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Title: Realistic Realtime Rendering of a Virtual Forest Environment

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Category	*Min*	*Max*	Chosen
Requirement Analysis and Design	*0*	*20*	20
Theoretical Analysis	*0*	*25*	0
Experiment Design and Execution	*0*	*20*	5
System Development and Implementation	*0*	*20*	15
Results, Findings and Conclusions	*10*	*20*	10
Aim Formulation and Background Work	*10*	*15*	10
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Quality of Deliverables	*10*		10
Overall General Project Evaluation (*this section allowed only with motivation letter from supervisor*)	*0*	*10*	0
Total marks		**80**	**80**

Realistic Realtime Rendering of a Virtual Forest Environment

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ABSTRACT

Being in nature is known to have positive benefits relating both to physical and mental health, but there are people that cannot access it due to reasons such as poor proximity, lack of transportation, and mobility impairments. Virtual nature is known to be a good substitute to access the same benefits offered by real nature, and we investigate the elements that constitute the design of a restorative forest environment, and techniques for rendering this virtual forest efficiently for viewing in virtual reality. This balance is important for virtual reality, since by making the fidelity too low there is a risk of breaking presence, and by making the fidelity too high an unresponsive environment will be produced. Both can result in cybersickness which will counter any restorativeness. Through the balance of performance and quality, we created a realistic and restorative multisensory virtual forest environment with both realtime rendering and feedback while maximizing immersion using interactable objects.

CCS Concepts

• Human-centered computing → Virtual reality.

Keywords

Virtual reality; real-time rendering; virtual forests

1. INTRODUCTION

Forests have relaxing qualities and when people immerse themselves in nature, they access important benefits for their mental health and wellbeing. Forests have relaxing qualities and this [Frumkin et al. 2017]. This, reducing stress [Ward Thompson et al. 2016], improving sleep [Grigsby-Toussaint et al. 2015], and bringing greater happiness and life satisfaction [Chang et al. 2020]. Because of the abundance of characteristics that are effective for restoration, some healthcare providers have even started to prescribe nature, referred to as "nature pills". However, it is sometimes difficult for people to access nature due to reasons such as poor proximity [Akpinar 2016], lack of transportation, or physical disabilities [Burt et al. 2013]. Thus, there needs to be a way for people to access the benefits of nature despite these restrictions, and simply viewing nature is known to be effective in achieving this goal [Ulrich 1984; Berto 2005].

Research shows that a virtual environment that simulates nature can provide the benefits of real nature [Kjellgren 2010; Brooks 2017]. There have been various attempts to create these nature pills in virtual environments including 360-degree videos of nature [Browning et al. 2020; Calogiuri et al. 2018], and computer-generated virtual reality environments [Yeo 2020]. The former is not interactive nor very immersive, while the latter allows a much more immersive experience [Yeo 2020]. This is because 360-degree videos are generally made only for viewing and listening, but not for interacting with objects that are in the scene. In virtual reality environments you are not only able to see and listen, but you are also able to interact with objects that are in the scene to potentially modify the environment in some way and receive feedback from actions you perform in it.

We have created a multisensory virtual forest environment, which is realistic and allows for interactive exploration. This means that the environment supports the auditory, haptic, optical, and olfactory responses of the human nervous system through various stimuli.

An important research question is then about the methods we can use to balance the real-time responsiveness of the interactive environment while maintaining high visual fidelity.

The system evaluation would be done with respect to whether the environment is sufficiently responsive, realistic, and does not induce motion sickness with moderate usage. A full user evaluation is beyond the scope of this paper, and instead we used heuristic evaluation with the aid of three academic staff from the University of Cape Town. We asked them questions to assess the restorativeness, realism and realtime rendering aspects, keeping track of important metrics such as latency, frame rates, and visual fidelity.

2. RELATED WORK

2.1 Restorativeness and Biomes

Some biomes are more preferable than others, and this is important because this preference is positively correlated with human restoration and might even promote it [Kaplan and Kaplan 1989]. There are many different aspects that influence preference, which include 'socially differentiating attributes such as age, gender, place of residence, and environmental experience' [Lyons 1983]. Another important aspect is familiarity, which is positively associated with liking biomes [Mangone et al. 2021]. Lastly, cultural background is another aspect that induces different levels of psychophysiological restoration when viewing different types of environments [Chang 2004].

There are some varying results about what kind of biome constitutes the best preferred environment. One study shows that tundra and coniferous forest areas are the two most preferred biomes [Han 2007], while in contradiction some studies show that deciduous forests are most preferred [Lyons 1983], or at least equally preferred to coniferous forests [Balling and Falk 1982]. There is disagreement in general as to what is the most preferred environment even between forests and savanna [Balling and Falk 1982].

Since savanna, deciduous forests, and coniferous forests have the most support for preference, it would be appropriate to select one of these to maximize restorativeness. We choose to create a forest as not only is it familiar to many people in the Cape Town region, but it is also common to other geography in the world covering 31% of the global landmass [FAO and UNEP 2020] while savanna only covers about a fifth of the global landmass [Sankaran et al. 2005].

When designing a preferred, restorative environment, there are four important perceived features that must be adhered to: openness [Tomao et al. 2018], complexity [Han 2007], water features [White et al. 2010, Han 2007], and true-to-life modelling.

Open forests with fewer understory (also known as underbrush or undergrowth) shrubs would have a stronger restorative effect than forests consisting of varying levels of stand that could even be natural. Stand refers to both the horizontal and vertical components of the forest, and is defined as the height, diameter, and crown layers of trees and shrubs, while understory is defined as the plants that are 0-50% of the maximal height of the stand height. Stand density, measured by greater levels of understory density, is negatively associated with perceived restorativeness and it should be avoided. They suggested this may be because dense forests obstruct vision and could induce negative feelings related to the perception of insecurity [Sreetheran and Konijnendijk van den Bosch, 2014].

Complexity of a scene is important because it positively contributes to the preference for an environment [Han 2007]. We can create a complex environment while maintaining the relatively sparse understory layer through details such as water features, rocks, plants and debris. Water features are especially of importance as they are known to be better than just green spaces and have a benefit for mental health [White et al. 2010]. True-to-life modelling of the environment is required, as planting with natural structure is most restorative [Hoyle et al. 2017]. In the environment, we maintain a balance between the natural structure and relatively less dense understory layer.

Figure 1. Varying levels of stand. From left to right, multi-layered stand, bi-layered stand, and mono-layered stand. [Tomao et al. 2018]

2.2 Rendering Techniques

Some of the rendering techniques that relate to our project are briefly discussed. These rendering techniques allow us to efficiently display images on any given screen, which is especially important for virtual reality applications as real-time feedback and real-time rendering are important factors that are needed to mitigate cybersickness, and because performance in VR headsets is especially important as the images are rendered twice, once for each eye.

2.2.1 Billboards

Billboards are one of the most common techniques used for rendering forests, due to their low cost. They can either be a single image that represents a whole model, or a set of arbitrarily oriented images called billboard clouds, where 3D models are simplified onto a set of planes with texture and transparency maps [Décoret et al. 2003]. Regardless of which type of billboards are used, they usually cause parallax problems. Other artefacts may also occur depending on the implementation, such as popping and ghosting. Popping occurs when an always camera facing billboard implementation is used. It is caused by the change in the relative order of the billboards, and refers to one image coming in front of another as you rotate the camera around the axes of two close billboards.

As this does not allow for dense forests this implementation is not often used in practice. Instead, billboards with multiple fixed textured quadrilaterals paired with scaled fading of the textured quadrilaterals that do not face the camera are more commonly used. This removes the popping but introduces a ghosting effect due to the duplication of features [Decaudin and Neyret 2004].

Figure 2. Use of billboard clouds to represent trees. Original model (left), billboard approximation using k-means clustering (right). [Behrendt et al. 2005]

2.2.2 Level of Detail (LOD)

Level of detail, or the complexity of a 3d model representation, needs to be adapted based on some criteria for the efficient rendering of images, and this technique is utilized in a majority of, if not all, recent virtual reality applications to make the rendering interactive and efficient. Rendering virtual nature involves rendering a combination of trees and terrain and we look at the two classes of LOD techniques. Figures 2 and 3 demonstrate the basic idea of LOD.

Most applications today use the discrete LOD technique to render trees, creating multiple versions of every object with a different LOD during an offline preprocess. Then, the appropriate version of the object is selected at runtime based on some criteria such as distance, size, or priority. For example, the further the object, the coarser version of the object we can use, reducing the number of polygons and decreasing the rendering time. A limitation of the discrete LOD is that it cannot predict the viewpoint of the camera from which an object will be viewed from and hence the LOD is reduced uniformly. The discrete LOD technique is the preferred method for most applications because of the decoupling of the simplification process and the runtime rendering, taking away the simplification computation during runtime [Luebke et al. 2003].

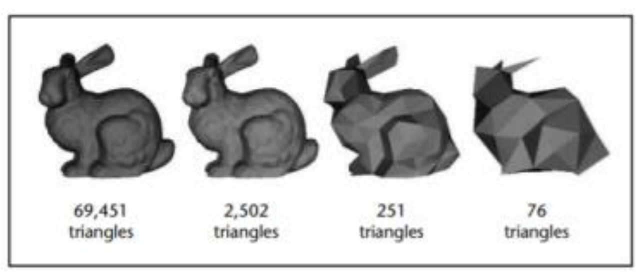

Figure 3. A model represented with different levels of detail. [Luebke et al. 2003]

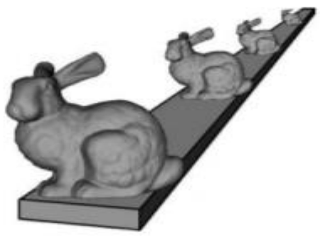

Figure 4. The level of detail of the model changing based on distance. [Luebke et al. 2003]

2.2.3 Skyboxes and Skydomes

The skybox is a cube in which the world is enclosed. A skydome is just a sphere or a hemisphere of a skybox. They are for backgrounds and has the property of being unreachable. They are very efficient because they often are fixed images that do not involve level of detail [Yang et al. 2011], but they can be modified for realistic rendering [Mitchell et al. 2007].

It would be suitable for the rendering the background of nature using skyboxes to generate scenes for nature including natural phenomena such as rain and snow [Wang 2007]. While this could be enough for a very simple non-interactive virtual environment, if this is the only feature that exists in the environment, the environment would be very limited as everything is unreachable.

However, when used in combination with other rendering techniques to build a virtual nature environment, that could increase rendering efficiency while a much more immersive experience while enabling exploration. In the case of rendering forests in combination with skyboxes, a suitable use could be to render mountains and celestial objects such as the sun, moon, or stars through the skybox while rendering other aspects through techniques such as billboarding, billboard clouds, and rendering simplified meshes through LODs.

2.3 Performance

Keeping high performance of the environment is important as low frame rates and latency has been found to increase the chance of cybersickness occurring [Mackin et al. 2019]. Research [Brunnström et al. 2020] shows that a display latency greater than 20ms starts to cause cybersickness in some users and should be avoided and kept below 30-35ms. For hand controllers longer delays can be tolerated but should be kept below 500ms before it becomes noticeable enough to affect the experience negatively. The focus of their research was not on whether it affects the emotional state but rather simulator sickness while performing some task using a joystick, so it would be worthwhile to investigate whether such latencies would significantly influence the emotional state of the user.

Graphics quality affects the perceived fidelity of visual and overall experience [Debattista et al. 2018]. Higher graphics quality would be desirable for a better experience, as it is associated with greater presence [Hvass 2017], which in turn is negatively associated with cybersickness [Weech et al. 2019].

However, there is conflicting evidence that visually highly realistic virtual environments are more likely to induce cybersickness [Tiiro 2018]. Realism on their part meant levels of detail, animated models, lighting and fog. This study did not refer to the frame rates of highly realistic renderings compared with the frame rates of less realistic renderings, so there could be a false correlation due to lower frame rates resulting from highly realistic renderings which may have been a major factor in inducing simulator sickness. Additional shortcomings of the work include not establishing a baseline metric for simulator sickness, using two different systems to run the experiment, and testing some users more than once, which would have affected the validity of their experiment. There is also weak evidence that highly realistic graphics could induce more sickness when moving [Pouke 2018].

Regardless, it would be less complex to create a less realistic environment compared to a realistic one, and it has been decided that visual fidelity for this project should be high, while maintaining high frame rates. Measuring visual fidelity will involve heuristic assessment of lighting, level of detail, and texture. A high visual fidelity environment would have realistic lighting, a good level of detail while using realistic models of trees, and realistic texture to render, for example, grass and branches on the ground.

3. ENVIRONMENT DESIGN

When developing the environment, we used a combination of paper prototyping, agile methodology, and user sensitive design. We initially did research and created a diagram of an initial design of the environment. We developed the environment incrementally, making improvements step-by-step, and repeatedly redesigned certain elements of the environment, consulting our supervisor multiple times who evaluated the environment and provided guidance on the design aspects that can be improved each time. The environment was created with the goal of realistic, realtime and restorativeness in mind.

The realism of the environment was instilled by modelling the environment as close to reality by implementing the readings on ecosystems of deciduous forests, the physics of wind in an area surrounded by hills, keeping lights realistic and through careful design of the texture of the terrain. Presence, or the illusion of the user being in the environment, is important as it is negatively associated with cybersickness [Weech et al. 2019]. It is positively associated with the ability of the environment to provide interaction [Slater and Usoh 1993], as well as the fidelity and realism of the simulated landscape to the senses [Witmer and Singer, 1994]. We included virtual objects that have physical counterparts which the user could interact with. This helps increase presence and enhance the immersive experience by enhancing the realism of the environment [Hoffman et al. 1998].

Realtime requirements were met by making performance optimizations that are explained in later sections, while the restorativeness was maximized by including features in nature that are known to be restorative.

3.1 River and Waterfall

Exposure to freshwater and “blue space” has been shown to play an important role in promoting mental health [McDougall et al. 2021], and blue space is also associated with higher positive affect and perceived restorativeness [White et al. 2010]. In addition, Aquatic-Green scenes were significantly better for restorativeness than green space alone, indicating that the interaction between water and land may be valuable [White et al. 2010]. This positive association with water bodies is suggested to be due to the significance of water in human survival and well-being, through biological needs and/or learned experiences [Ulrich 1993].

Herzog et al. [Herzog 1985] shows that rivers, ponds, and lakes are significantly preferred over swamps, and water features that are reflective are most desirable [Nasar and Li 2004]. To our knowledge there is no existing research comparing the restorativeness of rivers and lakes, so we acted on personal preference to model a river. Natural water sources are preferred over artificial water features, and a wide river is most relaxing, creating a sense of tranquillity [Sakici 2015]. We created a natural and wide river, with low flow and low turbidity as these are the preferred features of a large river [Pflüger et al. 2010].

We added a waterfall to increase the complexity of the environment and be an element of interest that enhances the experience. Harsh water jet sounds are not pleasant or relaxing [Patón et al. 2020], so we used a softer sound for the waterfall.

Figure 5. River and waterfall in the NaturePill Environment

3.2 Terrain

There are two components to the terrain design. First, the composition of the terrain or how the terrain will look with respect to its elements; second, the elevation of the terrain or how the terrain is shaped. The appendix shows an aerial view of the terrain without the forest (below).

3.2.1 Trees, plants, and debris

With regards to the composition of the terrain, the forest consists of beech trees which can be found in deciduous forests, and undergrowth for the forest floor consisting of shrubs, bushes, and herbs, which have been clustered primarily in the shaded areas of the map. Although beech trees are not endemic to South Africa, these forest environment nature models were of excellent quality and in terms of budget the most reasonable choice. There is a tree species *Rapanea melanophloeos* commonly known as the Cape beech which looks like the European beech tree family [Xaba 2021], so this does mitigate the unfamiliarity of the forest that might exist for the average user. Mushrooms grow on some of the trees adding to the detail, and debris such as rocks, logs, twigs and branches have been placed throughout the forest to enhance the realism.

Figure 6. Debris placement on riverbank

3.2.2 Terrain texture

Textures are a cost-efficient way of making the terrain look realistic without having to increase the detail, resulting in performance gain. The texture of the forest terrain consists of a blend of rocks, sand, soil, grass, moss, and leaves spread throughout the environment. Much attention was paid to the detail of texturing the terrain appropriately, such as placing moss primarily where there is shade, stones where areas are hillier, and blending this texture with moss where shady, and generally blending leaf textures throughout the environment. Where areas were exposed to sunlight, more grass texture was used.

3.2.3 Terrain elevations

Variations in the elevation of terrain is encouraged for environment design, as complexity positively contributes to the preference for an environment [Han 2007], and the presence of mountains when viewing landscapes produces positive psychophysiological reactions [Chang 2004]. It would be appropriate to include varying levels of terrain elevation such as mountains and valleys. However, due to budget limitations and modelling constraints, we decided not to include the mountain in our environment and instead settled for hills that surround the relatively flatter explorable area.

This elevation information is stored in a heightmap, a grayscale images that store height data, where white represents maximum height, and black represents minimum height. Heightmap resolutions are important to be able to make the terrain elevations look more detailed. The higher the resolution of the heightmap, the more detail in the modelled terrain. In our case, the resolution could be kept relatively low at 513x513 because our environment does not require a very large heightmap due to its relatively small size of 200x200 meters.

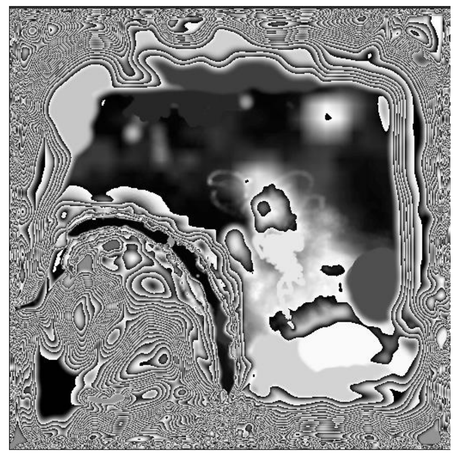

Figure 7. The heightmap of the NaturePill environment.

3.3 Bench and branch

A bench and branch were deemed to be appropriate for a natural environment since many parks have benches and branches are common in forests. These were carefully chosen so the user can feel the physical woody texture.

The measurement of each object was taken and hand-modelled using Blender, which had the advantage of being able to optimize the mesh of the polygons of each model by using the bare minimum of vertices needed to model each component, as opposed to the large number of vertices which are created by photogrammetry software. Each object was UV mapped onto royalty-free wood image textures, which gave good detail for very little performance cost.

Figure 8. UV map of the bench (left) and branch (right).

3.3.1 *Bench*

Virtual benches were placed in various locations in the environment, so the user may relax and peacefully enjoy the view while sitting on the bench. When the user is not aligned to sit on it, we have designed the bench to display with transparency, and while the user is aligned with the bench, for it to display opaque. Alignment simply means that the movement of the user will correctly position the user relative to the coordinates of the bench in the world coordinates, such that where the user sees an opaque bench in virtual reality, the bench is mapped to in physical reality.

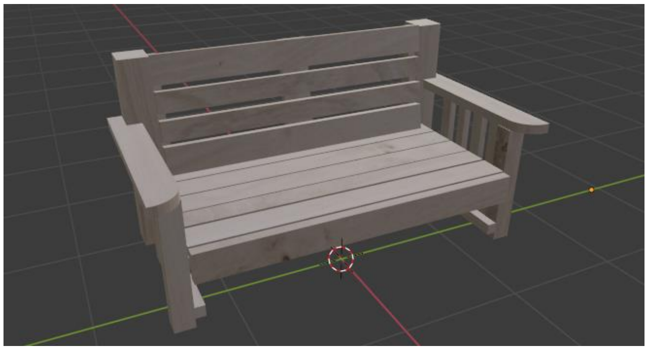

Figure 9. Bench modelled and textured in Blender

3.3.2 *Branch*

If there were physical objects that could be found in nature that the user could pick up and interact with the environment using this object, it would add to the immersive experience. A good candidate for such an object was a branch, which we decided to let the user to use as an aid for locomotion with which they can point to a location they can teleport to. The implementation of the locomotion is not the focus of this paper and is not discussed.

When modelling, the branch benefited especially from texture mapping, as we applied a bump map to it which allowed us to simulate the bumpiness of the branch while keeping the number of vertices low. There was no transparency needed for the branch as it could always be picked up. The branch, as it always follows the user in the virtual world so it can be picked up from the ground at any point. None of the heuristic evaluators noted that this broke their immersion, and the use of the branch did indeed increase their presence.

Figure 10. The physical branch that served as the model basis.

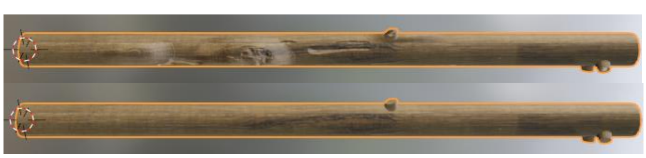

Figure 11. Branch modelled and textured in blender with (top) and without (bottom) bump map applied.

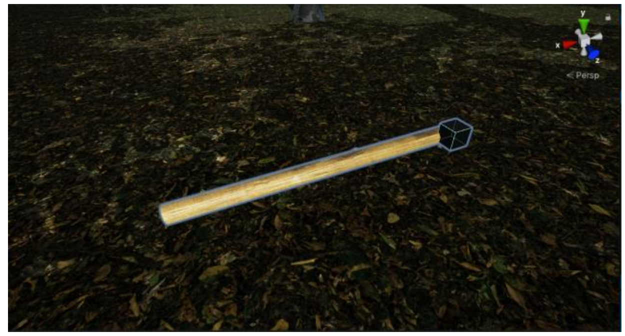

Figure 12. Branch in the virtual environment.

3.4 Background Elements

This section lists the background elements of the environment such as the sky, ambient light, fog, wind, and the smell of the environment.

3.4.1 *The Sky*

The skybox is a cube in which the world is enclosed. They are for backgrounds, being unreachable and are very efficient because they often are fixed images that do not involve level of detail [Yang et al. 2011]. Weather affects the mood of people, and accounts for 40% of its variability [Persinger and Levesque 1983]. There is evidence that sunny weather lifts the mood of people [Li et al. 2017] and is associated with less stress [Barnston 1988], while rainy weather is associated with depressive symptoms and negative feelings [Hsiang et al. 2013]. Thus, it is ideal to create an environment that features sunny weather. A 4K HDRI image-based skybox featuring cumulus clouds and the sun was used for the environment. To our knowledge there is no research done on if clouds are restorative, our subjective knowledge has found cloud watching to be of interest, and hope that this stimulates the user.

Figure 13. The HDRI image used for the skybox.

3.4.2 *Ambient light*

Cooler, sunny weather tends to be associated with less stress [Barnston 1988]. The lighting of the environment was made to be quite bright and sunny overall to support sunny weather, with a lower position of the sun in relation to the horizon to support the illusion of cooler weather.

The sunlight for the environment has been rendered as a directional light aligned with the position of the sun in the skybox. Color temperature of daylight can range from 4800K to 10000K, and we initially used cooler light temperature of 8200K to match the cooler feel for the environment. Although the environment was relaxing, research shows that warmer tones are better for relaxation [Noguchi and Sakaguchi 1999] and we decided to decrease the color temperature of the sunlight to 6700K. This is a slight increase in color temperature compared to the average outdoor noon temperature of 6504K [Schanda 2007] based on the D65 colorimetry standard created by the International Commission on Illumination. The actual color temperature is a function of time of day, season, and geographic location, and the slight increase in our sunlight color temperature is not based on formal calculations and should be taken as a rough estimate. Finally, we added a bloom effect to the sun to simulate its glow and add to its realism.

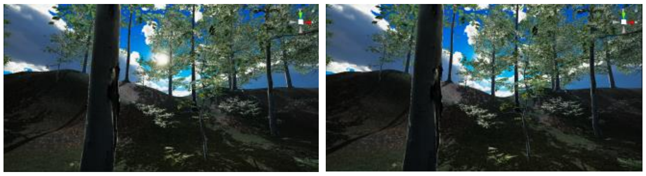

Figure 14. Sun with (left) and without (right) bloom effect.

3.4.3 Fog
We applied fog to the environment to add to the ambience and allow us to hide the clipping of objects and shadows to gain performance. The fog effect creates a screen-space fog, and light absorption increases based on distance involving an exponential squared as true atmospheric perspective necessarily involves this relationship [Foley et al. 1996]. It is possible to use heterogenous fog effect using Perlin noise as well [Zdrojewska 2004], but we settled for a homogeneous fog effect due to existing implementations native to Unity.

Figure 15. Environment with (left) fog and without (right).

3.4.4 Wind
There is a mild wind throughout the environment that affects the trees and plants. We created the environment with hills so that the trees are affected more by the wind, and the smaller shrubs are less affected by wind. This is due to the environment being surrounded by hills, which can have a shielding effect of the wind on the forest floor. The implementation of the wind was done through the using a wind zone object.

3.4.5 Scents
Scents will certainly add to the multisensory experience of the environment, and petrichor, undergrowth and forest scents were used simulate what it would smell like. These scents were designed to match the environment, having relatively sunny weather with cumulus clouds giving the feel of clearing skies after rainfall, and the forest filled with dense undergrowth clustered around trees.

Figure 16. The scents chosen (front) and the nebulizers (back) which released the scents in the experiment room.

4. SYSTEM DEVELOPMENT
To develop the environment, we used hardware at the courtesy of the University of Cape Town, and both open source and proprietary software.

4.1 Hardware
The computer used to benchmark the environment performance was equipped with an Intel Core i5-9400F @2.90 GHz CPU, an NVidia RTX 2080 Super GPU, and 16GB of DDR4 2666Mhz DIMM RAM. This was rendering to an HTC Vive Pro VR headset.

The base stations were attached to the perimeters of the experiment room, and trackers were attached to a bench and branch that was used in the environment. To support the multisensory experience, forest scents and nebulizers were released in the room at the time of testing. Locomotion, which is not the focus of this paper, was done through HTC Vive controllers, optionally aided by the branch through a custom C# script that allowed the user to point to where they wished to teleport to.

Figure 17. The apparatus used in the environment. From top left to bottom right: HTC Vive Pro. The physical bench that served as the model basis and tracker, the branch and tracker, Vive controllers, scent containers with nebulizers behind it.

4.2 Software
The software that was used to create the environment includes OpenVR, an API that allows its use to interface with various VR hardware; Unity, a cross-platform game engine through which we modelled the environment by hand; Unity assets, which include the models used in the virtual nature environment, and Blender, to create the branch and bench models. The performance of the virtual environment was measured using MSI Afterburner and Rivatuner Statistics Server, which recorded the rendering speed in terms of frames per second (FPS) for the environment.

5. GRAPHICS
When rendering the environment, we want the best possible graphics to create the highest sense of realism. However, this comes with a performance cost that must be accounted for, as realism and performance are conflicting goals and gaining on the one side results in a loss in the other, and there is a limit to the amount of computation in terms of time that we can fit in for each frame rendered. Efficient rendering is important because it provides a more immersive experience from the increased frame rates [Mackin et al. 2019]. Thus, it is a bit of an art of seeking the balance of these two aspects.

5.1 Realism
Along with the effort put into creating a realistic environment through the forest design we have used some graphical techniques to improve realism. Realism results in performance reduction. In

general, the models for the forest were high quality scanned models and enabled us to create a realistic environment using these models. The texturing of the terrain was meticulously done to blend combinations of grass, leaves, rocks, roots, sand and soil, and debris placed (Figure 6) throughout the environment in convincing locations. The trees used were of the same species, but such forests are not rare in the world [Peh et al. 2011].

5.1.1 High dynamic range (HDR)

In the natural environment a wide range of color occur, and standard dynamic range (SDR) is insufficient to create the sensation that a person is watching a real object. High dynamic range increases this range from SDR allowing for more realistic lighting through increased color gamut and contrast, resulting in brighter highlights, darker shadows, more details in the highlights and shadows [ACM 2021]. Through HDR we can create lighting that emulates the glare of the halo that forms around bright objects such as the sun [Seetzen et al. 2004]. Figure 18 is a collage of HDR image on the left and standard range on the right. There is a partial glare of the sun that can be observed on the left side of the collage while there is none on the right side, and a slight color divide occurs at the center due to the difference of HDR and SDR.

Figure 18. HDR with ACES tonemapping (left) and SDR (right) images attached together for contrast.

Another important aspect of HDR is the tonemapping, or the process of mapping color values from HDR to SDR. HDR stores color values in Any color intensity above 1 will be clamped at 1, if tonemapping is not applied, it introduces unwanted alterations in the luminance of the scene. This can be seen from Figure 31. We have decided to choose ACES (Academy Color Encoding System) tonemapping for a more vivid color from its greater contrast and saturation. The greater contrast in colors improved the visuals of the shadows as well.

5.1.2 Lights and shadows

Realistic lighting and shadows are important for the environment., and the elements of realistic lighting design were covered in the 0.

We used the highest shadow resolution provided natively by Unity to minimize the appearance pixelated shadows, but even using this, at very close viewing distances of the shadows were pixelated. While this effect exists universally on the environment, it is typically only visible on benches due to the shadows rendering closer to the viewpoint of the user (Figure 19).

The shadow distance was also scaled appropriately so that the discontinuity in the appearance of shadows to be unnoticeable to the user when shadows do not appear on distant objects, aided by fog to hide this artifact. There is also a bit of optimization involved with the scaling of shadow distances, as increasing the shadow distance to infinity will create shadows for objects that are not of interest and increases computation significantly which is undesirable.

Figure 19. Pixelated shadows can be seen on the bench.

5.1.3 Antialiasing

When rendering computer graphics, geometric objects are sampled which generates pixels, that are rendered on a computer screen. There is a fundamental problem of this discretization process, stemming from limited sampling rates of displays, and result in objects appearing blocky, or stair-wise along its edges, silhouettes, or creases. Due to this effect, sometimes very small objects disappear between samples, or complex details of the features may be lost [Jiang et al. 2014]. To avoid aliasing, we use an antialiasing (AA) technique to mitigate it. There are a multitude of AA techniques in the realm of computer science, and we very briefly discuss three AA techniques: MSAA, FXAA, and SMAA. We will compare the impact of these aliasing techniques and choose which one to use in the "Antialiasing technique selection" section. Figure 27 show the application of these antialiasing techniques to the environment.

5.1.3.1 Multisampling anti-aliasing (MSAA)

MSAA is a generic anti-aliasing algorithm that formed the basis for many future improvements. It does this by rendering the image at a higher resolution and scaling it down to fit the required resolution. It provides the best image quality out of the three and has the most performance impact. The quality ranges improve in factors of two, and it is available in 2x, 4x, 8x, and 16x MSAA, where the coefficients refer to the amount of additional sampling. It is worth noting that 4x MSAA is much better than 2x MSAA, but from 4x onwards the increase in quality diminishes in relation to the cost. Thus, 4x remains a good balance between cost and quality [Jiang et al. 2014]. Figure 20 demonstrates this diminishing increase in the quality as the level of sampling increases; the difference between 4x and 8x MSAA is barely visible to the human eye. It has a problem with processing transparent textures as there are no polygon edges inside for MSAA to apply. Transparent texture is used extensively in the case of our environment in the form of foliage in the models of plants in the environment.

5.1.3.2 Fast approximate anti-aliasing (FXAA)

Fast approximate anti-aliasing is a post-processing AA technique that attempts to maximize performance and is the quickest out of the three algorithms. It is agnostic to the geometric figures and simply analyzes and smoothens all pixels. It is thus very fast, but because of this smoothening of all pixels, it can cause unwanted edge reduction [Jiang et al. 2014]. It has difficulties in processing diagonal edges and produces unwanted blur along edges [Grahn 2016], and in terms of quality it is the least preferred option. It can deal with transparent textures, although not accurately, as it blends all pixels on the display. It is worth noting that it does not cause significant fatigue when used in VR, even though MSAA with the best visual quality caused the least fatigue [Jukarainen 2016].

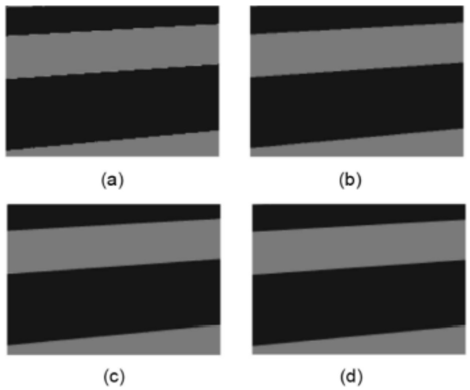

Figure 20. (a) Original aliased image; (b) 2x MSAA result; (c) 4x MSAA result; (d) 8x MSAA result. There is little visible quality improvement between 4x and 8x MSAA.

5.1.3.3 Subpixel morphological anti-aliasing (SMAA)

SMAA is an AA technique that involves finding discontinuities between pixels for some image, identifying patterns of the pixels, and blending the color of each pixel that according to weights calculated according to these patterns. It is well suited to process sharp geometric figures and diagonal figures. It has a limited amount of effectiveness in removing aliasing for transparent textures and performs better than MSAA in that respect. In terms of quality, it is worse compared to MSAA but better than FXAA [Jiang et al. 2014], with better performance than MSAA [Jiang et al. 2014] and worse than FXAA [Grahn 2016].

5.2 Optimizations

5.2.1 Frustum culling

Any camera must restrict the scene to a finite space for rendering scenes, which prevents it from rendering forever. This is done through a technique called frustum culling which clips objects outside the view frustum (Figure 21) and discards them. Through this process, unnecessary computation for objects outside the view frustum is removed and results in performance improvements [Parekh 2006].

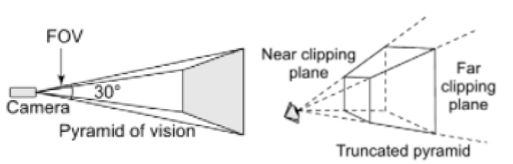

Figure 21. The shape of the truncated pyramid of vision, or the view frustum, is determined through the field-of-view (FOV) and the near and far clipping planes. [Parekh 2006]

In practice, instead of using actual objects to determine its culling, the bounding box of each object is tested for determining whether it should be rendered for efficiency [Assarsson 2000].

5.2.2 Single pass stereo instanced rendering

Multi pass stereo rendering performs the computation to render the same mesh twice but treats it as different meshes and issues two draw calls, once for each eye, and without optimizations it can take up to double the time rendering compared to a mono display [Ebert et al 1996; Miniel et al 2004]. This is inefficient, and single pass rendering uses the same mesh to create one image but issues two draw calls to render to each eye, by packing it into a single texture twice the width of one eye texture [Unity 2021a]. Single pass instanced rendering that we used optimizes this further and reduces the draw of a mesh into a single draw call that projects twice, once for each eye by instancing each draw call. Due to the cache coherency of draw calls, it greatly reduces the CPU use and slightly reduces the GPU use, resulting in significant performance improvements. [Unity 2021b]

5.2.3 Level of detail

To optimize the environment, we used models that had level of detail that changes with distance. Initially the smaller details of the environment had noticeable popping in and out of vision (Figure 22) due to the short culling distance, and the culling distance of the models that had this issue had to be scaled individually as it significantly distracted the user. Scaling the LOD distance of the entire environment by some factor did not work as the performance drop was significant and still did not solve the popping issue.

Figure 22. Objects popping in and out based on a small change in distance. Left is further, and right is closer to the ground.

There is a limit to the amount of scaling we could do since having everything visible all the time at infinite distance is unreasonable due to its computational cost, and we just scaled enough to make the popping of objects in and out of vision happen further out in the distance which made it less noticeable. The use of fog in the environment helped make this popping less noticeable as well.

5.2.4 Textures

To create a complex environment with a lot of detail, it is more efficient to use textures instead of creating models with every detail that is desired. They have been used extensively to create detailed surfaces of objects in the environment, including the terrain, trees, mushrooms, rocks, and other plants. The trees and plant foliage are implemented as a cloud of textured quadrilaterals which is alpha blended to make the textures transparent in the foliage section to simulate the leaves.

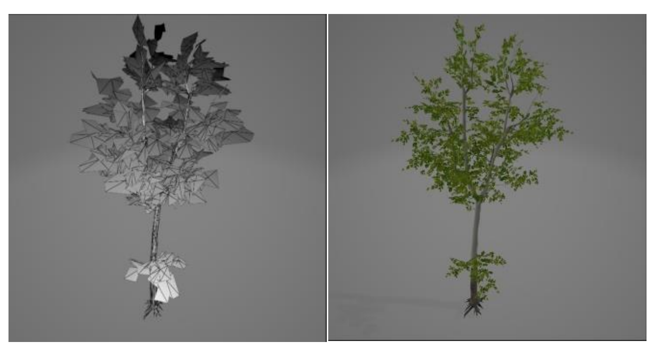

Figure 23. A tree model before without alpha blended textures (left) and with alpha blended textures (right).

5.2.5 Baked Lights

Realtime lighting is expensive because all the computation of the lighting of the environment must be done at runtime, fighting for resources that can be used elsewhere. Therefore, we chose to use a mix of baked lighting and realtime lighting for the environment to reduce this performance cost at runtime. Baked lights are light information for static objects that do not move in a scene and are stored in a lightmap which contains the pre-calculated brightness of surfaces in the scene. This stored information is loaded to light the scene at runtime reducing the rendering cost of shadows.

5.2.6 Occlusion culling

Occlusion culling is an optimization technique to avoid needlessly processing invisible portions of the scene by discarding invisible polygons early in the graphics pipeline [Coorg and Teller 1997]. It has a computational cost attached to it due to the additional processing, and it would not work well for the environment that we created. It works well when there is a large occluder that hides a portion of the environment, but we have optimized the scene by removing any objects that would be hidden by hills, and there is no large occluder that would let us benefit from utilizing this method. We cannot effectively set trees as occluders as not only are they small occluders, but there is wind that causes swaying for them, and any leaves are transparent and are a form of sparse geometry. As there are few cases where occlusion culling would be effective such as the user standing very close to a tree, we decided not to investigate this further.

6. RESULTS AND DISCUSSION

6.1 Heuristic evaluation

Three researchers from the University of Cape Town were asked to evaluate the environment. Two of them were active researchers in the graphics space, and one was a researcher in psychology.

The evaluators were overall very happy with the state of the environment and commented that the environment had very high realism, and no issues with performance in both the display refresh rate and controller latency. They experienced no significant cybersickness when viewing the environment and have agreed that the environment would certainly be relaxing, with the psychology researcher definitively stating that she was relaxed, while the computer science researchers stated that they were more focused that relaxed to give as much feedback as possible for the evaluation but mentioned it certainly would be relaxing. A few important points they made relating to the rendering, usability, and realism are discussed, while those relating to locomotion are not. The full heuristic evaluation questions that were asked can be seen in the appendix (below).

6.1.1 Lighting and Shadows

All the evaluators were happy with the use of lighting and shadows in the environment. One of the evaluators of the environment noted that the bloom effect made the lights look more realistic with respect to the sunlight, and even gave the illusion of volumetric light which has not been applied. No one noticed the pixelated shadows on the bench during heuristic evaluation, and shadows were said to be of very good quality.

6.1.2 Scents

The participants of the heuristic evaluation were unable to smell the scents without us directing their attention to it. They all mentioned that their sense of smell was bad, and this was likely amplified from wearing a mask due to Covid-19 and the fact that the scents released from the nebulizer were weak compared to the scent of the fragrances itself. To accommodate this, it may be necessary to either get a stronger nebulizer, run it for a longer time before usage, or get the user closer to the source of the scents. Upon smelling the scents from close, the evaluators all agreed that the scents adequately reproduced the scent of the forest.

6.1.3 Clouds

The two evaluators who by profession are computer scientist researchers, who have both done research in generating clouds noted that the clouds are not looking very realistic, especially the clouds directly overhead, giving away the use of textures. They also mentioned that a few clouds were looking quite dark, giving the sense of nimbus clouds and possibly incoming rain while the actual cloud itself was looking relatively thin. This was dominant and caught the eye as it contrasted with the sunny environment, and a suggestion was made to use darker, thicker clouds or brighter, thinner clouds. In contrast, the psychology researcher really liked the clouds. The clouds are indeed textures painted on a skybox, and they can certainly be improved by using better textures that are more realistic for the least performance impact. Otherwise, one could investigate the use of volumetric clouds to generate accurate modelling of the clouds, which is a much more computationally expensive method that could be of interest for future work.

6.1.4 Trees and Undergrowth

The use of undergrowth was universally liked by the three evaluators, which added to their visual interest. They appreciated the realistic modelling that met their expectation of real undergrowth, especially the ferns. Two researchers noticed that there is a bit of uniformity in the environment, and it seemed like a curated forest. There were suggestions to use different species of trees which requires more modelling. This is more of a budget constraint than anything else and has not been addressed. The size differences of the trees were good.

6.1.5 Branch and Bench

The evaluators have stated that the bench and branch have helped them feel more immersed in the environment, and the placement of the benches in the environment at points where they can observe nature was excellent. The models have aptly represented the real bench and branch.

6.1.6 Path through Environment

One of the researchers liked the fact that there was no path in the environment inviting the user for exploration, another wanted a path through the environment to direct the user such as a stone path giving visual cues to direct the user. This is an interesting point for further investigation, but the current environment is without a visual path. However, all the evaluators were prone to get lost as all the trees are of the same species and look similar. We have implemented their feedback to include a visual marker in the environment for guidance, in the form of an area with two large dead trees surrounded by tree stumps in the scene (Figure 24).

Figure 24. The area of interest that will serve as a visual marker with two large dead trees surrounded by stumps.

6.2 Performance Evaluation

The environment on which the baseline performance is measured has HDR, no SSAO, and no antialiasing. A unity project build has been created on which we measure the performance through the benchmarking software *MSI afterburner* and *Rivatuner Statistics Server* to measure the fps of the environment. There was no formal testing done to measure the latency of the controllers, but heuristic evaluation showed that there were no perceptible delays.

The protocol for testing involved travelling along the boundaries of the environment, which can be seen in the appendix (below). This allows us to get an exposure to the frame rates of the overall environment. After starting the environment, we waited for a minute before starting to take measurements to discard any frame drops from starting the application. Similarly, we discarded frames a couple of seconds after beginning the benchmark. We take the measurement for a period of 60 seconds in total, and report the average fps with its standard deviation, the 1% and the 0.1% fps. The 1% and 0.1% fps results indicate the fps at the worst 1% and 0.1% quantiles of frame rates recorded. This is better than using the minimum as the benchmark which can state that we have very low minimum fps even if it is for a negligible period.

A downside of our current protocol is that we will not be able to look at the exact route through each run as we do not have a fixed camera that travels in a fixed path which would guarantee accurate comparable results for the purposes of evaluating different techniques by rendering identical scenes as it traverses the environment. The advantage of the current protocol is that it will serve as an approximation of the frame rates the user will experience while using the locomotion techniques provided to them. Regardless, it will be able to serve as a mechanism for performance evaluation as the fps will average out for any given technique so that it can be compared.

6.2.1 Antialiasing technique selection

From literature it is expected that FXAA is the fastest, followed by SMAA, then MSAA [Jiang et al. 2014; Grahn 2016]. We tested FXAA, SMAA, and 4x MSAA as higher levels of MSAA do not offer visible benefits. Our performance testing results confirm that FXAA is the fastest, followed by SMAA, then 4x MSAA. FXAA has been selected for the current environment as it has the best performance comparable to that of no antialiasing.

In terms of quality, research on comparison of MSAA and FXAA shows that while over half of the people surveyed think 16x MSAA is the best, the number of people that prefer 4x MSAA over FXAA and FXAA over 4x MSAA are equal [Kesten 2017], which motivates our choice for FXAA further. However, a caveat of this research is that it did not give information about the sample size. The results for the antialiasing can be seen in the appendix (below).

6.2.2 Screen-space ambient occlusion (SSAO)

Realistic shadows in the environment were created without the use of ambient occlusion, a technique for calculating how exposed each point of the scene is to ambient light and results in more realistic shadows. It creates realistic lighting through the process of ray marching [Bavoil and Sainz 2008]. As the heuristic evaluators mentioned that the lighting was realistic without this technique and considering two out of the three heuristic evaluators were active computer science researchers with experience in graphics, this option was deemed to not be a necessity. We tried using SSAO which does its computation in realtime and negatively affects frame timings, but results show that performance drops below 60 fps by just applying SSAO without any antialiasing techniques (see Result for SSAO). While it offers slightly more realistic shadows at the expense of performance (**Figure 25**), we decided to choose performance over the relatively small visual improvement supported by the heuristic evaluation results.

Figure 25. Rock with SSAO (left). Rock without SSAO (right). The shadows are more realistic using SSAO than without, especially visible in the convex areas facing away from the sun where it is not to be lighted brightly by ambient light.

7. CONCLUSIONS AND FUTURE WORK

We created a realistic, realtime, and restorative environment through meticulous design of the environment to capture restorative elements of real nature, and the balance of quality and performance. The presence and usability of the environment was ensured through research in restorative environment design, psychology, various rendering and optimization techniques from computer science.

That said, there are a few shortcomings of the environment and testing procedure that could be improved. Visual improvements for the environment could be gained through the use of volumetric lighting, volumetric clouds, and volumetric fog. This will also give us better clouds, as the current clouds look textured when looking directly above. Further investigation could be done to check if it would be feasible to implement cutting-edge antialiasing techniques such as DLSS, which uses artificial intelligence to increase graphics quality while reducing computation time. Finally, using a true texture transparency anti-aliasing method such as TAAA [Jiang et al. 2014] would enable us to handle alpha blended textures better. For the testing procedure, there needs to be proper evaluation methods that survey a larger number and more diverse group of people, using more formal statistical methods. Regardless, this research would be a good basis for further development using more advanced rendering methods in future.

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Appendix

A. Aerial view of terrain. Click above to go back to the section you were reading.

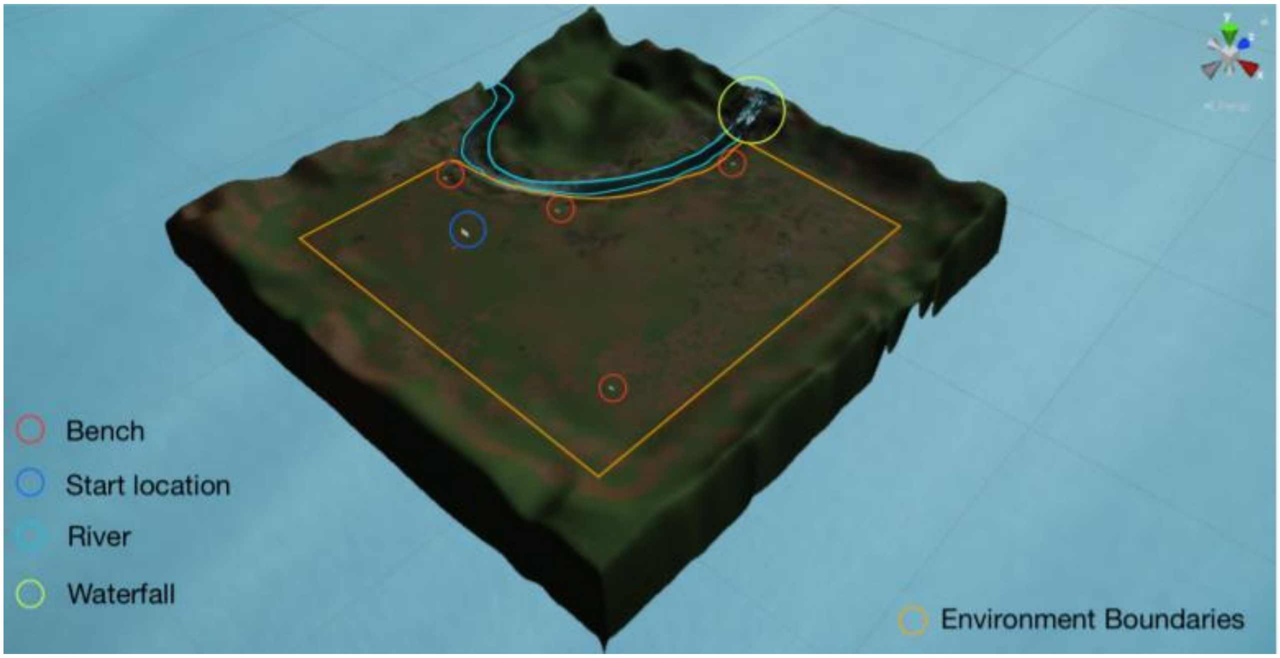


Figure 26. Aerial view of terrain highlighting the start location of the user in the environment, the benches the user may sit on, the river and waterfall, and variations in terrain elevation.

B. Antialiasing. Click above to go back to the section you were reading.

Figure 27. Aliasing can be observed, in the form of jagged edges on the tree stump at the left, the branch in the center of the screen, and the blocky appearance of the sapling about a quarter of the width of the image from the right. (2x zoom applied)

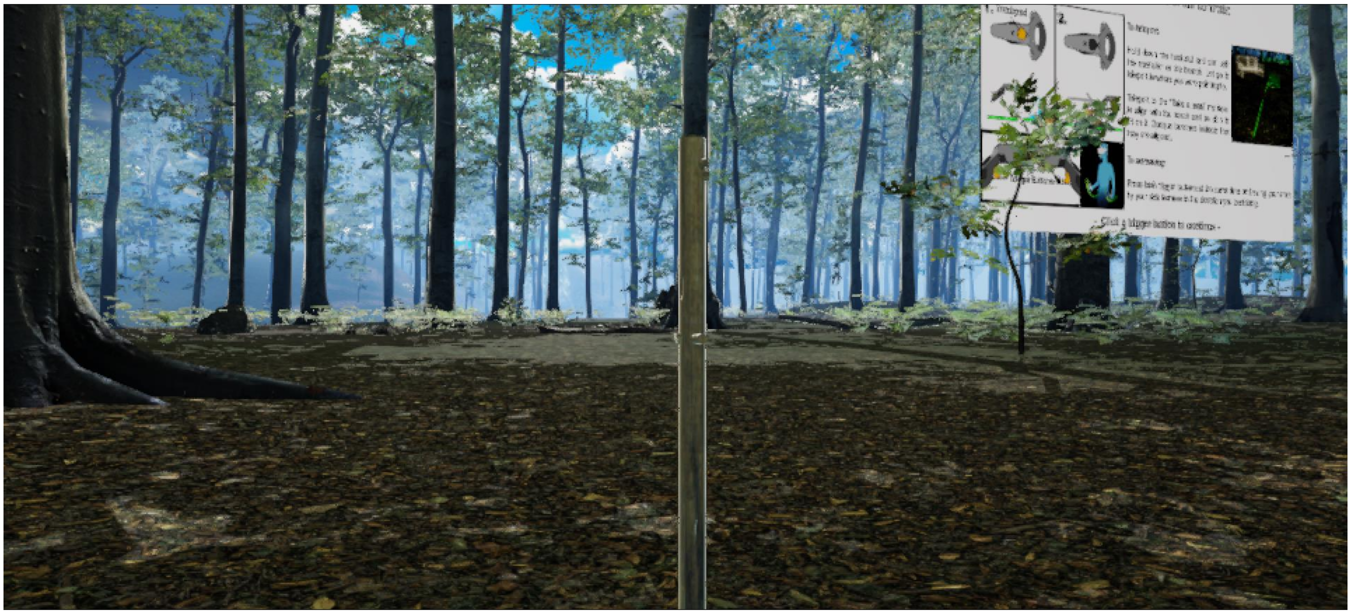


Figure 28. Image with FXAA applied. Blurring is more prominent here than MSAA and SMAA. Diagonal edges can still be seen. (2x zoom applied)

Figure 29. Image with MSAA applied. Edge reduction is much more prominent here and there is less blurring of pixels. (2x zoom applied)

Figure 30. Image with SMAA applied. Less blurring and less visible jagged edges compared to FXAA. Jagged edges slightly more visible compared to MSAA for the tree stump on the left, but better edges for the sapling on the right.

C. HDR Tonemapping. **Click above to go back to the section you were reading.**

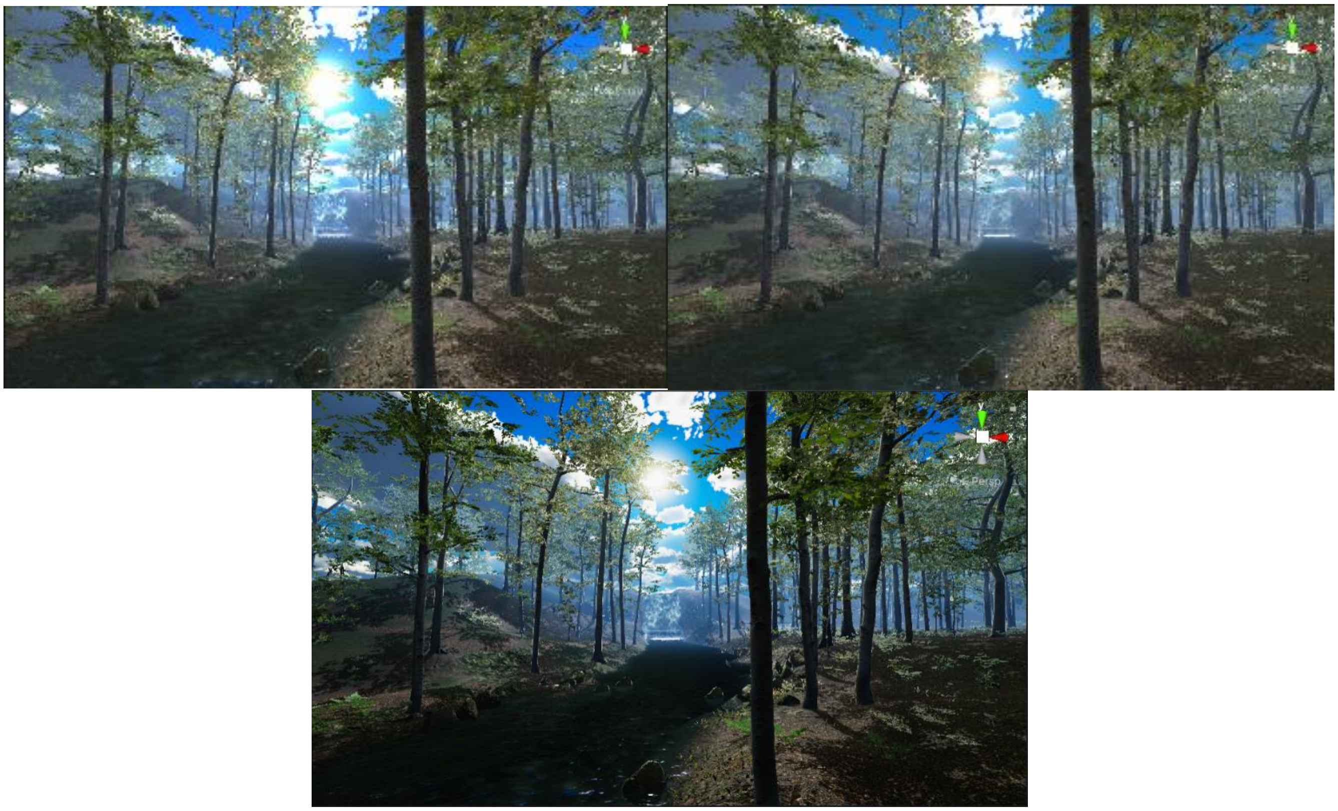
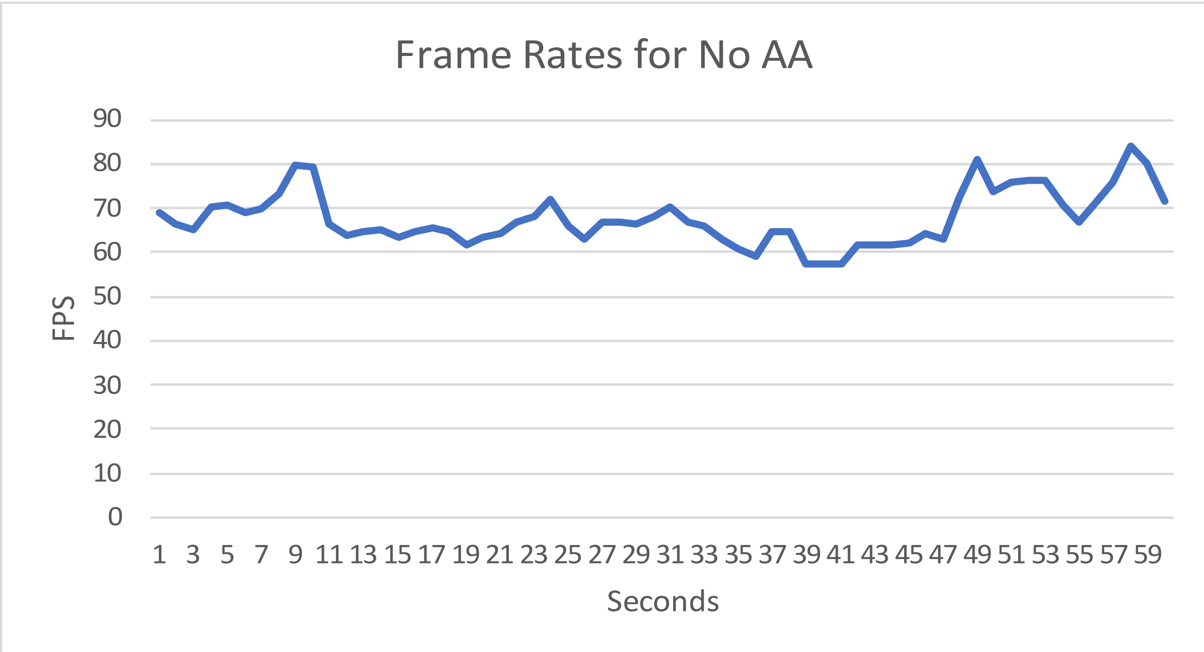


Figure 31. The top left image with no tonemapping results in a very bright halo of the sun and a brighter environment with lightly colored shadows. The top right image with neutral tonemapping is less bright compared to no tonemapping, but it is not sufficient with shadows still being light and the image having a pale, dull color. The bottom image with ACES (Academy Color Encoding System) tonemapping has the most vivid colors from its greater contrast and saturation, and dark shadows that would be seen in reality when an object is lit by a bright light source.

D. Antialiasing Results

a. No AA

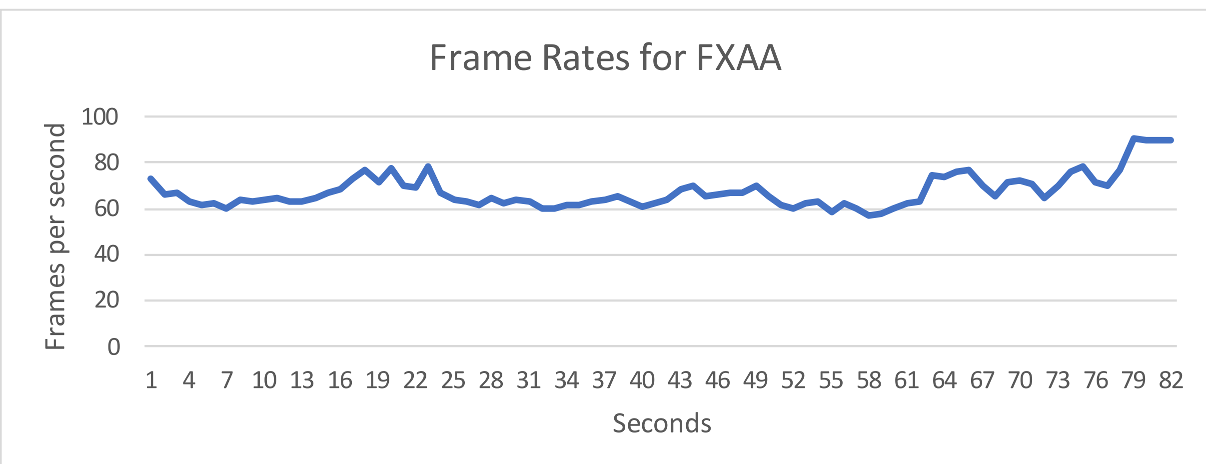


Average FrameRate: 67.75, stdev: 6.071200888

Average Frametime: 16.85993333, stdev: 1.208213205

Framerate 1% Low: 53.6 Framerate 0.1% Low: 51.8

b. FXAA

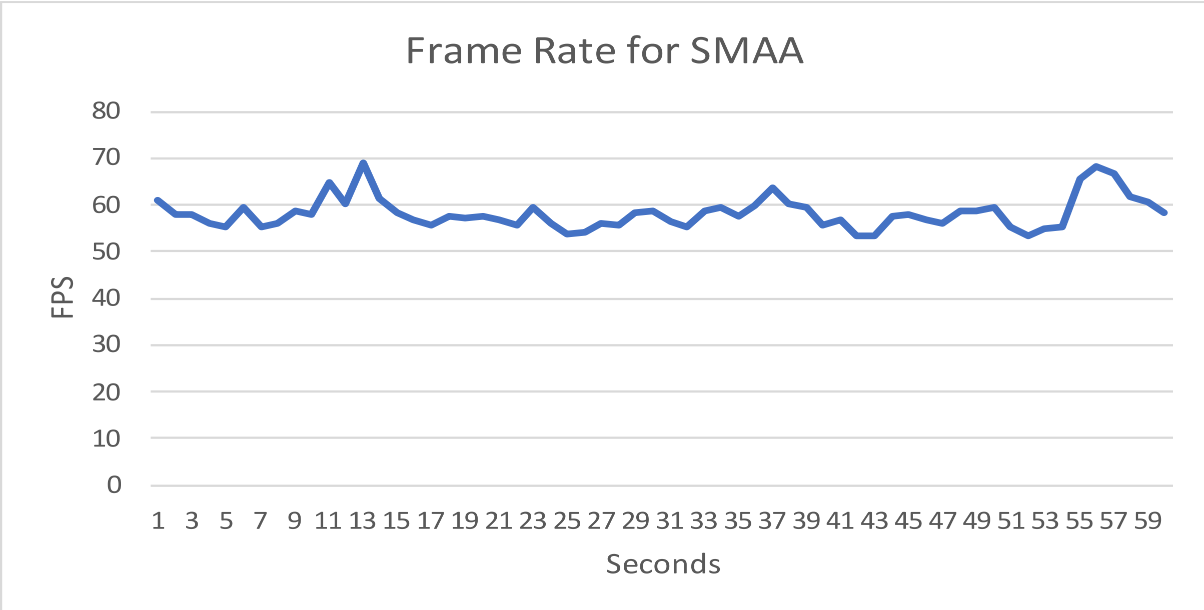


Average FrameRate: 67.50, stdev: 7.359380939

Average Frametime: 16.79223171, stdev: 1.479617512

Framerate 1% Low: 57.3 Framerate 0.1% Low: 56.5

c. **SMAA**

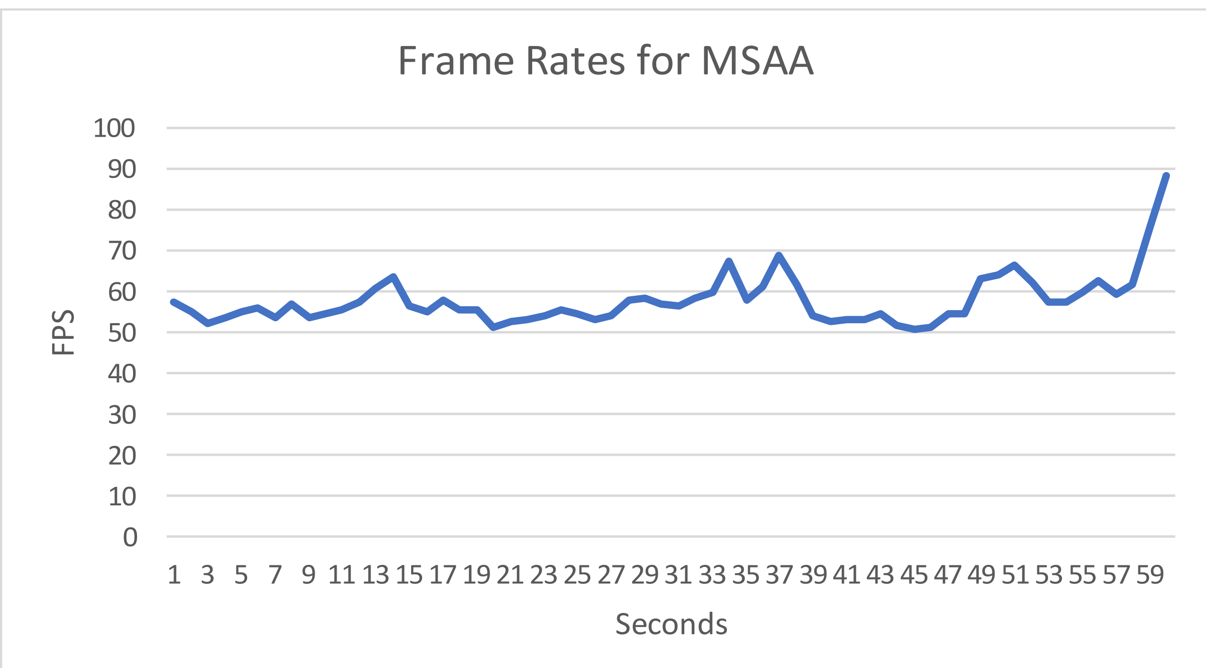


Average FrameRate: 58.22, stdev: 3.419741623

Average Frametime: 18.89891667, stdev: 0.910834657

Framerate 1% Low: 50.5 Framerate 0.1% Low: 48.8

d. **MSAA**

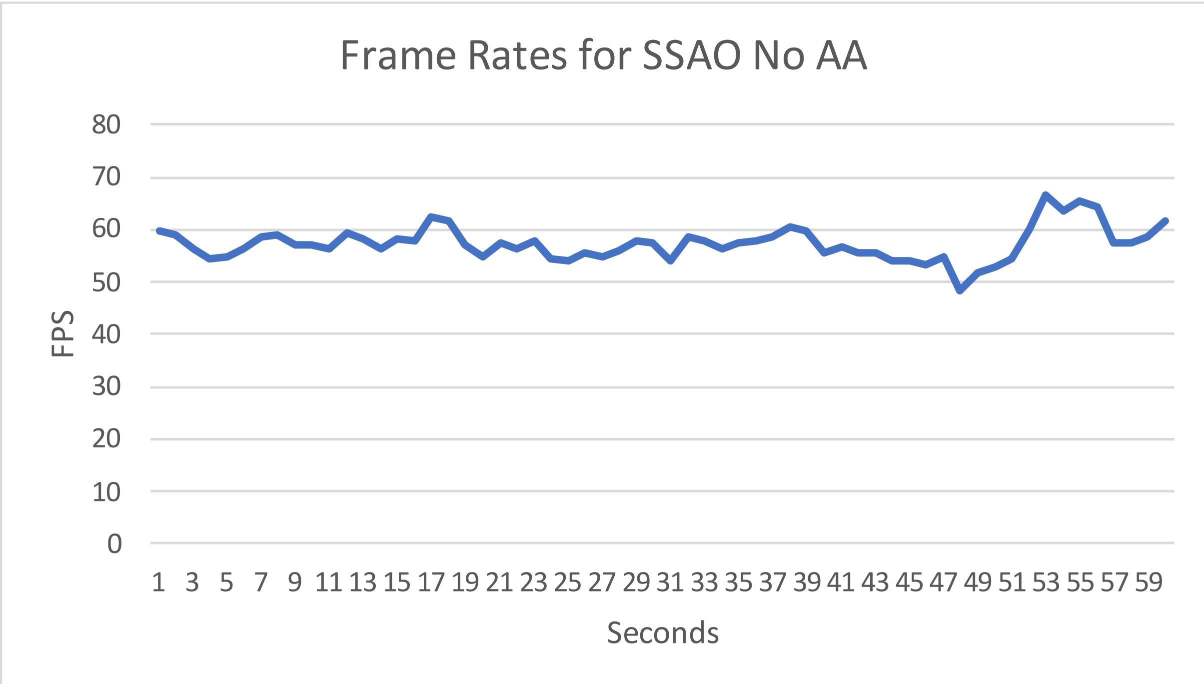


Average FrameRate: 57.78, stdev: 6.273425253

Average Frametime: 19.63811667, stdev: 2.915537698

Framerate 1% Low: 48.6 Framerate 0.1% Low: 47

E. Result for SSAO



Average FrameRate 57.29, stdev: 3.241200168

Average Frametime19.0871, stdev: 0.893333193

Framerate 1% Low: 48.4   Framerate 0.1% Low: 45.3

F. VR Heuristic Questions

Instructions: Please dictate problems experienced during the testing of our virtual nature environment. For each problem, please select a heuristic from Sutcliffe et al. [37] best relating to the identified problem, as well as a severity rating from the columns below. Any additional comments relating to the problems identified or the environment as a whole, are welcome. Then please answer the open-ended questions in as much detail as possible.

<u>Heuristics:</u>

1. Natural engagement.
Interaction should approach the user's expectation of interaction in the real world as far as possible. Ideally, the user should be unaware that the reality is virtual. Interpreting this heuristic will depend on the naturalness requirement and the user's sense of presence and engagement.
2. Compatibility with the user's task and domain.
The VE and behaviour of objects should correspond as closely as possible to the user's expectation of real world objects; their behaviour; and affordances for task action.
3. Natural expression of action.
The representation of the self/presence in the VE should allow the user to act and explore in a natural manner and not restrict normal physical actions. This design quality may be limited by the available devices. If haptic feedback is absent, natural expression inevitably suffers.
4. Close coordination of action and representation.
The representation of the self/
presence and behaviour manifest in the VE should be faithful to the user's actions. Response time between user movement and update of the VE display should be less than 200 ms to avoid motion sickness problems.
5. Realistic feedback.
The effect of the user's actions on virtual world objects should be immediately visible and conform to the laws of physics and the user's perceptual expectations.
6. Faithful viewpoints.
The visual representation of the virtual world should map to
the user's normal perception, and the viewpoint change by head movement should
be rendered without delay.
7. Navigation and orientation support.
The users should always be able to find where they are in the VE and return to known, preset positions. Unnatural actions such as fly-through surfaces may help but these have to be judged in a trade-off with naturalness (see heuristics 1 and 2).
8. Clear entry and exit points.
The means of entering and exiting from a virtual worldshould be clearly communicated.
9. Consistent departures.
When design compromises are used they should be consistent and clearly marked, e.g. cross-modal substitution and power actions for navigation.
10. Support for learning.
Active objects should be cued and if necessary explain themselves to promote learning of VEs.
11. Clear turn-taking.
Where system initiative is used it should be clearly signalled and conventions established for turn-taking.
12. Sense of presence.
The user's perception of engagement and being in a 'real' world should be as natural as possible
11. Additional heuristic (Please specify)

Severity Ratings:

1. No usability issue
2. Slight usability issue, should only be fixed once other problems have been solved and there is time available
3. Minor usability issue, fix with low priority
4. Major usability issue, important to fix with higher priority
5. Extreme usability issue that needs to be fixed immediately

VR-Environment Specific Questions

For questions where giving a severity is relevant, please give a score corresponding to the following scale:

0. Not at all
1. Slightly
2. Moderately
3. Fairly
4. Extremely.

Was navigating the scene intuitive?

Did you prefer teleporting with or without the branch, and why?

Did you prefer arm-swinging or teleporting, and why?

Did you experience any cyber sickness (discomfort, nausea, dizziness, etc.)? If so, how severe was it, and what do you believe caused it?

What was your favourite part of the environment?

Did you feel present? Was there anything you felt broke immersion?

Do you feel relaxed?

Did you experience any lag?

Did you notice any latency for the locomotion?

Did you feel that the environment was realistic? If so, in what respect?

Did you notice any areas of the environment that you expected a shadow, but it was absent?

Was the smell of the environment suitable?

What do you think the strengths of the environment are? How about its weaknesses?