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NORMAL MAPPING IN VIRTUAL REALITY ENVIRONMENTS

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NORMAL MAPPING VIRTUAALITODELLISUUSYMPÄRISTÖISSÄ

Virtuaalitodellisuudesta (Virtual Reality, VR) on tullut IT-alan yksi olennainen osa-alue, ja kiinnostus sitä kohtaan on tällä hetkellä koholla. Markkinoilla on myynnissä useita eri VR-järjestelmiä, joita yhdistää ainakin yksi tekijä: päähän aseteltava näyttö, joka ympäröi käyttäjän näkökentän sijoittaen hänet virtuaaliympäristön sisään.

Tämä opinnäytetyö koostuu VR-projektin esittelystä sekä tutkimusosiosta. Projektista esitellään sen pääidea, kehitystyö sekä käytetyt teknologiat. Tutkimuskysymyksenä tässä opinnäytetyössä oli selvittää, onko visuaalinen käyttäjäkokemus miellyttävämpi tai realistisempi, kun normal mapping -tekniikkaa käytetään ehostamaan virtuaalitodellisuusympäristöä.

Tämän selvittämiseksi luotiin kaksi virtuaaliympäristöä, joista kummastakin oli kaksi variaatiota. Toinen variaatioista sisälsi normal mapping -tekniikkaa, toinen ainoastaan 3D-mallien tekstuureja. Osallistujat olivat Turun ammattikorkeakoulun opiskelijoita, miehiä ja naisia ikävuosien 18 ja 30 välillä. Osalla henkilöistä oli aikaisempaa VR-kokemusta. Testauksen aikana osallistujat asetettiin jokaiseen variaatioon ja heitä pyydettiin vertailemaan näiden visuaalista miellyttävyyttä ja realismia.

Testitulosten perusteella lähempänä käyttäjää olevat 3D-mallit nähtiin miellyttävämpinä ja realistisempina kun niissä käytettiin normal mapping -tekniikkaa. Toisaalta kaukaisempien 3D-mallien osalta testihenkilöt kokivat ainoastaan tekstuureja hyödyntävät ympäristöt hieman miellyttävämmiksi. Tilastollisten analyysien perusteella lähempänä olevien 3D-mallien miellyttävyys todennäköisesti korreloi tietyssä määrin normal mapping –tekniikan käytön kanssa. Näin ollen VR-kehityksessä voisi olla hyödyllistä keskittyä etenkin pienemmän etäisyyden päässä olevien mallien ehostukseen kyseisellä tekniikalla.

ASIASANAT:

virtuaalitodellisuus, normal mapping, bump mapping, teksturointi, tietokonegrafiikka

BACHELOR´S THESIS | ABSTRACT

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NORMAL MAPPING IN VIRTUAL REALITY ENVIRONMENTS

Virtual reality (VR) has become an integral part of the IT field, and interest in VR is currently at an elevated level. There are several VR systems on the consumer market which have a head-mounted display which surrounds the user's field of vision, immersing them to the virtual settings.

The thesis describes a VR project created for an IT-oriented event: the core idea, its development and the technologies used.

The aim of this thesis was to find out whether the visual user experience is more pleasant or realistic when normal mapping is used to enhance the virtual reality environment.

For this purpose, two virtual environments were created, each having a variation with and without normal mapping. A total of 22 participants took part in the testing, and the group consisted of students from Turku University of Applied Sciences. The test subjects were males and females between the ages 18 and 30, with some having experienced VR before. During the experiment, the participants were put into each variation for 30 seconds at a time. After seeing both variations of one environment, they were asked which one they preferred in terms of visual pleasantness and which one they found visually more realistic. The answers were collected into a table, and later converted into figures for quantitative analysis.

According to the test results, it seemed that objects closer to the user were seen as more pleasant and realistic in their normal mapped form. However, normal mapped objects that were further away were experienced as less pleasing than their texture-only counterparts. While more thorough research on the subject is warranted, statistical analyses indicated that there probably was some correlation between the use of normal mapping in close-by objects and their perceived visual pleasantness. This would indicate that the work effort required by normal mapping in VR environments could be focused primarily into 3D objects in the user's vicinity to reduce the overall work load.

KEYWORDS:

virtual reality, normal mapping, bump mapping, texturing, computer graphics

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1 INTRODUCTION

With all its trends, the emergence of modern virtual reality (VR, see **Descriptions and clarifications**) devices such as Oculus Rift (Oculus Rift 2017) and especially HTC Vive (VIVE 2017a) made their place in the IT world. While the search-based interest in VR peaked in December of 2016, the appeal of VR seems to currently stay at an elevated level (Google Trends 2017). In addition to such high-end consumer VR machinery, several inexpensive alternatives have also entered the markets: Google Cardboard is a piece of downloadable software that enables the user to utilize his/her mobile phone's display as a VR device with the help of a physical viewer part that includes a frame to hold the phone in place, and two lenses that aid in the viewing of VR content (Google Cardboard 2017, Google Play 2017).

Bump maps are an integral part of 3D video game environments and objects. They are used to simulate surface geometry on objects without modifying the bump mapped object's mesh in any way (Tuan, Kim & Lee 2015, 7). This way there is no need to 3D model fine geometry to many objects.

Adding a large amount of details to the 3D models slows down the rendering speed (Isaacs 1999, 30) and is thus undesirable. This is especially important in VR, since the performance requirement is even more of an issue due to the demanding nature of VR display resolutions and the image refresh rate (Takahashi 2015). In my project and research, I focused on normal maps, a special type of a bump map: A 2D image that uses red, green and blue colors to represent the direction of surface normals, which in turn shape the way the object's surface responds to light (Huhtamaa 2007, 2; Unity Manual 2017d). In the most typical scenario, the surface normals are simply based on the angle the polygon is facing (see **Image 1**).

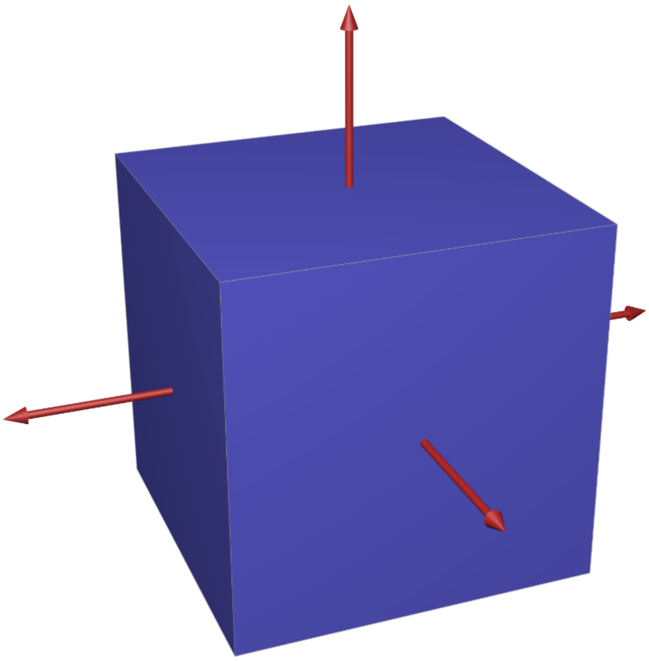


Image 1. Surface normals (represented by red arrows) on square-shaped polygons.

As a game technology student working on a demo game for the ICT Showroom 2017, I became deeply involved and interested in the world of VR and 3D graphics. Additionally, since the interest in VR is now at a higher level, investigating its technologies and implementation methods are in order. Due to the higher requirements posed by VR, performance optimization by keeping the 3D objects simple in geometry while using normal mapping could be particularly beneficial. However, more information is required on whether normal mapping actually enhances the experience of visual pleasantness or realism when VR is involved. Hence, my research question is: Is the user experience more pleasing and / or realistic when normal mapping is used to enhance the virtual reality environment?

2 DESCRIPTIONS AND CLARIFICATIONS

For better understanding what virtual reality is, MOT Oxford Dictionary of English presents a fairly accurate and concise definition:

> (VR is) the computer-generated simulation of a three-dimensional image or environment that can be interacted with in a seemingly real or physical way by a person using special electronic equipment, such as a helmet with a screen inside or gloves fitted with sensors (2017).

While this thesis focuses primarily on the video game-related aspects of VR, it is used for example in medical fields – even quite successfully – and in military training (Seymour et al. 2002, 3-5; Bowman & McMahan 2007, 2).

HTC Vive is an integral part of each and every aspect of this thesis, both in the project portion and in the test sessions, and therefore it is important to know some of its details. The VR system consists of both software and hardware (see **Image 2**), the latter including (most importantly) a head-mounted display, two wireless handheld controllers and two infrared base stations for tracking the player in the assigned area (VIVE 2017). HTC Vive's specialties include the possibility for room-scale movement, which means that the user does not have to physically stand still in one place while using it (VIVE 2017b).

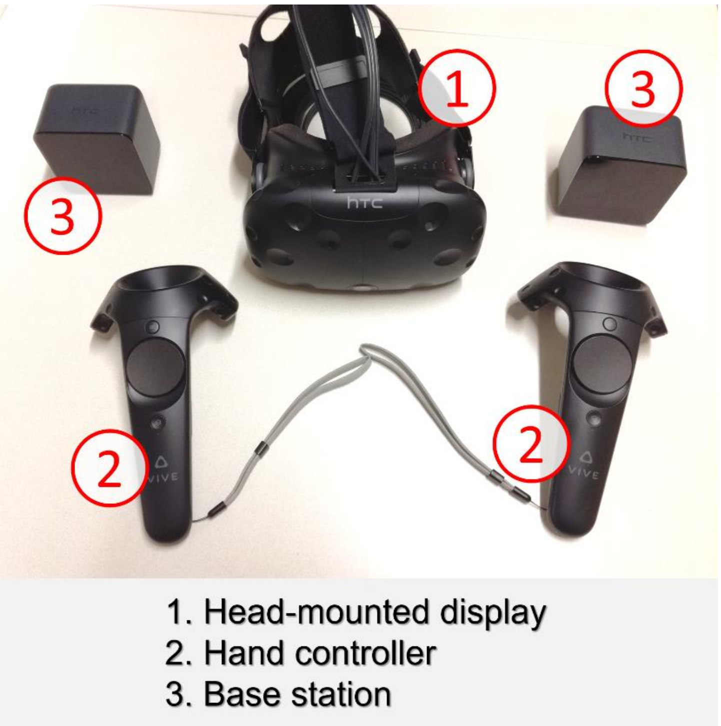


Image 2. HTC Vive’s main components.

Normal maps are essentially 2D images that function mostly in conjunction with 2D texture images. However, as stated by Mark J. Kilgard:

> In everyday usage the word “texture” refers to bumps, wrinkles, grooves, or other irregularities on surfaces. The computer graphics notion of a texture is more akin to the everyday notion of a decal (2000, 1).

Therefore, it is important to acknowledge this distinction. In a 3D virtual environment, there could be an entirely flat wall with a regular, colored stone brick texture added to it. Without using any additional geometry on the wall, some fine details could be added to it by attaching a normal map to the object (see **Image 3**, below).

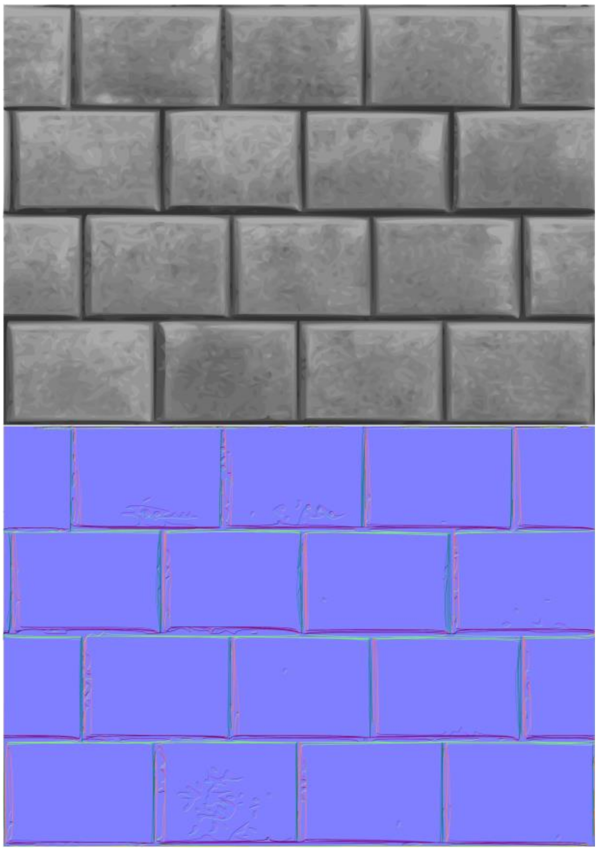


Image 3. Rock wall texture (above) with the normal map (below).

For better understanding how normal maps create the simulation of extra surface features (Tuan, Kim & Lee 2015, 7), it is important to understand how surface normals work in relation to the lighting in 3D scenes. Normals can be considered lines or arrows that represent the angle into which each surface – for example, a polygon – is facing (Microsoft Developer Network 2017). These normals are then used by lighting systems of the game engine or other 3D software to modify the lighting of each surface (Unity Manual 2017d). At the most elementary situation, a polygon only has normals “pointing” directly away from it (see **Image 4**, below).

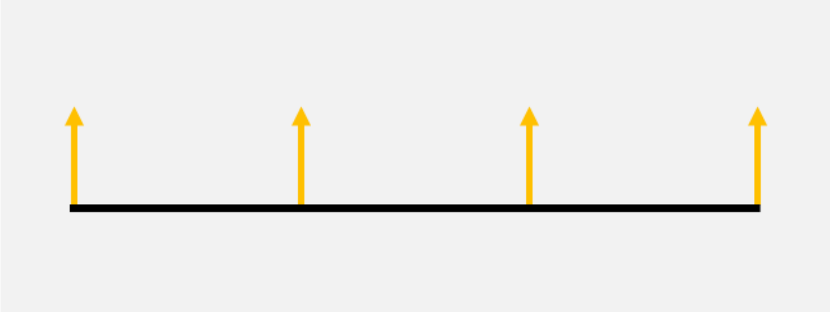


Image 4. A side view of one polygon with normals (marked with orange arrows).

However, this is where normal mapping comes into play. With the normal map attached, the object's surface shading reacts to light as though the additional geometry represented in the normal map existed (see **Image 5**, below), thus creating shadows and brighter areas on the object.

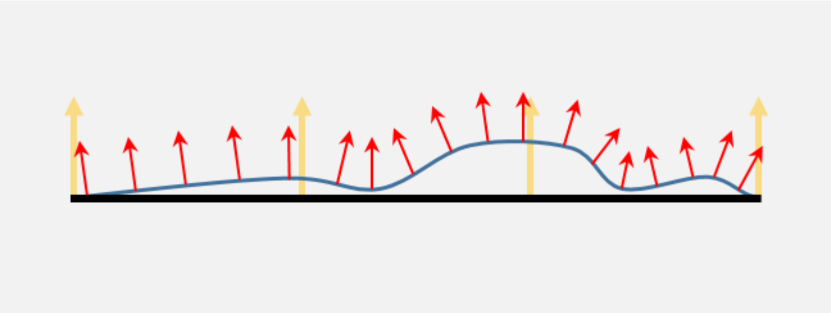


Image 5. A side view of a normal mapped polygon. The new normals are marked with smaller red arrows.

As for the project work portion of the thesis, I worked as the project manager and one of the developers for a VR demo created to show the abilities the FIRMA's student workers have to offer. The FIRMA is a project-based learning environment that functions within Turku University of Applied Sciences. These projects include web development, creation of marketing materials, other graphical work, and testing to name a few. Most of these come from external clients such as companies from around the Turku area but at times internal projects are introduced to, for example, facilitate some of our internal processes such as borrowing hardware. Apart from a handful of staff members, the FIRMA's employees are students either carrying out their mandatory internships, doing course-based work or simply working for extra credits. (The FIRMA 2017; Turku AMK – Turku University of Applied Sciences 2017).

3 PROJECT IDEA AND TIMELINE

Within the interns and project workers at the FIRMA, there were several gaming-oriented students. As we were able to get the HTC Vive virtual reality system in our office, we immediately started thinking about creating with the system and utilizing the game engine Unity. First, I organized a VR innovation day: a session where all the interested students were able to give their ideas on what we should develop, and also vote for their favorite ideas. The ideas ranged from various simulators and action games to raunchy humor-based games, but in the end, a game with room escape mechanics resulted as the winner. A small team of students was quickly formed in order to further develop the idea. The room escape idea was expanded into a type of a complex escape game where the player would not only try to escape one room, but a whole building. The game's main story focused around the player waking up from cryogenic sleep after crash-landing into a faraway space station. The player's goal in this scenario was to figure out what is going on in the station and to get back home to Earth.

After discussions with the FIRMA's management, we were able to make the game an internal project with the intent of presenting it in the innovation event ICT Showroom in early 2017. This project would act as a demonstration of the FIRMA's wide range of capabilities in ways that had not been presented publicly before.

Although the pitched idea was to have this whole space station as a playable area, we quickly noticed that programming, 3D modeling, and even game play design for VR were quite new things for the team, and took much more time than initially estimated. In order to have a presentable demo in time for the ICT Showroom, we later decided to limit the scope of the project to the player's spaceship and the first room on the station for the final demo version.

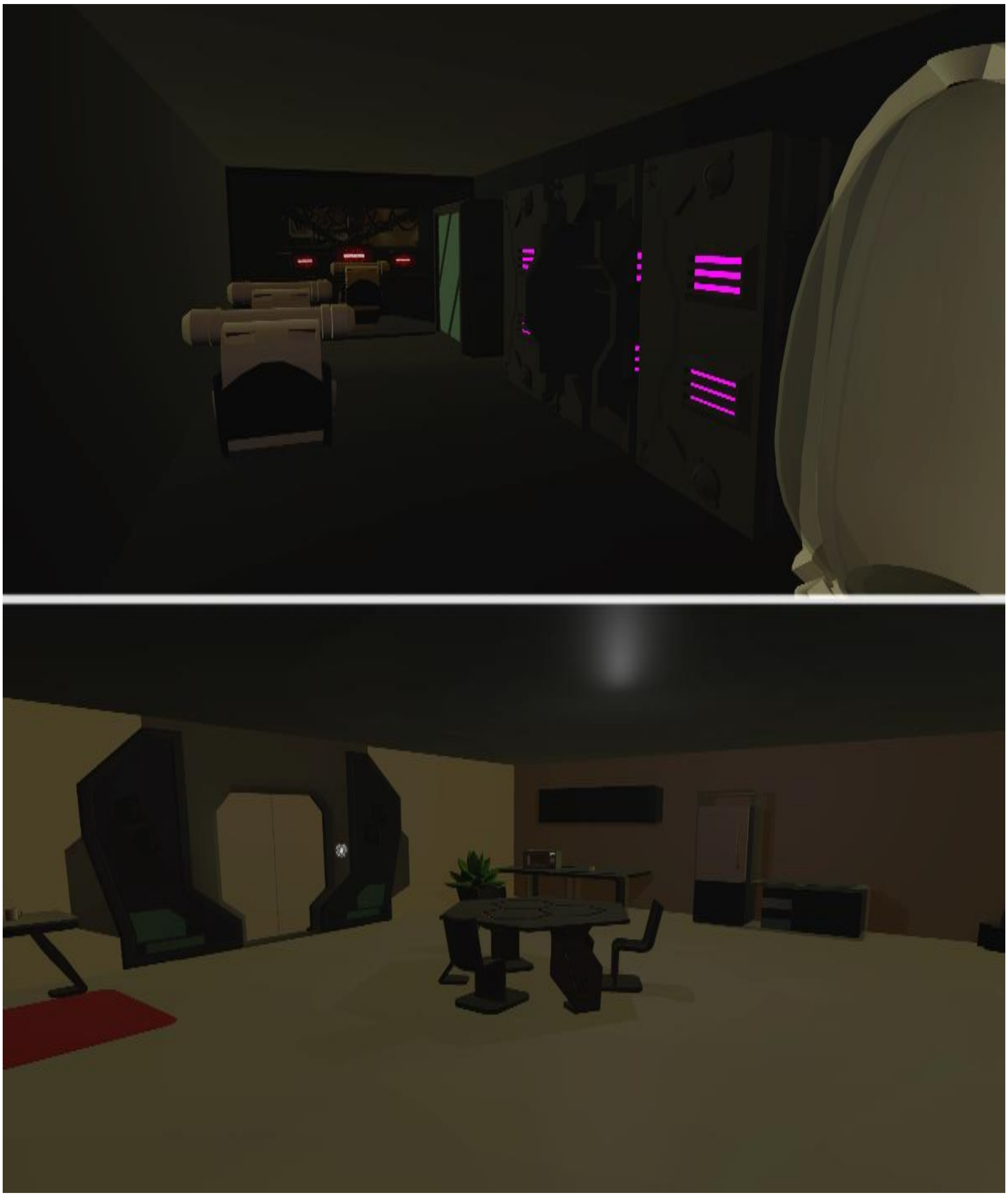


Image 6. Views from the ICT Showroom demo: the inside of the spaceship (above) and the first room on the station (below).

As seen in the **Image 6**, the settings themselves were quite simplistic in style and geometry. This was chosen because of two main reasons: The actual play area was very dark - leaving smaller details unseen - and performance optimization: we wanted the framerate to be as high as possible for a smooth user experience.

3.1 Technologies

Right from the start we knew we were going to use Unity as the game engine for the project. This was due to our previous experience with the engine, our knowledge of the programming language C# and the SteamVR plugin (Valve corporation 2016a). This made it quite easy to, for example, set the player into a virtual environment in such a way that the positions of the head-mounted display and the hand controllers tracked properly.

As a game engine, Unity includes for example a 3D physics engine (Unity Manual 2017e) and an effortless way to attach scripts – among other things – to objects in the game environment via easy-to-manage components (Unity Manual 2017a). Moreover, the software incorporates an intuitive user interface with the ability to visually edit the scene – the limited virtual environment – and all its objects (Unity Manual 2017c).

3.1.1 Physics

From the very beginning, we also knew that we would prefer to utilize Unity's own physics engine to make many of the interactions feel more natural: The player would have to carry things that would drop down realistically if let go, the player could maybe even throw objects around in order to solve puzzles. While using physics modeling in the game gave us new possibilities, it also led to additional obstacles to work through.

The first way of interaction with objects we implemented was to parent (Unity Scripting API 2017) the interactable object to the controller (or in this case, a hand) visible in the virtual environment when grabbing it with a certain button. While this did make it possible for the object to be picked up, swung around and carried, momentum and other forces were not correctly applied, and trying to for example throw the object resulted in it dropping straight down when the button was released. This was due to the removal of physics on the object (Unity Manual 2017g) which also made it possible for the player to push the object inside a wall and release it, causing the object to slip through. These problems were solved, however, when we found an open source project called NewtonVR. It handled the aforementioned issues by replacing the physics-removing parenting procedure with its own solution: The interactable objects would have an extra script attached to them that would cause them to closely follow the position and rotation of the virtual hand when grabbed while still retaining their own mass and physics attributes. This way the objects had momentum applied to them and they could be thrown and they could not be pushed through walls. (NewtonVR 2017). We looked through the NewtonVR scripts and modified them to better suit our needs by for example changing the button settings for a more natural feel for the players, and by tweaking some physics as well.

3.1.2 Movement in a VR environment

Before the development for the project started, we played several free VR games from Steam (Steam Store 2017) and a handful of paid ones. These games had a couple of different mechanics for movement within the virtual playable area: Teleportation in games like The Lab (Valve corporation 2016b), and trackpad-based, slightly more traditional movement in games like Onward (Downpour Interactive LLC 2016).

Additionally, depending on the SteamVR's chosen settings, the player can either play in in the room-scale mode (VIVE 2017b) or set up a more stationary standing-only play area (VIVE 2017c). While playing in the room-scale mode, the player is able to physically walk around in a dedicated area with his/her virtual reality manifestation moving correspondingly.

Initially, our team wanted to enable the player to have the option to use both the teleportation as well as trackpad movement to navigate the area. For the teleportation movement, we wanted to mimic the best parts of The Lab's system, and we found an open source project called "Vive Teleporter" (Biagioli 2016) which we were quickly able to adapt into our Unity scenes. Vive Teleporter included for example a functioning arc pointer (visualizing the teleport destination), a system for calculating the navigable space and visual cues that help the player to see where the limits of the teleportation area. On the other hand, our version of the trackpad movement was our team's creation, and it utilized the different areas of the trackpad for directional movement: The player could, for instance, look straight forward while using the trackpad to strafe to the side. After implementing both movement systems in our project, we had people outside of the development team unofficially test both movement methods. For the majority of players, only teleportation felt natural since many reported feelings of nausea when using the trackpad to move their player character in the virtual environment. Therefore, we decided to disable the trackpad movement for the ICT Showroom demonstration.

3.2 Personal contribution

As the project manager, I worked on various aspects of the game: 3D modeling, animating, programming, gameplay and map design (see **Image 7**). For example, I created models for the spaceship's hull, rubble, player's virtual hands and smaller objects. Furthermore, programming minor events and the finger movement based on the trigger button were my tasks.

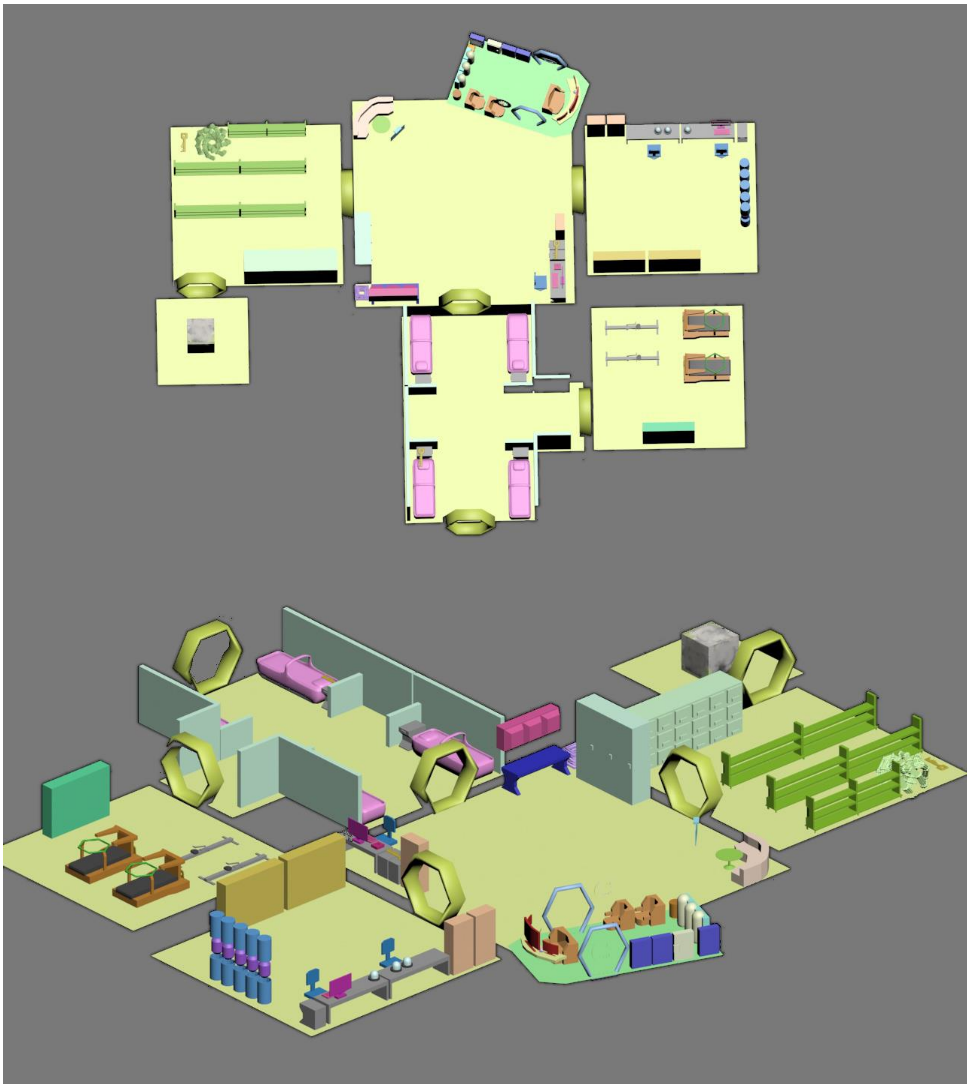


Image 7. The first map designs.

The process of map design was combined with some initial object design. This can be seen in **Image 7**'s various smaller, uncomplicated objects. I also took part in both partially designing and then 3D-modeling the mechanically augmented hands that replace HTC Vive’s hand controllers in the virtual world (see **Image 8**).

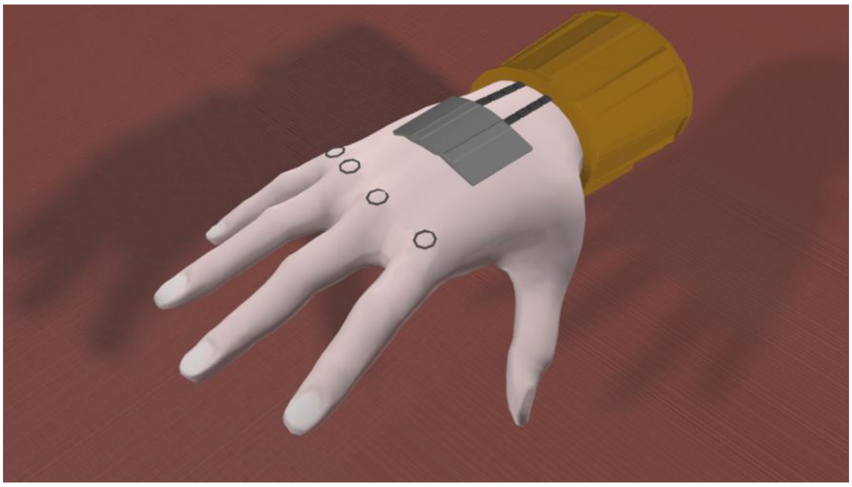


Image 8. The 3D hand model, created with 3ds Max 2016 (Autodesk 2016) and Make-Human (The MakeHuman team 2016).

While I was not our lead programmer or 3D artist, I started taking a special interest in normal mapping: I began doing tests in virtual environments utilizing normal mapping in walls, floors and small objects as well. In my Unity test scenes, I utilized both stationary and moving lights in order to test how the lights get reflected from a normal mapped surface.

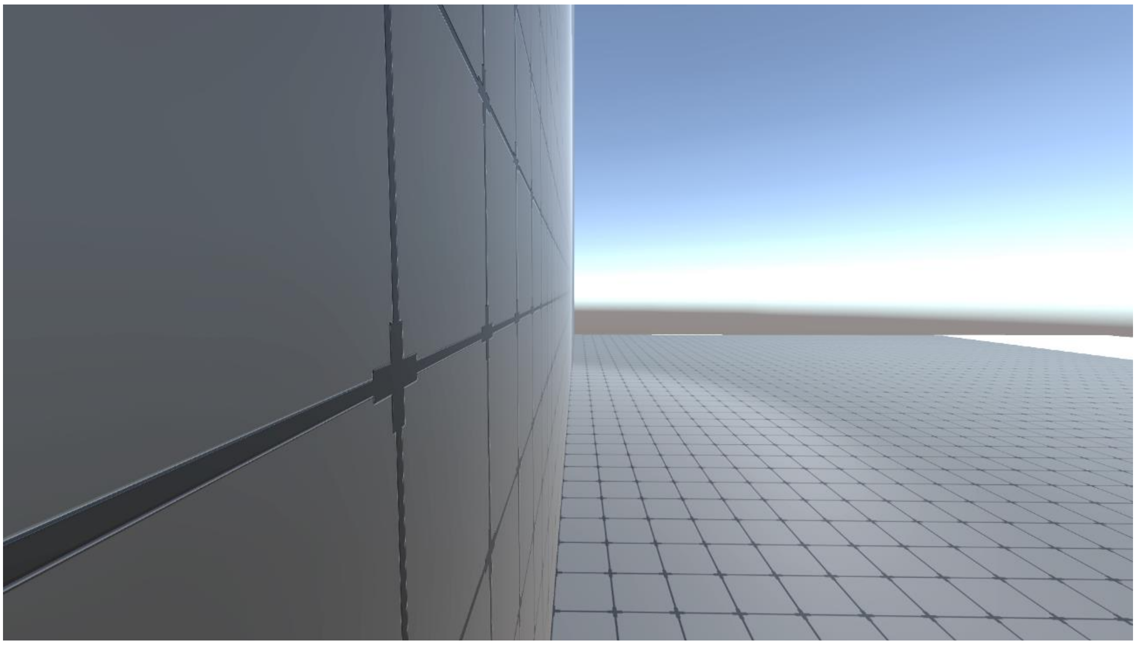


Image 9. A very close view of a softly normal mapped futuristic wall.

As the walls, floor and other such objects were completely opaque by their very design, I decided to test how normal mapped surfaces react to light when they are somewhat translucent: I combined a regular texture and a normal map of a shattered glass to experiment within these virtual surroundings (see **Image 10**).

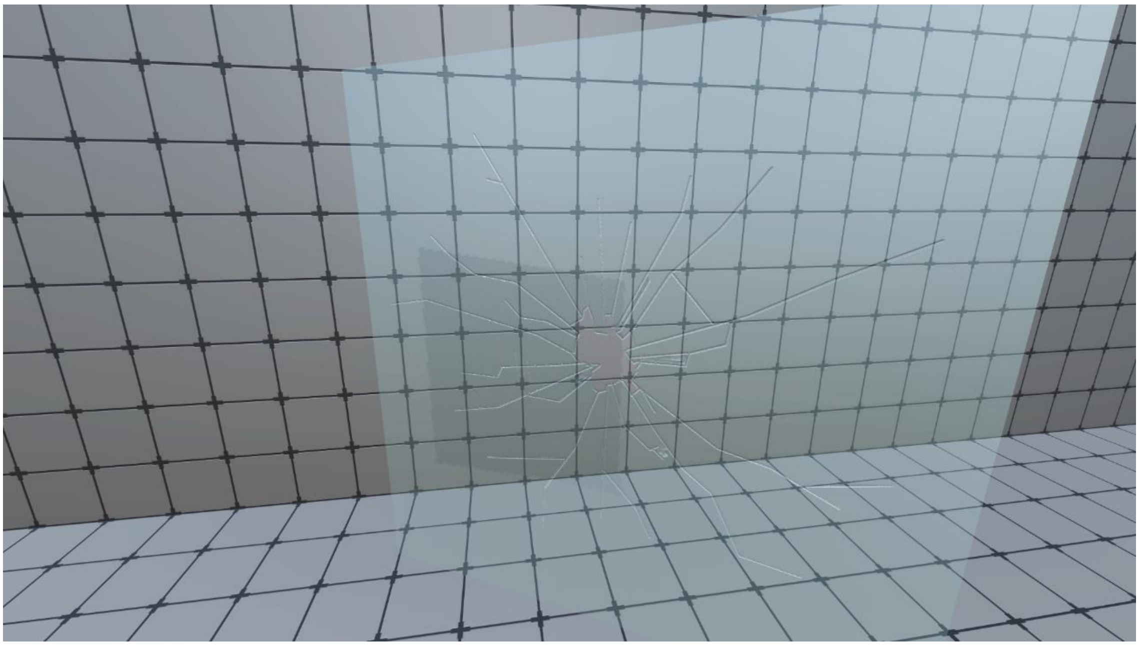


Image 10. A normal mapped plane simulating a shattered window.

I both tested these environments myself and requested others in the office to evaluate the effects they saw. However, since these tests were not properly controlled, I decided to build two minimalistic scenes and have a larger number of participants for better and more accurate results.

4 TEST SESSION AND RESULTS

In addition to my subjective brief normal mapping tests during the project development, I decided to investigate how people experience normal mapping in a VR environment compared to environments lacking any such surface mapping. Based on my personal testing, I noticed that distance played a key part in how convincing the normal mapping effect was. My original assumption was that VR users find the use of normal mapping more pleasant when the mapped objects are not in their immediate vicinity. I reckoned this would be the case due to the fact that the users could potentially see the lack of actual geometry in an object upon close inspection. To test this, I created two distinct environments.

4.1 The environments

The first of these environments was a room with textured and normal mapped walls and floor all around the player with slowly moving lights enhancing the effect created with normal mapping. An identical variation of the room was also created with the lack of normal mapping in the surrounding surfaces being the distinctive factor (see **Image 11**). As these two environments had identical geometry and light sources, they are both referenced with the name “Wall Scene”.

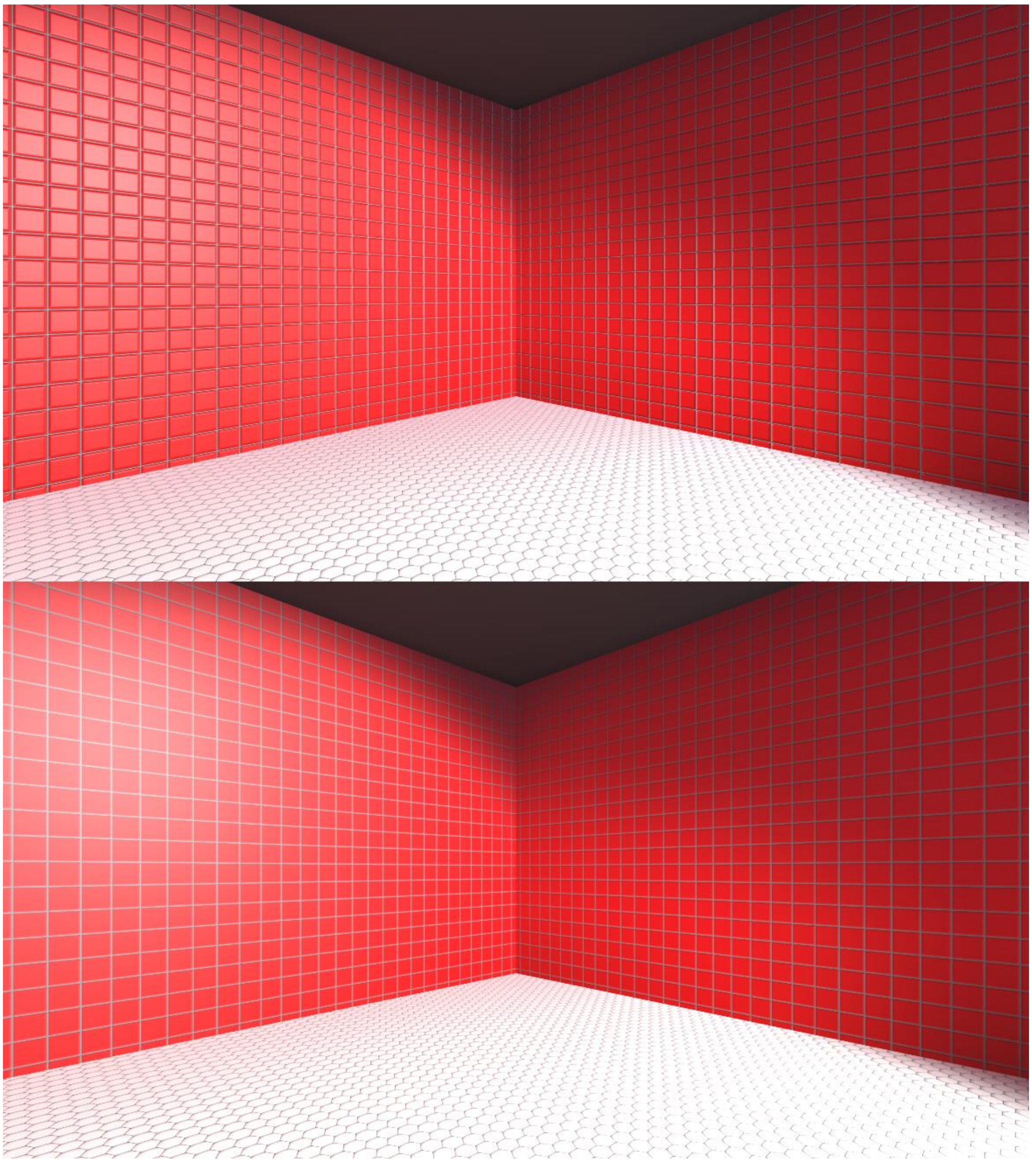


Image 11. Both variations of Wall Scene: Normal mapped above, texture-only below.

The second environment consisted of a room with a much simpler set of walls but that had a small normal mapped box in the center. The user could inspect the object very closely, even walking around it in the virtual area while a pair of spotlights slowly rotated near the ceiling. Naturally, a variation of this environment was also created without utilizing normal mapping functionalities, and each of these is called “Box Scene” (see **Image 12**).

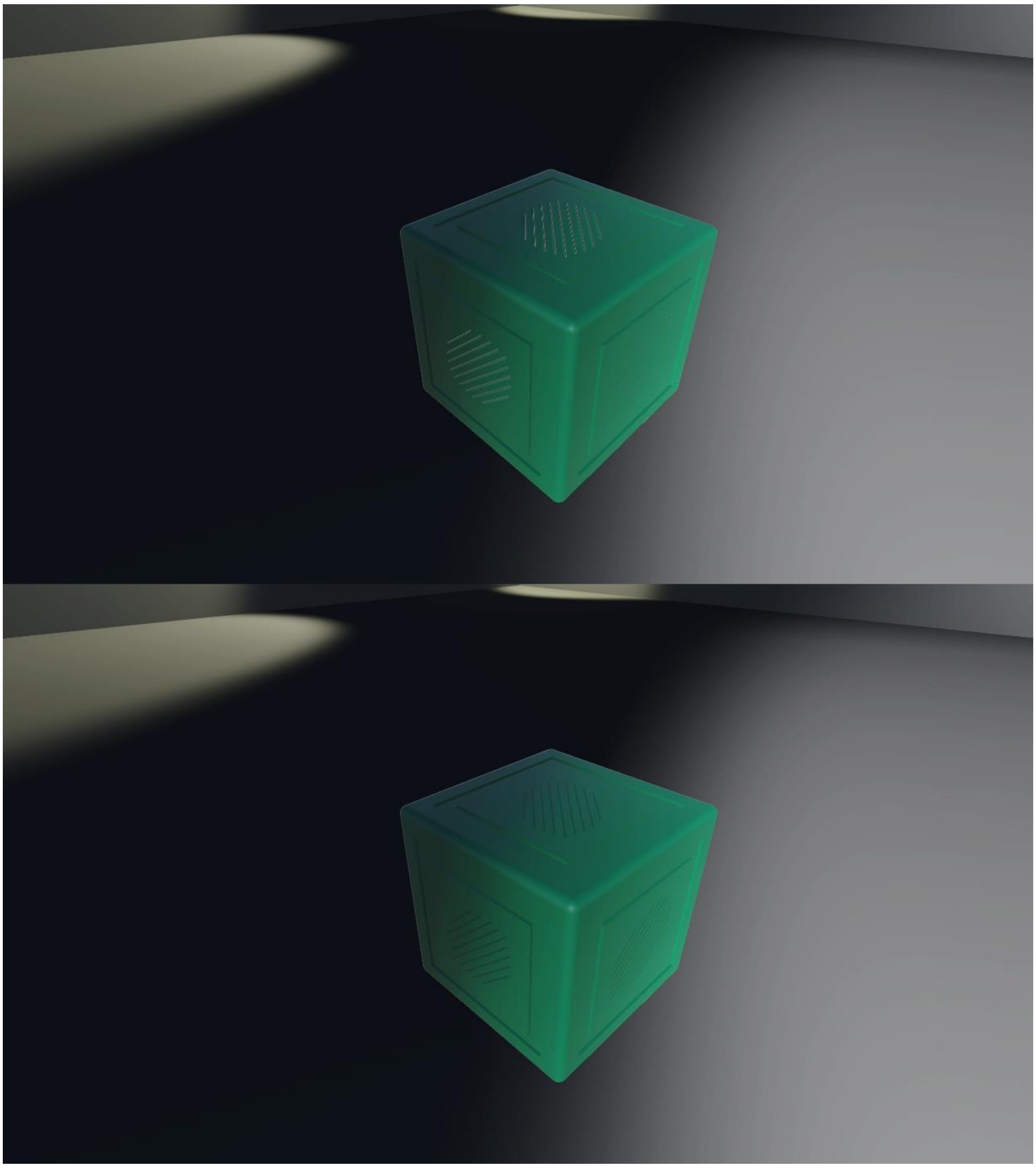


Image 12. Both variations of Box Scene: Normal mapped above, texture-only below.

I felt it was necessary to make the environments as minimalistic as possible in order to make the participants focus solely on either the walls and the floor or the box in the middle of the virtual space. This meant that in Box Scene, the floors, walls and the ceiling were all colored dark grey, leaving the box as the sole object on which to truly focus. The room in Wall Scene was entirely lacking in 3D objects, with emphasis directed at the walls and the floor by utilizing a brighter color palette. The leisurely spinning lights prevalent in both environments and their variations casted light into the scene similarly to spotlights. Their movement helped emphasize the differences of how light is reflected on a normal mapped surface compared to one with simply an ordinary texture.

4.2 Methodology

In order to test the fairly subjective concept of visual pleasantness and realism, a mixture of qualitative questions combined with a quantitative statistic-based analysis based on the answers was implemented. The participants were each first put into one variation of an environment with both the environment order and variation order chosen at random. Depending on the environment, they were asked to either focus on the walls and the floor or the box in the center, and told that they can move freely around within the assigned physical area limits. After a brief 30 second session in the environment, they were switched into the other variation for an equal amount of time. Before moving on to the other main environment, they were asked:

A) Which variation was visually more pleasant?
B) Which variation was visually more realistic?

While their answer options being:

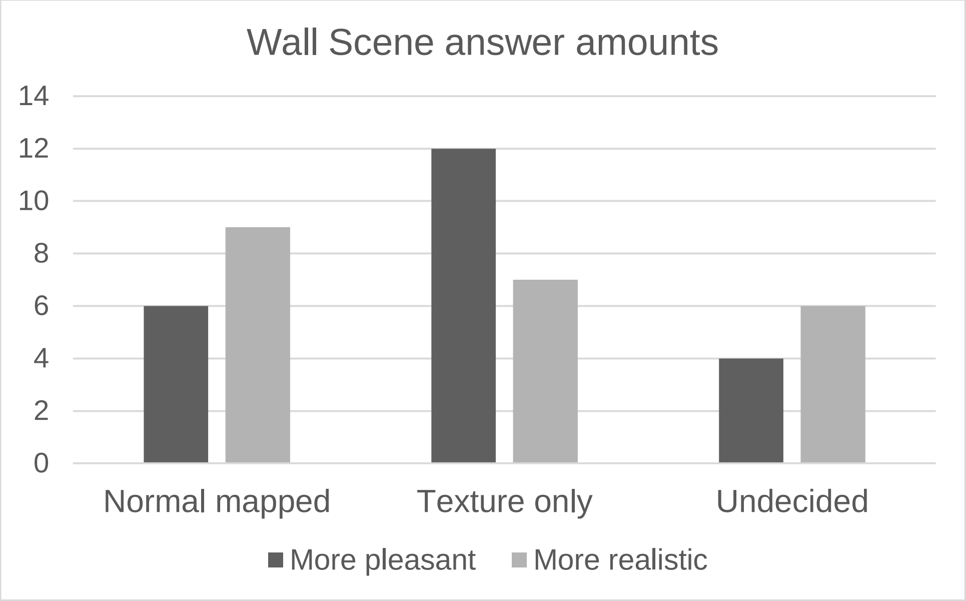
1) The first one
2) The second one
3) Undecided or cannot say

This is where the randomization in the variation order (see **Appendix 3**) became especially useful: It helped minimize some of the bias that the order of the answer options might cause. Following the first part of the test, the same method was repeated with the other main environment. Same questions and conditions applied. While the questions and answer options themselves were moderately qualitative in nature, the latter would later be used in deriving a statistical table and graphs for a quantitative analysis.

4.3 The results

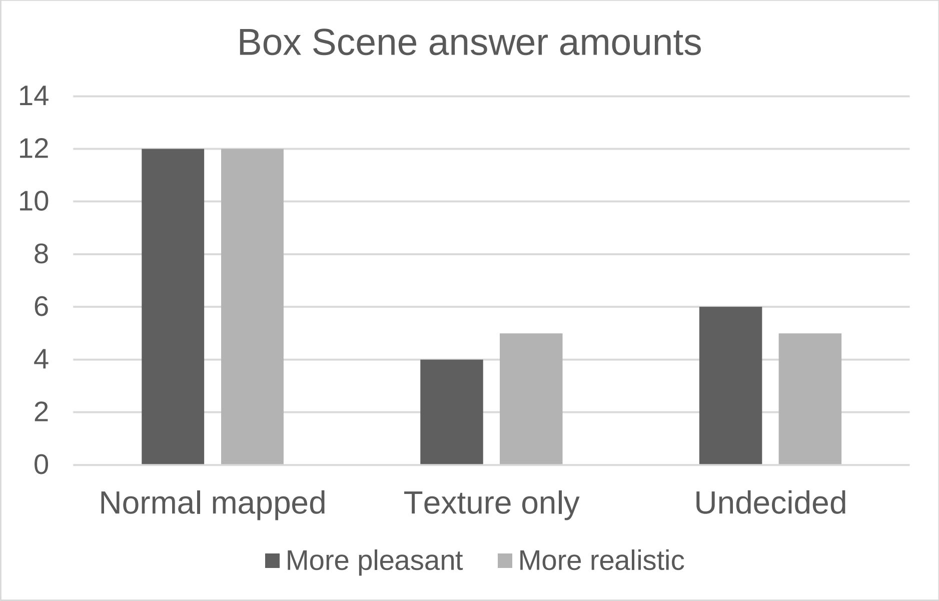
The total number of participants was 22, consisting of male and female students of Turku University of Applied Sciences between the ages of 18 and 30 with some having previous VR experiences. Prior to testing, the participants were informed only that they would be placed into a handful of VR environments and that a few of questions would be asked.

Each participant took the test alone, and a few precautions were taken so that the answers given could not be seen or heard by other participants: The other participants either waited on the opposite side of the office the test was conducted in, or they waited outside. All the result documents were hidden from the participants' view, and they only contained markings that were customized for this exact experiment.



Graph 1. Wall Scene: The visual experience of the participants (Appendix 1).

As seen in **Graph 1** (above), the participants viewed the normal mapped Wall Scene visually less pleasant than the texture-only version. They experienced realism slightly differently, favoring the normal mapped variation slightly more. Approximately 23 percent of all the answers given were either undecided or viewed neither as more pleasant or realistic.



Graph 2. Box Scene: The visual experience of the participants (Appendix 2).

Unlike in the Wall Scene, the trends in the Box Scene are more defined (see **Graph 2**, above). The normal mapped variation was a fairly evident favorite environment, while some did still lean towards the texture-only version as the preferable one. The amount of undecided answers also increased very slightly, bringing the percentage up to 25.

4.4 Analysis and Discussion

After gathering and graphically analyzing the data, a question of statistical significance had to be answered: Did the results show an actual trend favoring normal mapping or the texture-only variations, or were the differences simply due to normal statistical irregularities?

To calculate this, both chi-squared test (see **Appendix 4**) and Fisher's exact test (**Appendix 5**) were utilized. Knowing the observed frequency of answers for both pleasantness and realism in both main environments, we were able to compute the chi-squared value for both answer options in each scene. Undecided answers were ignored in both instances to simplify the calculations. The received values were following:

Environment / focus	Wall Scene Pleasantness	Wall Scene Realism	Box Scene Pleasantness	Box Scene Realism
x^2	2	0,25	4	2,88

Table 1. The chi-squared values based on the environment and area of visual focus.

Comparing these values to the ones found in Critical Values of the Chi-Square Distribution (Engineering Statistics Handbook 2017), probability of the significance can be estimated. Since there were two distinct options: preferring normal mapping or preferring texturing, the amount of degrees of freedom is one. Using a fairly conservative significance estimate of 0.95 – meaning that the likelihood of actual statistical importance is 95 percent when the relevant value limit is exceeded – we notice that only the chi-squared value for pleasantness in Box Scene surpasses the critical value limit of 3.841. Therefore, based on the chi-squared tests, only Box Scene's pleasantness seemed to have probable statistical significance when using normal mapping.

Due to the small sample size, Fisher's exact test was also recommended. This test required a slightly different table structure. The complete results (ignoring the undecided answers) were divided into two groups: one for Box Scene, the other for Wall Scene. Additionally, the answers were set into two distinct rows, one representing the ones preferring normal mapping, while the other showed the amount for the texture-only variations. First, visual pleasantness was investigated. Knowing the total sample size, sample size of the first group, the total sum of values in the first group and the value in the first row's first group, the Fisher's exact test could be used. (Lane 2017). The same method was then repeated for the results of visual realism.

According to these calculated results, the probability of getting the pleasantness answer distribution by chance was approximately 1,5 percent. However, the likelihood of the distribution in visual realism was almost 20 percent. Based on both the chi-squared tests and Fisher's exact tests, there was no statistical dependence in the perceived realism and the use of normal mapping when both scenes (and thus object distances) were considered. However, there was a slight significance between the distance of the object and the way its visual pleasantness is experienced when normal mapping is applied. These analyses indicate that while the use of normal mapping in VR does not significantly affect the perceived realism of objects – whether they are close or further away – it can affect their pleasantness: Players find normal mapped objects more visually pleasing when they are inspected from a smaller distance.

5 IN CONCLUSION

Regarding the ICT Showroom demo, with the limitation of the playable area to only two rooms, we were able to create an atmospheric environment with a few puzzle elements that served as a decent demonstration of the ideas and skills that students working in the FIRMA have. Out of a few VR projects presented at the event, our project was selected as the VR category winner. Additionally, the project taught all the participating students many lessons and was therefore a success.

5.1 Study limitations

While I attempted to make the user test into a more empirical and objective one by randomizing the order of the environments, there still were plenty of things that could be improved for further research sessions: The small number of participants is quite likely to skew some of the aforementioned differences and trends. It sparks certain uncertainty especially towards the less significant value contrasts such as the visual user experience of realism in Wall Scene's variations. Thus, I would view the larger differences as more reliable sources of accurate data.

The limitation to only having two distinct main environments, Wall Scene and Box Scene, might also have an effect on the results of the experiment. Roughly every fifth participant claimed that Wall Scene's lighting was too intense, making some of them slightly uncomfortable. Another main environment or even a variation with less intense illumination conditions could have been a better setting to evaluate the visual effects of normal mapped objects that are slightly further away from the VR user. I find it entirely possible that the normal mapped Wall Scene was seen as the less pleasant one because of the natural refractiveness that (Unity's) normal maps present: This could have intensified the feeling of excessive amounts of light.

The effect of adding a height map (Unity Manual 2017b) to the environments should most likely be investigated as well. Furthermore, objects with true detail geometry in the mesh might serve as a new comparison baseline for the research. An additional control test with completely identical environments should also increase the scientific merits of such a study, since it would take the placebo effect into account in a much better way.

5.2 Afterword

In the end, despite its shortcomings, I feel like my research serves as a contribution of value to the research in virtual reality graphics. While it does not show a link between the perceived realism and normal mapping in VR, the analyses exhibit a slight positive difference in visual pleasantness when normal mapping is applied to objects that are inspected from a short distance. Players prefer such objects to their texture-only counterparts. Therefore, when developing 3D objects and environments for VR purposes, the total work effort required by normal mapping could perhaps be primarily focused into the objects in the user’s vicinity.

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Appendices

Appendix 1. The results for Wall Scene testing

	Wall Scene
	P = More Pleasant
	R = More Realistic		

Participant number	**Normal mapped**	**Only textured**	**Undecided**
1	P		R
2		P + R	
3	P + R		
4		P + R	
5	R		P
6	R		P
7		P + R	
8		P	R
9	P + R		
10		P	R
11		P + R	
12		R	P
13		P + R	
14	P + R		
15		P	R
16		P	R
17		P	R
18	P + R		
19		P + R	
20	R		P
21	R	P	
22	P + R		
Total amounts	6P + 9R	12P + 7R	4P + 6R

Appendix 2. The results for Box Scene testing

	Box Scene
	P = More Pleasant
	R = More Realistic		

Participant number	**Normal mapped**	**Only textured**	**Undecided**
1	P + R		
2		R	P
3	P		R
4	P + R		
5	P + R		
6		R	P
7	P + R		
8			P + R
9	P + R		
10	P + R		
11			P + R
12			P + R
13	P + R		
14			P + R
15		P + R	
16	P + R		
17		P + R	
18	R	P	
19	P + R		
20		P + R	
21	P + R		
22	P + R		
Total amount	12P + 12R	4P + 5R	6P + 5R

Appendix 3. The randomized test orders

Participant number	1st environment: 1st variation	1st environment: 2nd variation	2nd environment: 1st variation	2nd environment: 2nd variation
1	W(n)	W(t)	B(t)	B(n)
2	B(n)	B(t)	W(t)	W(n)
3	B(t)	B(n)	W(n)	W(t)
4	B(n)	B(t)	W(n)	W(t)
5	W(t)	W(n)	B(n)	B(t)
6	W(n)	W(t)	B(n)	B(t)
7	B(t)	B(n)	W(n)	W(t)
8	W(n)	W(t)	B(n)	B(t)
9	B(t)	B(n)	W(t)	W(n)
10	W(t)	W(n)	B(t)	B(n)
11	W(n)	W(t)	B(t)	B(n)
12	B(t)	B(n)	W(t)	W(n)
13	W(t)	W(n)	B(t)	B(n)
14	W(t)	W(n)	B(n)	B(t)
15	W(t)	W(n)	B(t)	B(n)
16	W(t)	W(n)	B(n)	B(t)
17	W(n)	W(t)	B(n)	B(t)
18	W(t)	W(n)	B(t)	B(n)
19	W(t)	W(n)	B(n)	B(t)
20	W(n)	W(t)	B(t)	B(n)
21	W(t)	W(n)	B(t)	B(n)
22	W(n)	W(t)	B(n)	B(t)

W(n) = Wall Scene, normal mapped

W(t) = Wall Scene, texture-only

B(n) = Box Scene, normal mapped

B(t) = Box Scene, texture-only

Appendix 4. Chi-squared test

According to Penn State Science's online materials (Penn State Science 2017), the equation for calculating the chi-squared value is:

$$x^2 = \sum \frac{(O - E)^2}{E}$$

O = Observed frequency
E = Expected frequency

While the expected frequency, E, can be calculated by utilizing the row total, column total and the sample size in a following equation:

$$E = \frac{\text{row total} \times \text{column total}}{\text{sample size}}$$

Therefore, based on the results in **Appendix 1** while ignoring the undecided answers, the equation for Wall Scene's visual pleasantness is:

$$x^2 = \frac{(6 - 9)^2}{9} + \frac{(12 - 9)^2}{9}$$

$$x^2 = 2$$

On the other hand, the equation for Wall Scene's visual realism is:

$$x^2 = \frac{(9 - 8)^2}{8} + \frac{(7 - 8)^2}{8}$$

$$x^2 = 0{,}25$$

Regarding Box Scene's visual pleasantness according **Appendix 2**, the equation is following:

$$x^2 = \frac{(12-8)^2}{8} + \frac{(4-8)^2}{8}$$

$$x^2 = 4$$

And finally, Box Scene's visual realism is calculated in the following way:

$$x^2 = \frac{(9-8{,}5)^2}{8{,}5} + \frac{(7-8{,}5)^2}{8{,}5}$$

$$x^2 = 2{,}88...$$

Appendix 5. Fisher's Exact test

Based on the Online Statistics Education website (Lane 2017), the probability factor in Fisher's exact test can be calculated using the formula below:

$$\frac{n!(N-n)!R!(N-R)!}{r!(n-r)!(R-r)!(N-n-R+r)!N!}$$

N = total sample size

n = sample size of the first group

R = total sum of values in the first row

r = value in the first row's first group

Thus, based on both **Appendix 1** and **Appendix 2**, we get another table for the *visual pleasantness*:

	Box Scene (1st group)	Wall Scene (2nd group)	Total
Normal mapping (1st row)	12	6	18
Texture only (2nd row)	4	12	16
Total	16	18	34

Based on this table, the values of the formula's variables can be assigned:

N = 34

n = 16

R = 18

r = 12

These values are then utilized in order to receive the probability of such results (P):

$$P = \frac{16!(34-16)!18!(34\text{-}18)!}{12!(16-12)!(18-12)!(34-16-18+12)!34!}$$

$$P = 0{,}0153...$$

In order to calculate the probability (P) of the results in *visual realism*, the following table is constructed:

	Box Scene (1st group)	Wall Scene (2nd group)	Total
Normal mapping (1st row)	12	9	21
Texture only (2nd row)	5	7	12
Total	17	16	33

The table gives us the variable values:

N = 33

n = 17

R = 21

r = 12

Calculating the probability (P):

$$P = \frac{17!(33-17)!21!(33\text{-}21)!}{12!(17-12)!(21-12)!(33-17-21+12)!33!}$$

$$P = 0{,}1995\ldots$$