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Developing a Virtual Zoological Museum

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ABSTRACT

This is a documentation of our work developing a virtual zoological museum. Although it's challenging to create a virtual museum that lives up to the original, Unity3D and virtual reality technology are utilized in order to provide experiences that a traditional museum cannot. As we aim to digitize the museum that once was in University of Oulu, different ways of designing an educating and engaging virtual museum visit are explored.

The animals of the museum can be interacted with, being able to play back animations and audio while also providing information in text form. An interactive forest was also developed as a more natural and lively environment. Furthermore, 360° photos of local forests were added to improve the representation of nature. Virtual reality support was programmed for Oculus Rift, allowing movement and interaction as if one was there in real life. In order to achieve a comfortable experience, some performance optimization has been done to reach stable frame rates.

We evaluated users' sense of presence, experienced Game Transfer Phenomena (GTP), system usability and content quality. Based on our tests, users found the virtual museum visit enjoyable and immersive overall despite being distracted by some aspects, like the quality of the display. Users were also mostly satisfied with the environments and the quality of the animals. Experienced Game Transfer was low, however. All in all, this concept for creating a virtual museum has appeared to be successful, and it could be developed further.

Keywords: Virtual Reality, Virtual Environment, Photogrammetry, Game Transfer, Zoological Museum

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TIIVISTELMÄ

Tämä on dokumentaatio virtuaalisen eläintieteellisen museon kehittämisestä. Vaikka onkin haastavaa luoda virtuaalinen museo, joka on verrattavissa alkuperäiseen, hyödyntämällä Unity3D:tä ja virtuaalitodellisuusteknologiaa on mahdollista tarjota kokemuksia, mitä perinteinen museo ei pysty. Digitalisoidessamme sitä museota, joka Oulun Yliopistolla ennen oli, tutkimme erilaisia keinoja kehittää opetuksellinen ja kiinnostava virtuaalimuseovierailu.

Museon eläimet ovat interaktiivisia, pystyen toistamaan animaatioita ja ääniä sekä antamaan tietoa tekstin muodossa. Interaktiivinen metsä luotiin tarjoamaan luonnollisemman ja elävämmän ympäristön. Lisäksi 360° kuvia paikallisista metsistä lisättiin parantaakseen luonnon edustusta. Virtuaalitodellisuustuki lisättiin Oculus Rift:ille, sallien liikkumisen ja vuorovaikuttamisen kuin olisi siellä todellisessa elämässä. Luodakseen mukavan kokemuksen, sovelluksen suorituskkyä on optimoitu saavuttaakseen vakaan kuvan päivitystaajuuden.

Evaluoimme käyttäjien läsnäolon tunnetta, koettua Game Transfer -ilmiötä (GTP), järjestelmän käytettävyyttä ja sisällön laatua. Testien perusteella käyttäjät kokivat museovierailun miellyttävänä sekä immersiiivisenä yleisesti ottaen, vaikka jotkin piirteet, kuten näytön laatu, häiritsivät. Käyttäjät olivat myöskin pitkälti tyytyväisiä ympäristöihin ja eläinten laatuun. Koettu Game Transfer oli kuitenkin vähäistä. Kaikenkaikkiaan tämä virtuaalimuseo konsepti vaikuttaa toimivalta, ja sitä voisi kehittää pidemmälle.

Avainsanat: Virtuaalitodellisuus, Virtuaalinen ympäristö, Fotogrammetria, Eläintieteellinen Museo

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ABBREVIATIONS

VE	Virtual Environment
VR	Virtual Reality
CGI	Computer-Generated Imagery
SLR	Single-lens Reflex
FPS	Frames per Second
HMD	Head-Mounted Display
PC	Personal Computer
UI	User Interface
LOD	Level of Detail
API	Application Program Interface
CPU	Central Processing Unit
GPU	Graphics Processing Unit

1 INTRODUCTION

The University of Oulu used to have an animal museum that was well liked by locals and visitors alike. However, after some debate, the decision was made to remove the original museum in order to make use of the space for other needs [2], [12]. Due to this decision, the Virtual Zoological Museum project was put in motion with the intention of preserving the museum and its animals in the form of an interactive 3D environment so that people could once again visit the museum.

1.1 3D Environments

Interactive 3D environments are a digital model of an environment viewable on a display device. You can freely move the camera around and see a believable view of the scene from any angle. It is a 3D world in a digital form. On top of just looking around, you are able to interact with the world, typically to the extent that it is possible to do most things that the users are interested in, that are relevant to the purpose of the application with the limitations of hardware capabilities and extent of programmed features [5]. The constant improvements in computer technology and software have pushed the creation of 3D environments to immense heights and these environments are starting to come very close to mimicking reality. While the overwhelmingly most popular purpose for 3D environments is entertainment, it undoubtedly has uses for education. What instinctively comes to mind is 3D environment's ability to ground a person in an environment that would otherwise be impossible to find, and the ability to interact with objects in the environment. This creates undeniable utilizations in learning. For example Chau et al. [5] had students learn about cyber security through either a video or an interactive environment based in the virtual world Second Life. This study found that the students that used the 3D environment in learning achieved better learning outcomes [5].

1.2 Virtual Reality

With the emergent VR technology, the potential utilizations for virtual environments grows exponentially. VR enhances the feeling of actually inhabiting the virtual environment. Even though current consumer grade VR technology does not yet allow for the same photorealistic graphical fidelity that can be seen in the latest traditionally viewed games, it is still able to captivate the player enough to suspend the players disbelief in the environment [21]. Another key strength of VR is how intuitive and natural interactions are. With two handheld controllers, players have access to a wide range of motions and button interactions. These interactions can then be tailored to replicate motions that we are used to from reality. For example, picking up an object in VR is often simply hovering the controller over an object and pressing a button (simulating grabbing onto it) and then dragging the object wherever you want just as one would in the real world. Conversely, picking up objects in PC or console games is typically done by pointing a floating crosshair at an object and clicking a button to drag the object around with what feels like telekinesis.

There are some drawbacks to VR. One of the major problems that occur is cybersickness. For that reason, player movement in VR is very limited to moving in certain increments, for example by teleporting, to reduce the effects of nausea. VR also requires a high frame rate and resolution to keep the experience believable and natural [34], which typically leads to reduced graphical fidelity in the 3D environment. Most current head-mounted displays (HMD) can render 60 to 90 frames per second (FPS),

while in comparison, typical monitors and TVs support 60 FPS with most games and applications running as low as 30 FPS.

1.3 Motivation

Since many were fond of the animal museum in Oulu University, our goal is to create a comparable experience, albeit with a different approach. When moving from real world to virtual, a lot of detail and fidelity is inevitably lost, but many other aspects can be enhanced beyond normal limitations for example it is possible to animate the animals, the user can teleport or fly, and changing or adding environments is very inexpensive. Moreover it becomes much easier to make additional information, images and audio available to the user, which can all be quite useful in the context of a museum.

The Virtual Zoological Museum will also be an addition to the VirtualOulu [13] infrastructure, as our environment is based on the original museum interiors. There are plans to set up VR devices to the Oulu City Library and the Visitor Center of Oulu University that can freely be used to experience different VirtualOulu applications. On top of that, the web version of this project will be available online for anyone to use. With these different options, we hope to be able to offer something educational and entertaining to the public.

1.4 Contribution of the Authors

Uotila is responsible for most of the programming, VR implementation, lightning, performance optimization and audio. Pouke's contribution lies in photogrammetry, 3D modeling, textures, animations, shader programming and creation of the forest environment. Writing of this document corresponds the same division. Research, evaluation and other work was split evenly between the two of us.

2 RELATED WORK

Virtual museum experiences have been researched and attempted numerous times before with vastly different designs and implementations. Arguably the best results so far have been achieved with different kinds of picture and video tours of museum content. Multiple fully 3D and interactive environments have been made, but since real-time rendering requires better hardware, full-scale museum experiences have not been reached as such.

From one of the biggest tech companies in the world, the project *Google Arts & Culture* [9] features perhaps the most pictures, information and other material from many museums and other sites of interest around the world. You can browse many museums using 360° images in Google Street View, which can also be viewed in VR. Additionally, there are edited 360° videos including CGI recreations of animals that would otherwise only be seen the bones of, like for example a Giraffatitan dinosaur. The models, animations and audio are very high quality and believable, as they are accurately created in collaboration with multiple experts and researchers of different fields. Additionally, a brief summary of the animal is explained in voice and text. Similarly the *Smithsonian National Museum of Natural History* [20] has their own Street-View-like 360° photo tour of the museum, featuring an interactive map and VR support. Furthermore, a paper published by IEEE in 2015 elaborates on the process of creating 3D virtual tours with a virtual reproduction of the Santa Maria della Scala Museum Complex in Siena, Italy [1]. The production of this tour is separated into three

parts; image capture, combining the images into a 360° image, and finally creating a 3D visit path. These projects set the standard for visual detail and accuracy high, which is nearly impossible to match with a fully 3D environment as of yet. High quality scans do provide detailed models and textures, but some detail is lost particularly when dealing with animals with fur or feathers that complicate the form. 360° images can instead be embedded as an addition to a virtual environment, and we have decided to do so by adding 360° images of local forests, since for us it was not feasible to try to achieve comparable quality as a recreated 3D environment.

In 1998, problems of virtual representations of 3D works of art were researched [6]. For the project they managed to create a virtual museum environment, in which they could embed textured 3D models of pieces of art, and run it in a web browser using a plugin for 3D graphics. The level of detail (LOD) depended on the proximity of the player, and the objects could be moved around. A user interface (UI) was available, providing basic information on the art and a possibility to open an HTML page with more detailed descriptions. Furthermore, in 2001 the University of Athens discussed many of the drawbacks of real world museums, and how they can be fixed using a virtual environment [16]. Some of the suggested benefits include visualization of sites that cannot be seen in their original form anymore, or are difficult or even dangerous to visit, and ability to enhance the exhibition with interactivity. Utilization of VR technology like the Cave [8] was also discussed. In this project, existing real world material was digitized via photography, 3D scanning or 3D modelling. These techniques are largely what our project is based on as well, but expanded with current technology.

Steps have also been taken to create a user friendly experience for adding content into museums. The Augmented Representation of Cultural Objects project (ARCO) [14], [24], [29] developed technology that would allow for easy management of virtual exhibitions in the web and on interactive displays. This allows for quick creation of robust virtual exhibitions without the need for major IT expertise. Tools for adding data of animals to the database have already been developed for our project.

Lastly, activities in museums have also been experimented with. In 2009, a virtual version of the Olympic museum was developed [33]. This 3D museum contained static exhibitions but also included virtual reality based sports simulation systems, such as virtual table tennis. Our plan is to implement some entertaining activities as well, including slapping mosquitoes in a forest, as that is a good way to attract and retain the users' attention, particularly for the younger age group.

3 DESIGN AND IMPLEMENTATION

This report focuses on the time since restarting the project, prior to which multiple people have worked on it. The application runs on Unity [26], a powerful 3D game engine, with scripts written in C#. We are continuing the work from a state where some animals have already been embedded into the virtual environment, and the standalone Windows version is relatively presentable (*fig. 1-2*), albeit lacking of animals. One of our primary goals for this development period is to create a fully functional VR version.



Figure 1: Museum interior at the time of restarting the project.



Figure 2: Outdoor scene at the time of restarting the project.

3.1 Early Days of the Project

The project started with re-creating the original museum complex as textured 3D models. After that, some test animals were added before 3D scanning the actual content of the museum, along with an API for the database that was previously used by the museum, to fetch information about the animals in the 3D museum. At this point, we inherited the project and developed it for three months prior to restarting the project, which is what this report focuses on.

One of the first things worked on during the three months was the lighting of the 3D environment. New light sources were added to the environment, and to increase performance, most lights were changed to be pre-computed, otherwise known as baked lighting. This way the lighting is applied to a lightmap texture, which changes the color and brightness of all objects marked to utilize the lightmap. The museum environment was also improved by adding props.

The materials were either imported from online resources or self-made using pre-existing software. Most materials consisted of at least a diffuse map (the color of the object) and a normal map (affects lighting, creating illusion of depth). The props (e.g. clocks and outlets) were all 3D modelled and textured locally.

The UI for animal information was improved and a general menu system was implemented to allow for pausing the game and changing settings, including graphics quality, resolution, key bindings and other preferences. Language could also be changed between English and the local Finnish.

To complement the museum scene, it was decided to have an additional forest scene in the 3D environment (*fig. 2*). This scene would be used to try to show the museum animals in an environment more natural to them. This scene was constructed using the existing unity terrain system with trees, grass, and foliage created from scratch.

Attempting to add some fauna into the project, high quality images of the existing insect exhibitions were acquired and these were converted into materials that were placed on planes. To add illusion of depth, a custom distance based tessellation shader was used in tandem with a height map. The tessellation shader divides the plane into smaller triangles, with the number divisions depending on the distance to the material. Some triangles are then slightly popped up from the plane based on the given height map.

A handful of birds were also successfully implemented into the project. These birds were created by photographically scanning the original animal using a PI3DScanner [25], which was then virtually recreated using photogrammetry. Some of these animals were also given some basic animations, which can be viewed by clicking on the animal in the 3D environment.

An additional third scene was created with the purpose of providing lower end systems the option to view the complex animal models without overwhelming strain. This scene is a simple square room that could display one animal at a time. Later on, this scene was repurposed just as an introductory area, as it was determined unnecessary and inconvenient to view the animals one at a time in comparison to optimizing the museum environment further.

Finally, a digital version of the very cherished diorama was developed. This was achieved using photogrammetry. The diorama was divided into 12 different segments, and using photos from multiple different angles, meshes were computed for the segments. These meshes were then placed in their respective locations for the full diorama.

The aforementioned work was done by the two of us during those three months as full-time work. The following sections document our work after this period and as such are the core parts of this thesis.

3.2 Environment

One of the most worked on elements of the project was the forest scene. The scene went through many different reiterations, often requiring an overhaul of the complete scene. This was due to the many visual and technical challenges that the scene required us to overcome.

The first challenge was deciding the size of the scene. Ideally, it would be possible to make a real life size forest such that it would not cause the animals placed in to the forest to feel too densely packed together. However, we knew from the start that good performance would be difficult to achieve in a forest of such scale. We

decided to limit the playing space to roughly a 20x20m space from which the player could look outward. Thus, rather than having to create a complete forest, we could instead create an illusion of a full forest.

The most prominent feature of any forest is undoubtedly the trees. As we were intending to virtualize the average Finnish forest we chose to include the three main types of tree found; the pine, the spruce, and the birch. The first question to answer in modeling the trees was how detailed they could be. For maximum visual aesthetic it would be common practice to fully model the whole tree, including small branches and leaves. This method creates trees with very high vertex counts, which would be much too taxing on the performance of our scene. This was evident in some of the earlier trees in the project, which could contain up to 50,000 vertices. On the other side of the spectrum, it is possible to model the general shape of the tree and add detail to the tree using materials and textures. This version of the trees would grant us high performance but they would definitely look out of place as they would appear cartoonish next to the relatively realistic animal models. Our final models were in the middle of these two methods. The trunk and biggest branches were modeled, while the small branches and leaves were combined into one flat texture which was then applied to curved planes and placed on the bigger branches. This method gave us a good level of visual aesthetic while still keeping the vertex count under 10,000 per tree.

The next step was finding good textures for the trees. Although there were some ready-made free resources that could be found on the internet, we decided to create our own since it would be more suitable for our models, and would also be of higher quality. These textures were made by first photographing a selection of trees' bark, branches and leaves, which were then brought into image editing software and polished into seamless textures. Making our own textures also allowed us to improve performance, as we could create our own texture atlases, which amounts to less draw calls for the CPU. In addition to the 3D trees, we created tree billboards, essentially textures on flat planes, which could be placed far from the player's location without the player perceiving them as 2D, thus saving even more on performance.

Other props such as boulders, dead trees and other foliage were added into the scene. Most of these were simple to make compared to the trees, and as such we mostly relied on creating our own models and textures. There were some intricacies in creating the props, such as creating a shader that allows us to place another texture (e.g. moss or snow) on the top of the rock or tree mesh in addition to the original texture.

The final ingredient for the forest was grass. Although Unity has an inbuilt grass system that relies on 2D billboards, we did not find this method to provide a good balance of visual quality and performance for what we needed it for. Instead, we created our own grass mesh which we placed around the scene. This allowed us to achieve results that were more in line with what we had envisioned.



Figure 3. Mesh of spruce without textures



Figure 4. Single grass mesh



Figure 5. Forest Scene

3.3 Lighting

3D environments need lighting, which in our project is implemented with mostly preprocessed, baked lights. There are numerous visible ceiling lights that each have a baked light source attached to them. The rest of the light sources are not attached to a visual object, but are instead freely placed with the sole purpose of achieving visually pleasing results while trying to keep the amount of lights low to reduce bake time. Several lights exist to provide general lighting to the main area of the museum. Most lights exist around shelves, with each shelf containing one light combined with invisible shadow casting objects to mimic having an individual light above each animal. However animals themselves are lit by their own real-time directional light, since some of them are animated and require dynamic lighting. This light does not cast shadows. Instead, shadows are included in the baked lighting as if none of the animals moved. This implies that the shadows do not move when an animal plays an animation. For small animals and shadows, such as birds, this trick is fortunately not very noticeable, making it a viable optimization method.

Originally the ceiling lights had a real-time component that only affected the floor, providing pleasing reflections. This was not overly taxing when utilizing deferred rendering technique, but after coming to the conclusion that forward rendering serves the animals in the museum significantly better, it was necessary to significantly cut down on the amount of real-time lights. Using forward rendering, objects need to be drawn again for every real-time light affecting it. Thus, it is recommended that only one real-time light affects any given object at a time, if any. In comparison, deferred rendering handles lighting as something that could be considered a post-processing step, independent of scene complexity [15].

3.4 Animals

In a brainstorming session prior to starting work on the project, an idea was presented that the animals of the museum could be utilized for study purposes. As such, the animals created for the virtual museum would have to be adequately detailed and accurate to their real-life counterparts. Originally there were plans to fully model some

animals by hand, but tests showed these lacked many of the details and nuances that the real life animals would have. One of the biggest factor that caused this problem was the absence of high quality textures. Although a high quality mesh could be created, the animal would lack the correct skin or fur color. For example, attempting to create a lynx model proved problematic as the textures were adapted from the pelt of a lynx. Firstly, this caused a disconnect between the body and the head as the textures for the head and body had to be taken from separate sources. Secondly, the pelts for the lynx were of the Canadian lynx which is different from the Eurasian lynx which appears in Finland.

Soon after experimenting with creating animals we discovered that the best way to achieve the quality we desired was to utilize photogrammetry to create 3D models from pictures. Using photogrammetry for 3D models is a multi-step process. First, images of the target are taken from multiple angles. These images are then compared to each other, finding matching color patterns, to estimate the camera locations and the 3D geometry of the target, creating a point cloud. This cloud can then be turned into a mesh, which then in turn can be textured by combining the original images into a texture map [18].

As the original zoological museum had closed down, most of the taxidermied animals were available to be converted into digital form, and thus we had all the possible models for the animals we wished to put in to the virtual museum. There were a couple of methods used to capture the images of the animals. For small animals we were able to use a scanner constructed specifically to convert objects and humans into virtual models using photogrammetry. For bigger animals we had to take the pictures by hand using a standard SLR camera. After acquiring the image data, we then used photogrammetry software to convert these images into point clouds, meshes, and finally textured meshes. The model received from the photogrammetry software is incredibly detailed and therefore contains a massive amount of vertices. Many models reached well over a million vertices. Therefore the model has to be turned from high-poly (fig. 6) to low-poly (fig. 7) by using the decimation tool available in Blender. To preserve the level of detail of the high-poly model, its details can be baked onto normal- and occlusion maps which can then be applied to the low-poly model (fig. 8).

Another idea that was presented in planning sessions was to have some form of movement for the animals. This would give an extra level of intrigue to the animals that the original zoological museum could not provide. However, in development it was realized that the degree of movement freedom we could give to the animals was quite limited. While experimenting with giving flight to a certain bird in the museum, we realized we do not have enough knowledge of the specifics of the flight characteristics to create an accurate animation for the bird. As we had intended for the animals to be used in study, we could not leave in animations that misdirect the user on how the animals would actually move in real life. We decided to limit the animations to simple head and body movements which do not require meticulous research into the animals' movements yet makes the animals feel more life-like.

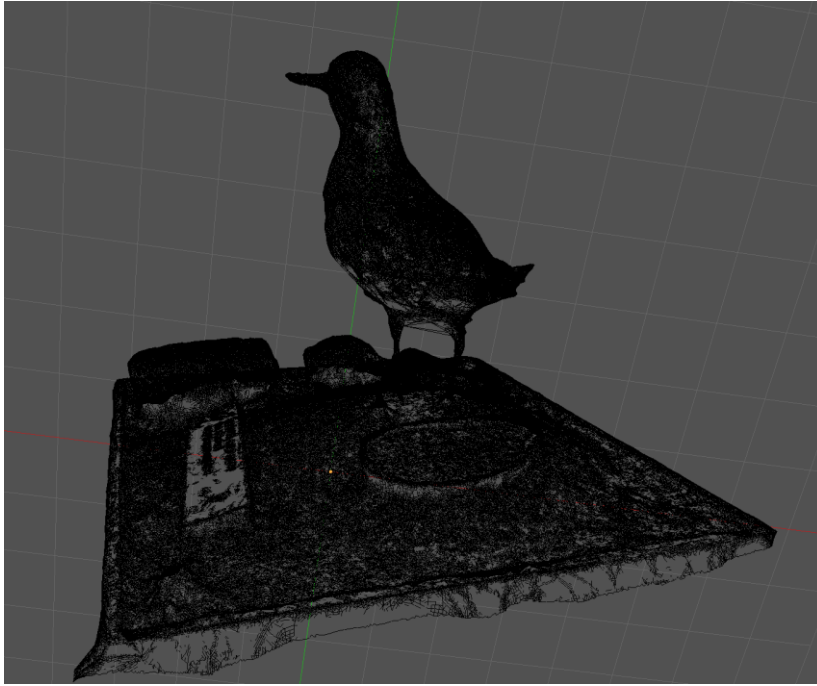


Figure 6. High poly wireframe of the Red knot

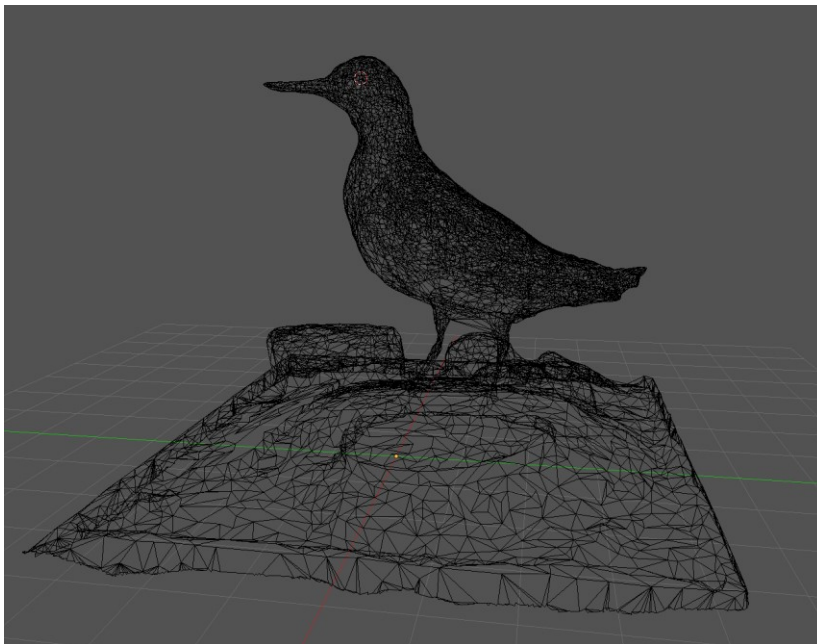


Figure 7. Low poly wireframe of the Red knot



Figure 8. Final model of the Red knot

Finally, furry animals required fur coating. One common method for creating hair or fur on 3D models is to use “cards” which have hair strands as a texture. These cards are placed on the model, and their normals are then recalculated to form seamless and correctly directed hair. To use this method would require us to manually place these cards on animals, each with a unique texture. We estimated that this would be too complex for our purposes, and instead we developed a simple fur shader. This shader worked by layering textures on top of each other and providing an opacity map which created hair strands. Additional features to the shader, such as fur length mapping and fur direction mapping, were added for increased graphical fidelity. This method has been used in various video games to great effect. The shader method allowed us to get satisfactory fur coverage on our animals without the large complexity and effort that the card method would present.



Figure 9. Fur shader applied to the European Polecat

3.5 Performance

Around the start of this project, it was decided that the application should be publicly available. We envisioned that it could be used in schools to study animals. In other words, the application should perform at least at an acceptable level on most hardware configurations. Additionally, it was planned that it could be run directly from a web browser, using Unity's built-in WebGL support. These requirements set limitations on RAM usage and the load on the CPU and the GPU.

It is essential that the content of the museum looks the best it can. For that, high resolution textures are inevitably required. From our tests, we perceived 2048 by 2048 pixels to be sufficient for the birds in the museum. Loading dozens of textures of that size or larger takes up a sizeable amount of memory. However, realistically the user could be viewing only a handful of animals up close at a time, and only those animals need the highest detail. Using this to our advantage, lower resolution textures of each animal were made, and the high resolution textures are loaded only when the user is close and has that particular animal in sight, and unloaded when the he or she looks or walks away. This can be adjusted based on available memory. In the case of WebGL, it is necessary to manage memory more aggressively, while on a desktop or VR build it is often better to make use the available RAM to cut down on the performance impact that texture loading causes. Additionally, Unity allows adjusting texture import resolution per platform, allowing us to easily use smaller textures in the WebGL to avoid encountering any memory issues.

To optimize CPU usage, attention needs to be paid to the efficiency in written scripts and the amount of objects running code on every frame. While you may not need to know the exact implementation of built-in functions in Unity, it is important to have an idea of how much processing time different tasks take. For example, operations that are used to find objects in the scene are slow, so the result should always be stored in memory if there exists any need for it later. The result of such functions is a reference type that points to a value type that holds all of the actual information of the about the object. In short, a reference type consumes very little memory, since the actual object data doesn't need to be copied [11]. Many of our scripts require the transformation of the main camera, and even if not needed regularly in a script, it is best to have the reference saved.

In any program, large loops need to be dealt with carefully. There are two important aspects that affect their required processing time; the time a single iteration of that loop takes, and the number of iterations that have to be done. If all loops that need to be run regularly are run on every rendered frame, it easily adds up and requires significant processing power to keep up. Instead, it should be considered how frequently these loops should run. By setting up loops to run only part way through on each frame and continuing from there next frame, CPU stress is alleviated steadily. For example, our texture streaming script utilizes this technique to check only a small number of animals each frame, since it is not necessary to update the textures immediately.

A less apparent but important aspect to CPU performance is the amount of draw calls that happen each frame. A draw call is the CPU ordering the GPU to draw something on the screen [17]. Without any optimization techniques, each object needs to be drawn separately, generating a draw call. First of all, since the GPU is also stressed when drawing objects, it is best to minimize the amount of objects to draw. The simplest way to do this is to ignore objects behind the camera and its field of view.

This is called frustum culling [28]. The other method is called occlusion culling, which means leaving objects completely occluded by others undrawn. Since this is more complicated to calculate, it can in itself be taxing to the CPU, or inaccurate.

In addition to culling, objects can be combined into bigger meshes to reduce draw calls, which can be done either manually or through a method called batching [7]. There are two types of batching; static and dynamic, out of which we rely on static, since most of our objects in our scenes do not move. That is required, since the method of static batching combines meshes in Unity in our case, and thus, moving just one object would require editing the combined mesh, resulting in an expensive operation. It is also required that objects share the same material. In other words, it is best to use as few materials as possible, and only one material per object. In order to avoid reduction of variance due to such optimizations, texture atlases can be used. In short, an atlas texture contains multiple different looking textures, and the meshes of objects contain so called UV maps, that control which part of the texture is displayed in which parts of the mesh. For example, our museum shelves consist of wood and metal parts. Instead of using two different materials, only one material utilizing atlas textures is used for not only the albedo texture, but also normal and metalness maps. This allows light to affect these parts differently from each other, and Unity can easily batch shelves together to reduce draw calls. Many other objects in the museum simply share one single material without utilizing atlas textures, for example the walls.

GPU requirements are mostly affected by the complexity of 3D models, shaders, textures, real-time lighting and post-processing. Animal and diorama models are modified from what is provided by scanning to a point where geometry is simplified as much as possible without perceivable loss in detail. Textures receive the same treatment; environment textures have their resolution dropped suitably low without affecting the overall presentation of the application, while the textures of the museum content are handled the same way as their models.

3.6 Virtual Reality

We initially started working on the Oculus Rift [22] using its Touch controllers for a full desktop VR-experience. Soon after we added support for HTC Vive [31] with its own controllers to match with the Rift version. These act as our main development platforms that we have a separate Git branch and separate builds for, allowing us to make any changes without having to worry of further implications on other platforms. Any common changes and additions are added to the master branch, from which other branches can be updated.

As mentioned earlier, performance is a significant concern when developing VR applications. However, we have had to keep the non-VR version light on performance, leaving little further work to do. It is still good practice to regularly view performance metrics to ensure that potential issues are noticed early.

Implemented movement options include teleporting and free locomotion, in other words controlling the camera artificially, typically using analog input on the controllers. Such artificial movement can induce a form of motion sickness called cybersickness, commonly understood to be caused by a sensory mismatch [19]. Consequently, constant artificial movement causes more stress to the user than room scale movement or artificial instant relocation [4], and for that reason, free locomotion is disabled to avoid its accidental usage but can be enabled, in which case both movement options are available to the user. On top of enabling the movement input on the controllers, this option enables the player character to be affected by gravity,

allowing walking down stairs or other angled surfaces. Using this setting, trying to lean through objects will push the player back, while without it, physics are ignored, allowing pushing the camera inside objects. While both of these alternatives can feel unpleasant, the issue is difficult to get around as the mismatch between the virtual and real environment has to be resolved one way or another. However, to avoid the user getting near walls too often, teleporting path, which is aimed as an arc from the right controller, will bounce back a little from other colliders while aiming, and trying to teleport too near is disallowed, which is all represented by visual effects (fig. 10). Independent of this setting, the user can instantly turn 45° in chosen direction using the controllers, which is a helpful feature specifically when the play area is limited, or if the user is having trouble with cables or tracking sensors when turning in the room. As an additional feature, flying can be enabled. With free locomotion, the user can freely fly towards the direction their left controller is pointing at. Without it, teleport can instead be used to freely teleport to chosen direction even when floor is not detected.

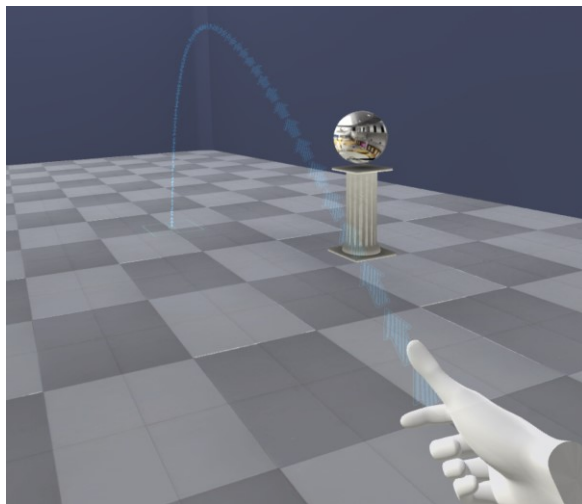


Figure 10: Visual indicator for teleporting

Interaction for the most part is done by pointing at objects with a laser that can be enabled by holding a trigger on the controller. The primary usage of this feature is to point at animals, which then shows the name of that particular creature in Finnish, English and Latin. This information is provided in a card-like form on your left virtual hand. If that animal has an animation or sound, those will play as well. However, portals, which are used for traveling between different scenes, can be interacted with by putting them in your head, causing the user to load into the chosen scene while unloading the previous (fig. 12). Moreover, the user is given some tools, including a magnifying glass and a swatter. The magnifying glass essentially allows zooming in comfortably, which we deemed nearly necessary for viewing the insect collection. The swatter on the other hand is specifically used for the mosquito game. In our forest environment, mosquitos can be spawned. They fly around unpredictably, hovering slightly towards the player. All of them emit spatial sound typical to the species, and as such, it will become louder and more unbearable as they get closer. The visual side is implemented with a simple texture on a plane that is always turned towards the camera. The swatter can be used to slap these insects, making an exaggerated sound as feedback that the mosquito was defeated. Due to limitations set by hardware, creative liberties had to be taken for the purpose of this game, as slapping two

controllers together would ultimately not provide the traditional experience of Finnish nature.

In order to help new users familiarize themselves with the controls of the application, 3D models of the Oculus Touch controllers are shown on startup along with help texts that label each input that has a function. Transparent virtual hands are shown on top to visualize the user's current grip on the controller, which is a built-in feature by Oculus that utilizes the proximity sensors in the controllers. In short, the user can see an accurate approximation of the input options along with positions of their fingers in relation (fig. 11). This view can be disabled and re-enabled with the button labeled as "Help". When disabled, the virtual hands are only slightly transparent, and the controller models are invisible.



Figure 11: Controller help texts

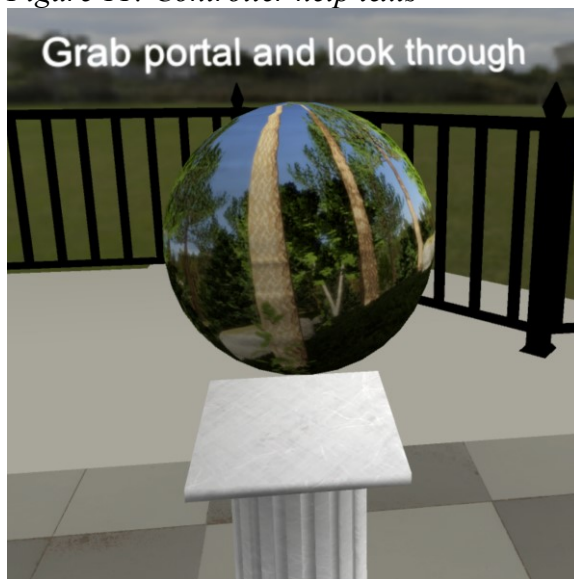


Figure 12: Portals to other environments in VR

3.7 Audio

Especially for Virtual Reality applications, fitting audio is required for an immersive in addition to aiding the user to perceive the environment. For our museum scene, simple ambient sound simulating air conditioning plays in the background. Despite being very simple and uninteresting, it can help bring the users' audio perception to the virtual environment, increasing immersion. Additionally, within the diorama area, a recording from a forest including general ambient and bird sounds plays with the purpose of adding an auditory experience to go alongside the visual.

Our goal is to include accurate audio for as many of the animals included in the virtual museum as possible. Since recording them ourselves is unrealistic, we have to rely on some external source, which is still in process. However, a system for playing back the animal's audio and animation when pointed at has been implemented, and functions whenever either or both are in place.

In our forest environment, wind is simulated by controlling the volume of a simple artificially generated noise loop. The wind comes in gusts of random amplitude and intervals. Moreover, the leaves in trees shake and bend based on the same strength of wind that determines the audio volume. The mosquitos in the forest use recorded audio of the actual insects, edited to reduce noise and other distortions.

As for other sound effects, the portals used for traveling between scenes (fig. 12) use spatial, edited, synthesized noise to simulate the energy emitted by them. We believe this helps arouse curiosity to approach the portals. Furthermore, aiming and activation of teleportation produces a similar but softer sound as means of providing feedback to the user.

4 EVALUATION

The focus of our evaluation is in application performance, immersion and content quality. While performance can be evaluated internally, participants must be recruited for everything else. Due to the hardware requirements and our software not being publicly available at this time, it was decided that said participants would have to be invited to experience it on our hardware setup. We planned a cognitive walkthrough with an approximate length of 10 minutes along with questionnaires about the participants' prior experiences of related technology, immersive tendencies, game transfer, sense of presence and overall content quality. Additionally, we could screen capture the application for future reference.

4.1 Participants

Our target was to recruit a minimum of 10 participants to our tests. Optimally these participants would be from two different groups: students and young children. This way we could evaluate the experience for a more study focused audience, as well as a more curiosity focused. Due to the challenges involved in attaining such young participants, we decided to restrict the evaluation to fellow students and others that we could find around the campus. In the end, we managed to get 22 participants for our tests. It was also decided that before these tests, system usability would be evaluated, for which we got eight volunteers.

4.2 System Usability

Each of the eight participants individually tested our application using our setup. They were informed about the purpose and the main features of the software, as well as being instructed on general usage of Oculus, mainly regarding putting on the HMD and staying within the tracking area. After around 15 minutes of testing, each participant answered the standard System Usability Scale (SUS) questionnaire, providing us with a final score of 74.7. This score implies a top 30% SUS score. What this measures is the overall usability and to some extent learnability of the product. For the most part, participants were able to learn the essential features and controls within 10 minutes despite not having significant prior experience of VR or Oculus Rift in particular. However, while observing the participants during testing, we came across some difficulties on multiple occasions.

Firstly, most users struggled to figure out how portals should be used until they went back to read the text on the wall, instructing to put the portal in your head. Portals themselves have a text above them instructing to “look through” the portal. This did not seem to guide users towards the correct way of interaction.

Secondly, while not necessary for the core functionality of the program, the ability to interact with the card in the user’s left hand was entirely undiscovered during the usability tests. In order to interact with the card, the user must use the laser pointer with the right hand to point at interactive elements. This is used to toggle between movement options and to browse 360 photos in the corresponding scene. This functionality is never explicitly explained within the application, which appears would be essential.

Some additional confusion to the functionality of pointing is caused by diorama animals not providing the user information. This is particularly problematic since many users might view the diorama before the animals on the shelves, which leads to them getting a negative first impression about the pointing mechanic. This particular issue can however be easily solved by adding colliders and names to the animals in the diorama.

Especially when grabbing the Oculus Touch controllers for the first time, many of the participants took a firm grip, accidentally squeezing the trigger for teleporting. While the sensitivity of this analog input could be adjusted, the physical trigger on the controller provides very little resistance to being pushed, which results in the trigger getting pushed all the way in most of these accidents. We have yet to determine an appropriate solution to this problem, as more testing is required.

4.3 Performance

By utilizing performance metric tools provided by Oculus, we can see that our workstations manage to render the native 90 frames per second of the HMD stably in scenes other than the forest, which seems to cause excessive GPU load due to the amount of trees combined with the real-time lighting. Although this scene requires more optimization, fortunately for this evaluation, the experience can remain relatively smooth thanks to Asynchronous Spacewarp [3], which essentially predicts what the next image will be in the case that the application itself takes too long to deliver the next frame.

4.4 Cognitive Walkthrough

The cognitive walkthrough proceeded as follows:

GOAL#1: Learn controls and enter the museum environment from the starting environment.

- a) Read the text on the wall (this wall contains information on interacting with the environments)
- b) Learn how to move in the virtual environment (controls are shown to the participants)
- c) Find a portal to the museum
- d) Grab the portal and put it in your head to use it.

GOAL#2: Explore the museum

- a) Find an animal
- b) Point at an animal and read its name from the card located on the left hand
- c) Find the different types of animals in the museum (birds, insects, mammals). Upon finding the insects, participants are instructed to use the magnifying glass.
- d) Visit the diorama

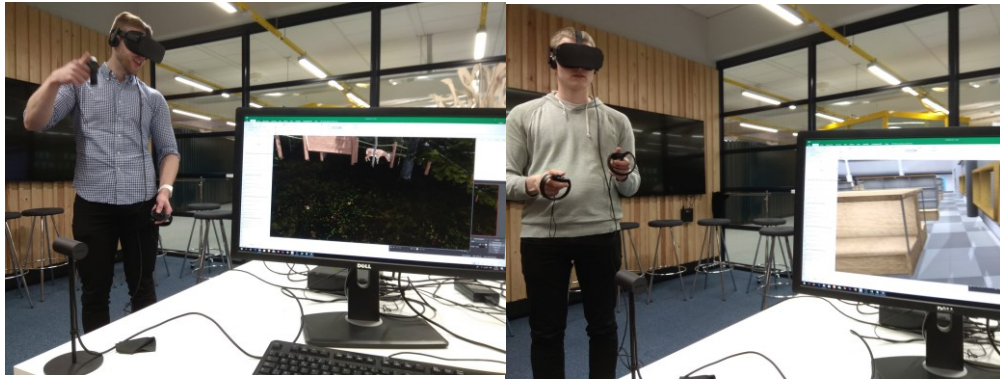
GOAL#3: Visit the 3D forest environment

- a) Use the portal to enter the forest environment
- b) View the signboard in the environment
- c) Search for and view animals in the environment
- d) Spawn mosquitos in to the area by swatting the mosquito poster with the swatter

GOAL#4: View 360° forest photos

- a) Use the portal to enter the 360° forest photo environment
- b) Point with the right hand at the arrows on the card on your left hand to browse 360° images

The approximate average duration of the walkthrough was 11 minutes, and the duration for filling surveys was around 5 minutes per participant.



Figures 13, 14: Participants during their cognitive walkthrough of the application

5 RESULTS

5.1 Game Transfer

Immediately after going through the cognitive walkthrough, participants filled the game transfer questionnaire, which measures alteration in perceptions, automatic mental processes and behavior due to re-experiencing something related to the game that was played [10], [23]. Most questions received low scores, and average experienced game transfer was weak during the tests. The table lists the amount of votes each Likert scale option received and the average score of all votes per question and subsection.

Table 1. Game Transfer Phenomena (GTP)

Question/Given scores	1	2	3	4	5	6	7	Average Score
Altered perceptions	124	25	8	8	3	3	5	1.69
I have seen distorted real life environments and/or objects due to the museum visit	11	6	3	1	0	1	0	1.91
I have seen mosquitos after or during the museum visit, when in reality there weren't any anymore	20	1	0	0	0	0	1	1.32
I saw one or more of the animals in the museum breathing	7	4	1	3	2	1	4	3.36
I have heard some sounds from the virtual museum after the visit	19	3	0	0	0	0	0	1.14
I have heard mosquitos after or during the museum visit, when in reality there weren't any anymore	16	4	1	0	0	1	0	1.50
I heard other animal sounds during the museum visit (excluding near diorama)	18	2	0	2	0	0	0	1.36
I have experienced bodily sensations of movement as if I was still in the virtual museum	12	4	3	2	1	0	0	1.91
I have experienced itching as if a mosquito was on my skin during or after the museum visit	21	1	0	0	0	0	0	1.05
Automatic mental process	20	8	8	7	1	0	0	2.11
I have wanted or felt the urge to do something in real life after seeing something that reminded me of the virtual museum	8	7	3	4	0	0	0	2.14
I have experienced still being in the mindset of the virtual museum after I have stopped playing	12	1	5	3	1	0	0	2.09
Behaviors and actions	34	7	1	1	0	1	0	1.39
I have sang, shouted or said something unwillingly due to the virtual museum visit	17	3	1	0	0	1	0	1.45
I have acted out a behavior or performed an activity influenced by the virtual museum	17	4	0	1	0	0	0	1.32

5.2 Sense of Presence

The intention of the presence questionnaire [32] is to measure different factors that affect the users' sense of presence in the virtual environment. In other words, how easily users can become immersed in the experience. This is divided into different categories that are shown in bold in the table below.

Table 2. Sense of Presence in VR

Question/Given scores	1	2	3	4	5	6	7	Average Score
Realism	2	12	23	33	47	21	16	4.55
How natural did your interactions with the environment seem?	0	1	5	6	7	2	1	4.32
How much did the visual aspects of the environment involve you?	0	0	1	6	6	7	2	5.14
How natural was the mechanism which controlled movement through the environment?	1	6	4	4	7	0	0	3.45
How compelling was your sense of objects moving through space?	0	1	3	5	7	2	4	4.82
How much did your experiences in the virtual environment seem consistent with your real world experiences?	0	3	7	2	8	2	0	3.95
How compelling was your sense of moving around inside the virtual environment?	1	0	3	4	8	3	3	4.77
How involved were you in the virtual environment experience?	0	1	0	6	4	5	6	5.36
Possibility to act	0	2	10	12	27	26	11	5.11
How much were you able to control events?	0	0	2	3	8	7	2	5.18
How responsive was the environment to actions that you initiated (or performed)?	0	0	5	2	9	3	3	4.86
Were you able to anticipate what would happen next in response to the actions that you performed?	0	0	3	4	4	8	3	5.18
How completely were you able to actively survey or search the environment using vision?	0	2	0	3	6	8	3	5.23
Quality of interface (reverse)	13	18	12	13	9	1	0	5.15
How much delay did you experience between your actions and expected outcomes?	9	9	3	0	1	0	0	6.14
How much did the visual display quality interfere or distract you from performing assigned tasks or required activities?	3	4	3	9	3	0	0	4.77

How much did the control devices interfere with the performance of assigned tasks or with other activities?	1	5	6	4	5	1	0	4.55
Possibility to examine	0	2	5	9	21	18	11	5.23
How closely were you able to examine objects?	0	1	1	2	10	4	4	5.23
How well could you examine objects from multiple viewpoints?	0	0	3	2	6	7	4	5.32
How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities?	0	1	1	5	5	7	3	5.14
Self-evaluation of performance	0	0	4	6	12	11	11	5.43
How quickly did you adjust to the virtual environment experience?	0	0	0	4	4	7	7	5.77
How proficient in moving and interacting with the virtual environment did you feel at the end of the experience?	0	0	4	2	8	4	4	5.09
Sounds	1	2	7	11	21	24	7	5.04
How much did the auditory aspects of the environment involve you?	0	2	2	4	11	9	1	4.90
How well could you identify sounds?	0	0	1	6	3	8	4	5.36
How well could you localize sounds?	1	0	4	1	7	7	2	4.91
Haptic	3	6	4	10	12	6	3	4.18
How well could you actively survey or search the virtual environment using touch?	1	3	4	5	7	1	1	3.95
How well could you move or manipulate objects in the virtual environment?	2	3	0	5	5	5	2	4.41

5.4 General Impressions

One of our questionnaires was centered around the overall quality of the content, including the animals and the different environments. Most comments we received during tests were positive, which coincides with responses to the questionnaires.

Table 3. Content Evaluation

Question/Score	1	2	3	4	5	Average
How believable were the birds in the museum?	0	2	5	12	2	3,67
How detailed were the birds in the museum?	0	1	5	15	0	3,67
How believable were the quadrupeds in the museum?	0	3	5	10	3	3,62
How detailed were the quadrupeds in the museum?	0	2	6	12	1	3,57
How believable were the insects in the museum?	0	3	4	8	6	3,81
How detailed were the insects in the museum?	0	1	5	9	5	3,9
How believable was the diorama?	0	4	8	8	1	3,29
How detailed was the diorama?	0	3	4	13	1	3,57
How believable was the museum environment?	0	4	4	9	4	3,62
How pleasant was the museum environment?	1	0	5	12	3	3,76
How believable was the virtual forest environment?	0	1	2	11	7	4,14
How pleasant was the virtual forest environment?	0	0	1	13	7	4,29
How believable were the 360° forest images?	0	2	7	8	3	3,6
How pleasant were the 360° forest images?	0	3	6	10	2	3,52
How pleasant was moving in the environments?	0	4	6	10	1	3,38
How pleasant was reading data on the animals?	2	1	5	11	2	3,48
Was searching for animals in the forest pleasant?	1	3	1	12	4	3,71
How believable were the mosquitos	1	5	4	8	3	3,33
Did you find the mosquitos annoying?	2	3	2	9	5	3,57
How entertaining was the mosquito game?	0	10	5	6	0	2,81

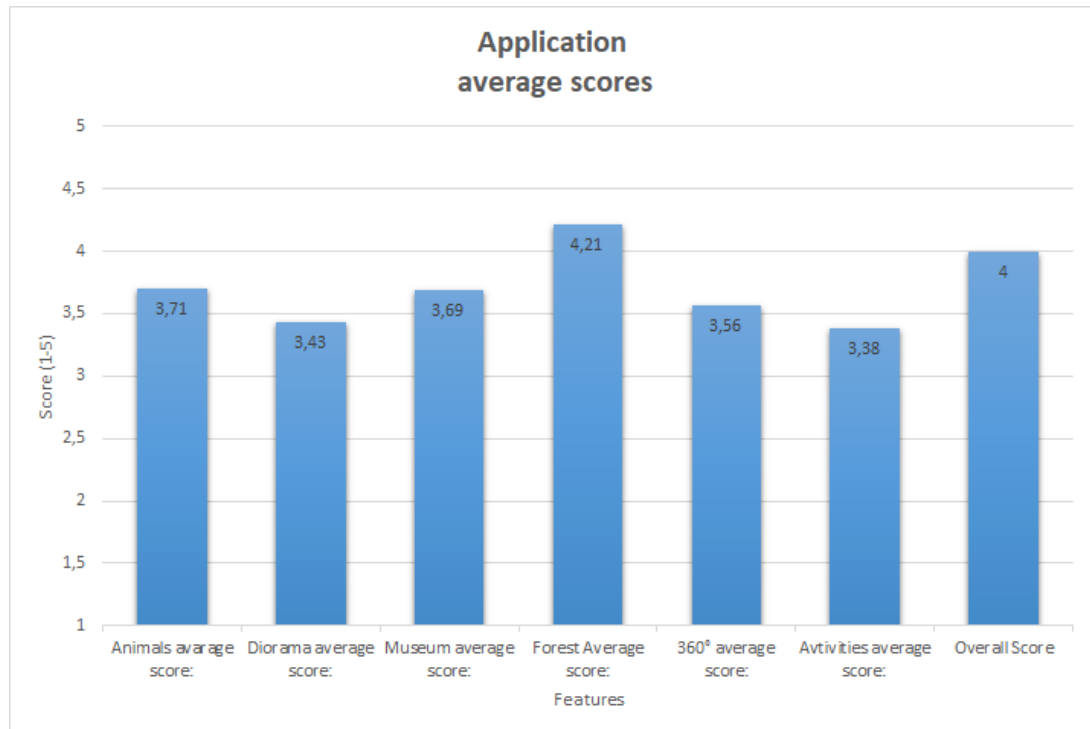


Figure 15. Content Evaluation section averages

6 DISCUSSION

6.1 Game Transfer

To pick a few outliers, the question that inquired whether the participant felt as if some of the animals were breathing in the museum received suspiciously high scores compared to others. The intent was to probe whether participants added an extra level of immersion to the experience without it actually being there. However, in the museum some of the animals performed various animations which we believe some participants considered as breathing. As such, we doubt responses to this question provide reliable and meaningful data.

Other than that, the subsection for automatic mental processes received the highest scores. This may be due to how differently one needs to approach the concept of moving in space in VR, which many of our participants were not accustomed to. Related to this, bodily sensations of movement as if still in the virtual museum were a relatively common occurrence as well.

In addition, some participants reported seeing distorted environment or objects due to the museum visit with varying degree of magnitude. Low prior experience of stereoscopic HMD technology may explain this phenomenon, but it's difficult to draw definite conclusions.

6.2 Sense of Presence

Overall results of our questionnaire on sense of presence in our VR application are positive. In terms of realism, visual aspects were highly rated while moving and interacting was considered less convincing. Some of the received open feedback also mentioned wanting to somehow walk instead of teleporting. Unfortunately we did not

have the resources to let users try free locomotion due to the nauseating effects it causes for many. Hopefully some upcoming peripherals offer new, more natural ways to allow the user to move in VR.

All questions related to sense of having control received relatively high scores. Some of the inconsistency seen in the responses are likely explained by the amount of interaction found within the application, which we would say is somewhat low. We would like to add more interaction and allow the user more control, but the challenge in that is maintaining usability. For software that many users might only try for 10 minutes, it is important that they can use that time efficiently.

Regarding the interface, the quality of the display was found to be somewhat distracting by most, while the control interface received much more varied responses. The delay between performed actions and expected outcomes was seen as very low by all but one participant. Based on the recording, some possible explanations for this response could be tracking issues that were present during the test, having to wait for animal information to load, or a hit on a mosquito at the very end of the swing. One way to speed up fetching of animal information would be storing them locally. In that case, the information would have to be sometimes updated to keep it up to date with possible changes to the database. As for the mosquitos, more testing and adjusting might be required to allow the user to have increased control during the game.

Most participants were satisfied with how closely and from different angles you could view objects. One person with particularly negative feedback on being able to examine objects closely appeared to stay at a distance when looking at animals or insects, perhaps due to difficulties moving short distances using teleportation. This could be improved on our part by improving the bounce on the aim of the teleport in a way that the user could simply aim towards the shelf to end up in front of it. At the same time, free locomotion movement is suitable for finer positional adjustment as it is, and therefore introducing it as an option to users would likely be beneficial. As for viewing objects from different angles, it could be further improved by allowing grabbing and rotating. This would however break the illusion of shadows of animals as it currently is implemented, and could cause disorder if not restricted. Both of these difficulties could be overcome with additional design and development time.

On average, our test users felt like they were able to learn and get used to using the application with relative ease.

6.3 General Impressions

Responses on the quality of bird type animals are consistently good, while feedback on insects is more varied. Opinions on diorama appear to be very mediocre. Environments were mostly seen as believable, with the forest environment being seen as most pleasing, but 360 photos were received as more average. Considering this evaluation and our own views, we are interested in improving the quality of the diorama. This could be done either by taking more pictures to use for photogrammetry or by manually editing the generated 3D-models. Alternatively, some new methods of presenting the diorama could be experimented with. Furthermore, some pictures of the insects are of lower quality than others, as well as some of their heightmap textures being inaccurate.

Feedback on teleportation as movement is somewhat higher than average, as well as attaining information about animals, albeit more varied. Most users found searching for animals in the forest environment enjoyable. Mosquitos were seen as somewhat believable, mostly irritating, and slapping them as somewhat entertaining.

Only one person experienced sensation of itching during the mosquito game, which is surprising to us, as both of us have experienced that during the development.

On average, participants rated their Virtual Zoological Museum visit 4 out of 5. This overall rating feels satisfactory to us, but we believe the experience can be improved in multiple different areas (fig.15).

6.4 Limitations

The amount of participants that took part in our evaluation could be considered low. Furthermore, they were all either students or employees at the University of Oulu. These two factors significantly restrict the ability to draw definite conclusions based on the overall results of the questionnaires. Another factor to consider is the environment and execution of the user tests. Although the environment was quiet and calm, the participants were likely affected by time constraints and instructions being spoken from outside the virtual environment, affecting their ability to become immersed or fully familiar with the contents and features of the application. Despite the limitations, as a preliminary evaluation we find our study successful in pointing out new directions for future evaluation and development of our VR museum.

7 CONCLUSION

The purpose of this work was to further develop the Virtual Zoological Museum for use as both an inspiring environment for children and an environment meant for studying animals in a new and different way. Furthermore, the goal of this project was to create a VR version of the application that previously only ran conventionally on the desktop.

First and foremost, full support for Oculus Rift and its Touch controllers was implemented with accessibility, comfort of use and ability to view and interact with the museum contents in mind. The virtual forest environment was completely overhauled, achieving improvements in performance, visual quality, features and realism. A framework for scanning and implementing new animals was created, starting from photographing the animals and finishing with placing them in the scene. This process was designed with consideration to quality, performance, and speed of implementation. New animals were added, some of which make use of the fur shader that was made. Lighting was optimized for each scene using a combination of baked and real-time lighting, balancing between good performance and visuals to the best of our capabilities.

Some of the biggest challenges that we came across were lighting and VR controls, which both went through many iterations. We were also faced with the challenge of handling all the different aspects that go into a VR application. Some of it we had prior experience in, but much had to be learned along the way. Still, more expertise would be needed in order to achieve more realistic animals, especially when it comes to adding animations. A project of this scale requires cooperation with different parties to achieve best results.

7.1 Future Work

Going forward from here, most importantly, more animals should be added into the museum. Additionally, some of the issues that surfaced during evaluation require touching up on, as well as further improving performance.

Since the design aspect of this project is of major importance it is highly recommended that future design choices are documented thoroughly. The documentation of a certain aspect of the design may turn out to be the most important scientific contribution of this work.

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