall, roof, stair, door and window. Figure 4.25 shows the textures used for walls, roofs and stairs and in Figure 4.26 the textures used for doors and windows can be seen.



Figure 4.25: These are the texture assets used for the buildings. The first one is the texture for the walls, second is the texture for the roofs and the third one is the texture for the stairs. These can easily be replaced, or add more to a pool to create even more variations in the generated environments.



Figure 4.26: These are the textures used for the doors and the windows in every environment created. As with the building textures, these can also be replaced or more can be added to a pool to create even more variations.





# Chapter 5

## Results and Evaluation

In this chapter we will discuss the VR system that resulted from this thesis work, as well as discuss the results from testing the system with restoration study participants, to examine if there are any problems with it that might prevent or interfere with the collection of restoration data.

### 5.1 Resulting System

The result of this thesis project is an application that can be used to automatically generate a variety of large city environments with ease (see Figure 5.1). These environments have been created with virtual reality in mind and are therefore optimized and perform very well in VR. Multiple variables can be controlled by designers, such as the layout of the city environment and some variables that are more detailed such as the color of each building, the roof silhouette, the ornamentation on the buildings as well as the buildings height. It is also possible to control vegetation, i.e. where parks and trees should be placed. The system has been developed with extensions in mind, so adding new variables and variable ranges, is supported.

A virtual survey interface can be placed at specific locations through out the generated city environments (see Figure 5.2). These specific locations are referred to as survey points. The survey interface is used to gather data from restoration study participants while they navigate the environments. Navigation is in the form of teleportation between survey points, to reduce the danger of simulation sickness [13].

A tutorial environment was created as well. The purpose of the tutorial environment is to get study participants familiar with the interactions required of them, such as interactions with the survey interface within the virtual environments and teleportation.

In terms of technical specification and features, the application achieved the goals that were set forth, i.e. it allows the creation of a large city with the click of a button and with some knowledge of Unity3D it is possible to easily create surveys that can be placed inside a city environment. These city environments perform very well in VR, i.e. there is no stuttering in the frame rate while navigating through them. Figure 5.2 shows two different city environments from a first person perspective, as a user might experience them from within VR. In Figure 5.1 we can see a complete overview of a city created with the application.

It is not enough to implement the system to specification, as it is also very important to show that it properly supports the collection of data from real study participants. Therefore, user testing with study participants was performed.



Figure 5.1: An overview of a city generated with the application.

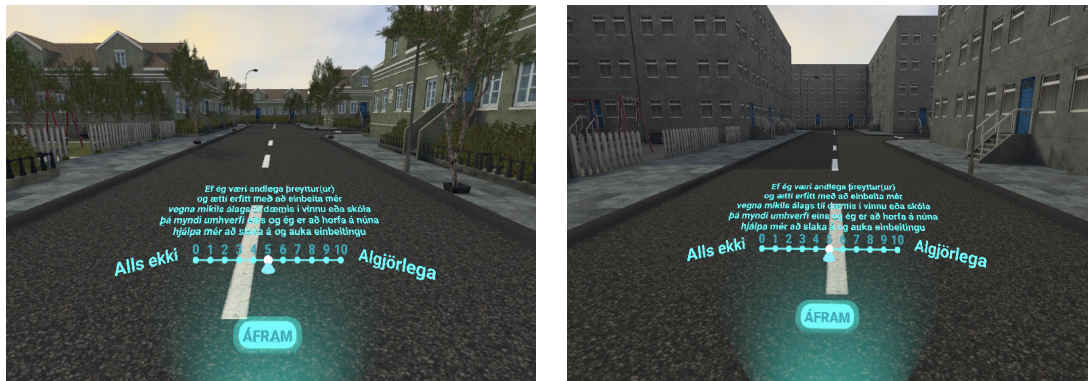


Figure 5.2: First person perspective of two very different environments generated with the procedural generator, and the participant is presented with the survey interface.

## 5.2 User Testing with Study Participants

### 5.2.1 The Question

Before the system can be used to collect data for real in a restoration study, we need to answer the following question: *Are there any major problems with the application that might prevent the collection of reliable restoration data from study participants?* The study described in this section aims to answer this question.

### 5.2.2 Method

#### 5.2.2.1 Participants

It has been shown that most major problems in a user interface can be found even with few participants [20]. A total of 7 users were recruited for this user testing, 2 female, 5 male and

all Icelandic. Their age ranged from 20 - 40 years old. All the participants said they play video games once a week or more, and they all had previous experience with virtual reality but to different extents.

#### 5.2.2.2 Environment/Task

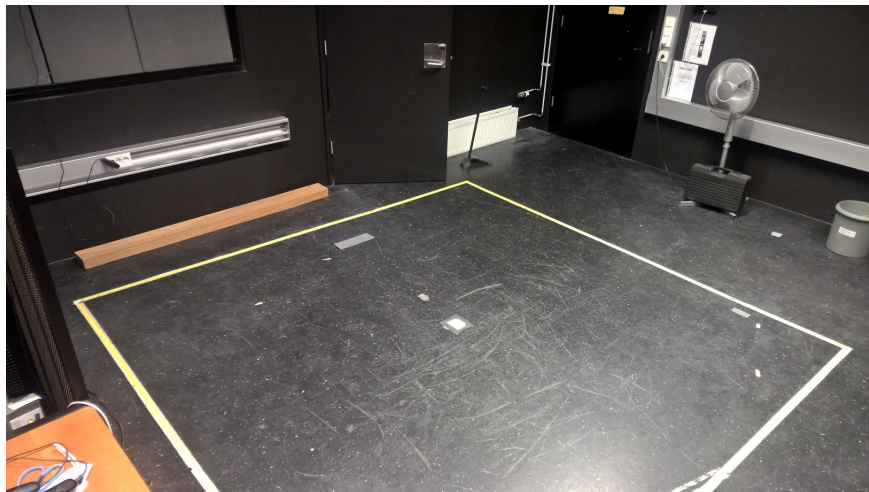


Figure 5.3: The blackhole room at Reykjavik University.

The application was tested on participants as if it were a proper study on the restorative qualities of a city environment. The participants experienced the virtual environment in two parts using the HTC Vive VR headset. The user testing took place in the *Black Hole*, which is a room at Reykjavik University that is used for VR research. The *Black Hole* can be seen in Figure 5.3, as well as the physical space within which participants can move while in VR. The physical space is approximately 3m x 3m and can be seen by the lines marking the square on the floor.

The two parts experienced in VR by the participants were the tutorial environment and the city environment. There are different tasks expected of the participants depending on which part they are in. When the participants are in the tutorial environment they are supposed to follow the instructions within it, presented to them via the survey interface. The task for the city environment is to navigate through it and answer questions presented to them at the survey points using the the virtual survey interface. These questions related to the restoration likelihood of the environment.

A total of 6 survey points were placed in the city environment where participants answered questions relating to the restorative possibilities of their surroundings within the environment at that location. In Figure 5.4 we can see the surroundings of the participants when they are answering the restoration survey questions at points 1 through 3. In Figure 5.5 we can see the surroundings of the participants for points 4 through 6. Empty survey points were added in between the actual survey points as teleportation stops, to keep the jumps to a reasonable length.

#### 5.2.2.3 Measurements

To answer the main question of the user test, whether there are any problems with the application preventing collection of reliable restoration data, the following analyzes and instruments were used:





Figure 5.4: Restoration survey points 1, 2 and 3 (from left to right)



Figure 5.5: Restoration survey points 4, 5 and 6 (from left to right).

- *Restoration Data* To assess the quality of the restoration data itself, the results of the restoration survey are quickly compared with the expected potential for restoration at the survey points, based on the surroundings.
- *Interface Difficulty* To assess whether there were any difficulties in performing the tasks required by the participants in the tutorial or the city environment, several methods were used. During their experience they were instructed to think aloud and speak if anything seemed difficult or strange to them, they were also told that they could ask questions (however, they were told that those questions might not always get answered). The participants were also observed by the researcher while they experienced the VR environments. After the VR experience they were asked to answer a questionnaire. This questionnaire contained 5-point Likert Scale rating of statements and open form questions relating to their experience with the virtual survey interface and their general experience within the VR. The full questionnaire can be seen in Appendix B.
- *Simulator Sickness* To test whether the application is making any of the participants feel any discomfort related to simulator sickness, the Simulator Sickness Questionnaire (SSQ) [21] was used. Such discomfort might interfere with collected restoration data, and therefore important to analyze.
- *Attitude* To test if the participants have a particular aversion towards VR, either before or after the experience, the Associations Towards Virtual Reality Questionnaire (ATVR) (i.e. [22], [23]) was used. Such aversion or strong negative feelings towards the VR experience might influence the quality of restoration data.

#### 5.2.2.4 Procedure

In Figure 5.6 we can see the procedure of the user test for each participant. When the participants came into the room they were greeted and briefed, they were only told that they were going to experience a virtual reality environment and that they would have to fill out some questionnaires. First the participants were asked to fill out a consent form and answer

some background questions, such as their age, nationality, computer game usage and previous experience with virtual reality. Then followed the SSQ and ATVR questionnaires before participants experienced the VR environment (both the tutorial part and then immediately the city part). Before experiencing the VR environment participants were only told to follow the instructions within the environment itself. After the VR experience, participants were asked to answer the SSQ and ATVR questionnaire again as well as answer questions and statements about their virtual reality experience. Finally the participants were debriefed and thanked for their participation.

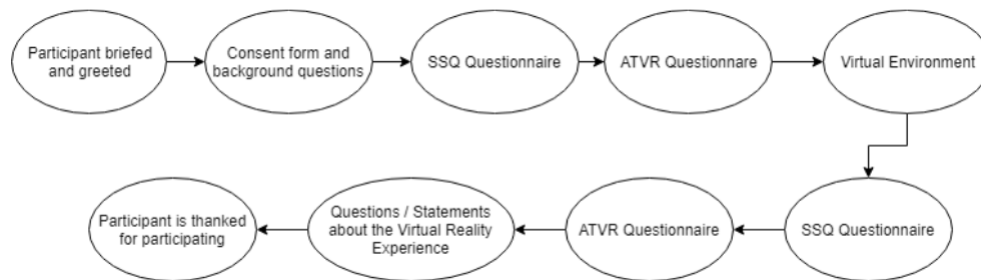


Figure 5.6: The User Testing procedure.

### 5.2.3 Results

The user testing took approximately 30 minutes on average, and all participants successfully finished their tasks. The results from each of the measures will be reported in turn below.

#### 5.2.3.1 Restoration Data

The data collected from the 6 survey points seem to indicate that the participants experienced higher rating of restoration likelihood at certain survey points which goes hand in hand with the expected potential for restoration at those specific survey points. This can be seen from previous research where vegetation and increased architectural complexity increase the potential for restoration [15]. The results from the data collection can be seen in Appendix C.

#### 5.2.3.2 Interface Difficulty

Participants were asked to rate statements about their experience in interacting with the virtual survey interface as well as statements about their general experience of the virtual reality. The results from these statements can be seen in Appendix D. To summarize the results:

- None of the participants felt that it was confusing to use the HTC VIVE controller, or interacting with the button or the slider on the virtual survey interface.
- One of the participants felt it was confusing and disorienting being moved to another spot when the teleportation marker appears.
- Some of the participants felt it was uncomfortable to wear the HTC VIVE headset.
- One of the participants disagreed with the statement that experiencing the VR was comfortable, others were either neutral towards that statement or agreed.

Participant	SSQ Before	SSQ After
1	22	26
2	26	7
3	19	0
4	71	67
5	26	22
6	0	0
7	11	0

Table 5.1: Results from Simulator Sickness Questionnaire. Higher number mean increased measured simulator sickness. The highest possible score that can be achieved in the SSQ questionnaire is 235.

Through researcher observation two very important discoveries were made relating to the user interactions within the virtual reality. Those discoveries were the following:

- **Interaction with the button on the podium.** One participant was not exactly sure at first how to interact with the button on the survey podium.
- **Interaction with the teleport marker.** Two participants tried to walk towards the teleportation marker, instead of teleporting to it, which would result in them leaving the available physical space that has been cleared out for the HTC VIVE. This could result in them walking into objects in their real surrounding area which might, in the worst case, cause minor injury to them.

Participants were asked to answer some general open form questions about the experience and the environments. The main comments are summarized below.

When asked if the directions were clear in the urban city environment, all participants replied that it was very clear.

One participant mentioned that he tried to pick up the red balls in the tutorial environment but noted that he could not do so. It was not intended for the participants to be able to pick up the red balls, they were only meant to be touched. Their purpose was to encourage participants to physically move a little bit within the virtual reality environment and it was also explicitly noted that you were only required to touch them. Perhaps the instructions for this part of the tutorial environment could be improved.

Some of the participants also commented on the virtual reality headset giving them discomfort, i.e. that the actual HTC VIVE helmet caused discomfort.

Participants were asked if they thought something was strange or did not work as intended in either environment, to which all participants replied that they felt nothing strange and everything seemed to work as it should.

One participant noted that he felt it was unclear how to use the controller to teleport between places in the tutorial environment.

### 5.2.3.3 Simulator Sickness

The scores for the Simulator Sickness Questionnaire before and after the virtual reality experience can be seen in Table 5.1. The low simulator sickness scores overall, indicate that the application does not cause any notable discomfort in participants.

Association Word	Before VR	After VR
Happiness	3.14	3.14
Loveliness	2.43	2.71
Joy	3.14	2.86
Friendliness	2.71	2.57
Disgust	1	1.14
Sadness	1.14	1
Horror	1.43	1.29
Hate	1	1

Table 5.2: Results from the Associations Towards Virtual Reality questionnaire. These results are averages of participant answers for each word.

#### 5.2.3.4 Association Towards VR

As done in [13] 8 words were used to measure participants associations towards VR before and after experiencing the virtual environment, i.e. 4 positive words (happiness, loveliness, joy and friendliness) and 4 negative words (disgust, sadness, horror and hate). Participants rated the statement "Virtual Reality evokes in me the feeling of..." for each word on a scale from 1 (not at all) to 4 (very much). In Table 5.2 we can see the average score for each word before the VR experience and after it.

#### 5.2.4 Discussion

The main goal behind the user testing was to check if there were any problems with the application that would prevent researchers from gathering data about the restorative possibilities of the generated environments. Here the results will be discussed with respect to whether they indicate any threat to the data gathering.

*Restoration Data* The application was successful in collecting the survey data from the participant about the restorative possibilities of the city environment. Since the preliminary results from the 7 participants also show an expected result for the restorative possibilities in the 6 measured survey points, it can be concluded that basic data reliability has been achieved.

*Interface Difficulty* There were no major interface problems that hindered task performance, or are likely to interfere with restoration data. Almost all the participant had no problems interacting with the virtual survey interface. However, two important observations were made by the researcher, where one participant had a problem interacting with the button on the podium, and two participants tried to walk towards the teleportation markers instead of teleporting to them. Both of these issues have been addressed in an updated tutorial environment, with more explicit instructions. From the open questions, nothing stood out to the participants as odd or not working properly. In general participants noted that directions were clear. This can be interpreted to mean that the tutorial environment did serve its purpose well. It was supposed to prepare participants for the city environment by teaching them how to interact with the survey interface and how the teleportation worked. However there were no participants that experienced the city environment without experiencing the tutorial environment first, so attributing this solely to the tutorial environment is not something we can be certain about. Some of the comments indicated smaller things that will be addressed

before a real restoration study starts. However, possible discomfort felt from the VR headset on the participant's head, is hard to fix, but will be incorporated into future data analysis by asking participants about it.

*Simulator Sickness* The results of the SSQ indicate that the application does not cause simulator sickness in participants. This can be seen from the low scores as compared to the highest possible score, and the changes in simulator sickness before VR and after VR are nominal. It is therefore safe to assume that simulator sickness will not affect gathered restoration data.

*Association Towards VR* Results from the ATVR Questionnaire show that a negative change appears in three words, these words are *Joy*, *Friendliness* and *Disgust*. While not extreme, this negative change could be related to the experience of traveling through a relatively lifeless city environment (not much there to evoke feelings of joy or friendliness) or perhaps the discomfort of wearing the VR headset. This should be studied further.

Overall, the results of the user testing are promising as they indicate that there are no major problems with the application. In the user testing the application was used to gather a small sample of restoration data from participants within a particular virtual city environment. This was successful and the restoration data gathered about the virtual city environment looks promising, and is unlikely it got compromised by interface problems, simulator sickness or a strong negative experience with VR.

### 5.3 Summary

The goal of this application was to create a city environment in virtual reality where the psychological impact of certain architectural and planning features and their effect on people could be measured.

Specific variables relating to the generated city environment needed to be controlled, such as building height, ornamentation, color and roof silhouette among others. Participants go through this city environment while data is being gathered through a questionnaire as well as numerous events are logged. A tutorial environment prepares them for going into the city environment, in order to get them familiar with the virtual survey interface that they are required to interact with.

These goals were achieved, with this software it is possible to create a large virtual reality city, with ease, and collect data from participants while they are navigating through it. The virtual city environment performs quite well, reaching a stable frame rate of about 90 frames per second. The tutorial environment seems to work rather well in preparing participants how to interact with the virtual reality survey interface presented to them, as there were no major problems discovered during the user testing. This can be seen from the results of the user testing, where restoration data from the 7 participants was successfully collected.



# Chapter 6

## Conclusion and Future Work

### 6.1 Summary of Contributions

An application was created that can be used to do research in Restorative Environmental Design. The following were the main contributions of this thesis work:

- **Procedural Virtual Reality City Generator.** A procedural city generator was designed with it in mind that it would be easy to create a variety of urban city environments with ease. All these city environments can be experienced in first person inside a fully tracked VR without any performance problems. The city environments that can be created with this application are unlimited. They both vary in the layout of the environment, as well as varying details of buildings in the environment. These varying details of the buildings can be height, color, ornamentation and roof silhouette. It can also be specified where to place parks in the environment as well as where trees should appear.
- **Virtual Reality Survey Interface.** A VR interface was designed that can be used to put forth information as well as questions to study participants. The questions must be on the form that they only accept numbered answers. Through these questions researchers can collect data from participants about the restorative potential of the various designs of environments.
- **Virtual Reality Interface Tutorial Environment.** A special tutorial environment was created for teaching study participants the fundamentals of interacting with the VR survey presented to them. This includes showing them which button to use on the HTC Vive controller by highlighting it, as well as teaching them how to interact with the button and the slider on the VR survey interface. The button is used to accept information or questions presented by the interface, and the slider is used to give a numbered answer to these questions.
- **Data Gathering.** The application can gather a number of information from a study participants traveling through a generated city environment. This information can be seen in Table 4.1. This information can for example be used to analyze how much time each participant spends at each survey point in the virtual environment. And additionally to this data, if there are any questions present in the environment the answers to those questions will of course be stored as well.

## 6.2 Future Work

The application presented in this thesis work will be used in an upcoming research study at Reykjavik University by the Cities That Sustain Us (CiSuUs) research team. Before that a short pilot study will be performed, and the application will be evaluated further. During that period further requirements may arise, and/or changes that may need to be made to the application.

There are however many things that need to be made for this application to be more accessible for other researchers in the field of Restorative Environmental Design. As it is currently, the procedurally generated cities must be created within Unity3D which might require some specialized familiarity with Unity3D. As well as the creation and placement of survey point locations within the city environment. There are a number of items that will be implemented in the future to make this application more accessible that will require no specialized knowledge of any other software. These items are the following:

- **Layout Creator.** Creation of a built in layout creator within the application. This would allow designers to create multiple layouts within the application in a MS paint like way. These layouts could then be saved and stored by the application. These saved layouts could then be used at any time and fed into the application to create a procedural city environment.
- **Procedural City Viewer.** With a procedural city viewer within the application, it would be possible to explore a generated city in a special overview mode without VR equipment. This special mode would allow designers to view the generated city environment from above, or any way desired, and place survey point stops at accurate positions within the environment.
- **Questionnaire Creator.** As it is currently, a questionnaire can only be created within Unity3D. To make it more accessible, the questionnaires could be created within the application. These questionnaires could then be accessed while in the procedural city viewer mentioned above, and specific questions and/or instructions could be placed at specified survey point locations within the environment.
- **Pre-Built Tiles.** With the support of pre-built tiles it would be possible to add more diversity to generated cities. There could be various types of pre-built tiles, such as landmark tiles and more general tiles such as a service type, i.e. a gas station or a store for example.
- **Curved Roads.** As is currently the application generates a grid like layout. By extending the application and allowing curved roads as well, a much greater diversity can be accomplished for the complete look of a generated city. This is already a work in progress.
- **Adjustable Terrain.** With the addition of adjustable terrain, e.g. Unity3D terrain, it is possible to read in heightmaps from real locations and generate a very realistic terrain for which the generated cities are placed upon. This would greatly increase the depth of the generated cities. This is already a work in progress.

## 6.3 Conclusions

With the application presented in this thesis work it is safe to say that researchers in RED have gained an important new tool. This has been achieved by harnessing procedural generation to create endless variations of urban city environments with relative ease where a number of elements can be controlled. Experiments can then be run within these urban city environments where their restorative potential can be measured with study participants. This has the potential to help us in advancing knowledge about how different urban city environments affect us, where the end goal would be to allow us to design and plan real urban city environments that will sustain us all on a psychological level and prepare us for future population growth.



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# Appendix A

## Credits

Here are listed resource portals where certain resources were gathered from.

### A.1 Textures

Textures for materials were gathered from <http://www.textures.com>.

### A.2 Sounds

Sounds were gathered from <http://www.freesound.org>.

### A.3 Models

Various models were gathered from the Unity3D asset store (<https://assetstore.unity.com>), such as vegetation and car models.





# Appendix B

## Participant Questions

How would you rate the following based on your experience? (put X by a number from 1-5)

"Using the controller was..."

Very Confusing	Confusing	Neutral	Not Confusing	Not at all Confusing
1	2	3	4	5

"Using the button on the virtual podium was..."

Very Confusing	Confusing	Neutral	Not Confusing	Not at all Confusing
1	2	3	4	5

"Moving the slider on the virtual podium was..."

Very Confusing	Confusing	Neutral	Not Confusing	Not at all Confusing
1	2	3	4	5

"Moving to another spot when the marker appeared was..."

Very Confusing	Confusing	Neutral	Not Confusing	Not at all Confusing
1	2	3	4	5

How much do you agree with the following statements? (put X by a number from 1-5)

"It was disorienting when being moved to another spot when the marker appeared..."

Completely Disagree	Disagree	Neutral	Agree	Completely Agree
1	2	3	4	5

"It was comfortable to wear the headset..."

Completely Disagree	Disagree	Neutral	Agree	Completely Agree
1	2	3	4	5

"It was comfortable to experience the virtual reality..."

Completely Disagree	Disagree	Neutral	Agree	Completely Agree
1	2	3	4	5

Below are some questions about the experience you just had (feel free to write them on the back of the page if more space is needed):

In general, what did you think of the tutorial environment?

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In general, what did you think of the city environment?

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Was there anything that you felt was strange in either environment?

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Was there anything that was not working correctly in either environment?

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Was there anything that was unclear in either environment?

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Did you feel any discomfort at any point?

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Did you feel it was easy to place yourself in the situation described in the city environment?

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Were the directions clear in the city environment? If not, what did you feel was unclear?

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When asked about the design and architecture of the city environment, which of the following did you feel you were being asked about? (Pick one)

☐ The architecture and design as if it were a real environment.

☐ The technical design and the look of the virtual reality environment.

Anything else you would like to say about your experience?

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## Appendix C

### Restoration Data

In Table C.1 we can see the results from the restoration likelihood questions from the 6 survey points.

Stop	Being Away	Fascination
1	3.57	2.71
2	4.28	4.28
3	5.57	5.28
4	6.43	6.57
5	4.86	5
6	6.14	6.43

Table C.1: Results from the restoration likelihood questions. Higher numbers mean the potential for restoration is higher.

The questions that were asked of participants relate to *being away* and *fascination*, which are restorative qualities. "*Being away* involves a sense of distance from daily routines and the projects that require directed mental activity" [15]. "*Fascination* refers to an effortless form of attention engaged by features of the environment or exploration of the environment" [15].

The questions were presented to study participants at each of the 6 survey points and were asked in the following order. The questions were written in Icelandic and were the following:

- *Ef ég væri andlega þreytt(ur) og ætti erfitt með að einbeita mér vegna mikils álags til dæmis í vinnu eða skóla þá myndi umhverfi eins og ég er að horfa núna hjálpa mér að slaka á og auka einbeitingu.*
- *Hvað finnst þér um arkitektúr og hönnun umhverfisins sem þú ert að horfa á?*



## Appendix D

### Participant Statements

Participants were asked to rate statements after experiencing the virtual reality. The statements can be categorized into two groups. The first group consists of four statements about the participants experience in using and interacting with the virtual survey interface. These statements and their answers can be seen in Table D.1.

Statement	P1	P2	P3	P4	P5	P6	P7	Average
Using the controller was...	3	5	5	5	5	4	5	4.6
Using the button on the virtual survey interface was...	3	5	5	5	5	5	5	4.7
Moving the slider on the virtual survey interface was...	3	5	5	5	5	4	5	4.6
Moving to another spot when the marker appeared was...	4	5	5	5	4	2	5	4.3

Table D.1: Results from statements related to the participants experience to the virtual survey interface and teleportation. Answers are numbered from 1 - 5, where 1 is Very Confusing and 5 is Not at all Confusing.

The second group of statements consisted of three statements about the participants general experience of using the virtual reality. These statements and their answers can be seen in Table D.2.

Statement	P1	P2	P3	P4	P5	P6	P7	Average
It was disorienting when being moved to another spot when the marker appeared...	2	1	1	2	2	4	1	1.9
It was comfortable to wear the headset...	1	2	4	2	3	3	4	2.7
It was comfortable to experience the virtual reality...	2	4	5	4	3	3	5	3.7

Table D.2: Results from statements related to the participants general experience to the virtual reality experience. Answers are numbered from 1 - 5, where 1 is Completely Disagree and 5 is Completely Agree.





# Appendix E

## Participant Comments

Below are comments from participants about the city environment:

Anonymous participant 1: *Very nice. Would have liked to see variation in lighting and in the sky. More plants is always better.*

Anonymous participant 1: *Strange to stand in the middle of the street. The environment looks nice with plants or tall buildings. Weather in the sky was kind of dull.*

Anonymous participant 2: *The buildings were too much alike, I thought it needed a little bit more variation in the environment.*

Anonymous participant 3: *Generic. Needs more parking spaces and more designs for buildings.*

Anonymous participant 4: *The sound should move with you, weird that the same sound hears after you have jumped further away.*

Below are general comments noted from participants:

Anonymous participant 1: *Very well done interface, but I could not pick up the balls by holding the button. The room looked nice.*

Anonymous participant 2: *Nice environment, fun to change the color of the balls.*

Anonymous participant 3: *No littering or graffiti.*







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