The Illusion of Infinite Space Inside a Positional Tracked Virtual Environment

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1 author:

Dennis Reimer
Hochschule Ravensburg-Weingarten

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The Illusion of Infinite Space

Inside a Positional Tracked Virtual Environment

Dennis Reimer
Leutkircher Straße 32
88239 Wangen

Adviser:
Prof. Dr. Daniel Scherzer - Hochschule Ravensburg-Weingarten
Prof. Markus Lauterbach - Hochschule Ravensburg-Weingarten

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Abstract

Virtual reality devices, which are distributed for private use, are limited in their possible area of tracking. The HTC Vive can perform this task within an area of approximately 16m^2. Inside this space, free movement is limited.
This thesis focuses on possibilities how to use this available space to create an infinitely big virtual environment, in which the user can move freely by real walking. To achieve this, two approaches are implemented: first separately and after that in combination. One approach uses the technique of Redirected Walking and the other one uses dynamic spaces. Both aim to create worlds, which are bigger than the available tracking space. To find out, how applicable these methods are with the HTC Vive, a small group of testers had to fulfill different motion tasks.

Foreword

The present master thesis was created in the period from March 2017 to August 2017. It is part of the Master of Science studies in the field of computer science at the University of Applied Sciences Ravensburg-Weingarten.

Acknowledgment

I would like to express my gratitude to some people, who supported me during the creation of this work. I like to thank my supervisors Prof. Dr. Daniel Scherzer and Prof. Markus Lauterbach for making it possible to carry out this thesis and helping me with all questions and problems I had.
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Lastly, I want to thank my parents Peter and Renate Reimer, with whose help it was possible for me to study and to create this work.

Contents

1 Introduction

The following sections shall give an overview on the subject and goal of the thesis. Firstly, a short overview of the problem on movement inside virtual reality is introduced. This is to show the two possible approaches and on which one this thesis will focus. After that, the motivation why this approach is selected is explained in more detail. Lastly, the exact objective and its limitation is presented.

1.1 Precondition - Movement Evaluation

Virtual reality (VR) is a technology, which has been worked on for many years. Since 2012 its popularity has increased and it is now a large field to research and develop on. Although it often is connected to video games, some techniques which were used in classic game development have been adapted to the new systems.
One of these is the possibility to move around in the virtual environment (VE). Because some of the virtual reality systems are able to track the position and the rotation of the user, movement inside VR can be divided into two areas:

- **Natural Movement inside the trackable space**
- **Movement with the help of metaphors**

The latter describes a movement, which either uses controller inputs to move around in the VE, or uses additional hardware to simulate walking. One example for this is Hilsendegers approach, where he maps the input from the Wii balance board into virtual reality[8]. But because these do not provide actual walking, they can be categorized as movements with the help of metaphors.
This thesis will focus on the movement without the need of metaphors. The user should move freely inside the trackable space and can use the controller for other tasks than movement. Like with metaphors, this movement has to be examined for applicability as well as the effect on the user.

1.2 Motivation

Current Virtual Reality systems come with its own room tracking devices. One of these is the *Lighthouse Tracking-System*[1] by *Valve* used from the *HTC Vive*[2]. This VR-Setup comes with two base stations for the tracking, one head mounted display (HMD) and two game controllers. These are tracked by the base stations and can be used to operate inside the virtual reality application. With this system, a maximum play area of 16 m^2 can be created. When experiencing a VR application, the user is restricted to physically stay in this area.

[1]https://vrjump.de/lighthouse-erklaert
[2]https://www.vive.com

Since many VR experiences offer a larger virtual environment, the developer has to find ways to let the user move around in this setting. A natural way to achieve this, would be to allow actual walking in the trackable area[19]. Because the walkable area is limited, the user has to be tricked into thinking he does not have to stop walking and therefore creating the illusion of infinite space. Two methods, which cover different aspects to create this illusion, will therefore be developed and compared.

1.3 Objective and Limitation

The goal is to create the illusion of infinite walking space. The user should not have the fear of leaving the tracking area. Therefore, a high level of immersion has to be created. For this, two methods are presented which follow different projections by using the available tracking space for moving around in a virtually bigger area. After implementation, both methods will be compared in terms of immersion, applicability and possible improvements. Furthermore, they will be analyzed on the aspect of success and failure. The reason why a method works or not and on how to possibly improve them will be presented. A subsequent experiment which combines both presented methods will give insight into similarities and disadvantages of these methods.
The applications do neither aim to create a fully immersive illusion of infinite space inside VR, nor does this thesis cover all possible approaches in realizing free walking inside virtual environments. Furthermore, two possibilities of achieving this goal are presented. They will be analyzed and compared and deliver insight on how to approach them and on what to avoid when facing this problem. Also these methods are carried out with only the HTC Vive and its capabilities. No additional hardware is used to enlarge the tracking space.

2 Basis and Requirements

In the following chapter, some basics are shown to understand the surrounding conditions for the experiment. First, an overview over VR systems along with the requirement of positional tracking is given. This leads to the choice of the final used hardware and its unique tracking system. The general conditions for the use of this hardware is shown after that. This includes the usage of the development software, language and the general setup of the tracking space. Lastly, this chapter gives a preview of the used techniques in the experiments for real walking.

2.1 Virtual Reality Systems

Virtual reality with head mounted displays is something which has existed for many years. One of the first systems with a head mounted display was created by Sutherland in 1968[21]. The idea is to give the user the illusion of being physically present in a virtual world. He has to wear a HMD, which shows him the virtual environment while masking the real world around them. With head tracking and good applications, these systems aim to create great immersive experiences.

Figure 1: Virtual Boy from Nintendo [4]

First commercial attempts were made in the 1990's with the *Virtual Boy* from Nintendo (see figure 1). Because the device was not strapped to the head and displayed only a monochrome image which caused headaches, the Virtual Boy was not very successful. The commercial virtual reality production has therefore decreased until the middle of 2012.

Thats when the Oculus Rift[3] received a lot of attention and VR systems became attractive to the public. With the success in its Kickstarter campaign and its popularity, other VR systems have emerged. There are currently four main systems with different functions and capability of tracking positions and display resolutions (see figure 2). Because of the requirement of positional tracking for physical movement in virtual reality, not all systems are suitable for the experiment. The HTC Vive with its own *Lighthouse* tracking system currently has the most accurate position tracking on the market[10].

Figure 2: VR Comparison 2016 [6]

2.1.1 Tracking in VR

One big difference between virtual reality systems and conventional media, which is usually presented on a single screen, is the possibility to transfer real body movement into the virtual world. This means that the systems are able to reflect the positional data of trackable objects as well as motions like leaning with the help of sensors. Different systems handle these movements diversely. The *GearVR*[4] for instance does not have the capability to track the position of the HMD and only the head rotation can be transferred into the application. Other big systems come with their own camera systems and are therefore able to deliver the following information about the HMD and the trackable hardware:

[3]https://www.oculus.com/rift
[4]http://www.samsung.com/global/galaxy/gear-vr

- **Position** - The position of the hardware inside the trackable field visible to the cameras as a 3-dimensional vector
- **Rotation** - The rotation of the hardware around the x-axis (pitch), the y-axis (yaw) and the z-axis (roll)
- **Velocity** - The velocity with which the hardware is moving inside the 3-dimensional room
- **Acceleration** - The acceleration of the hardware, either measured by the hardware or calculated in the software

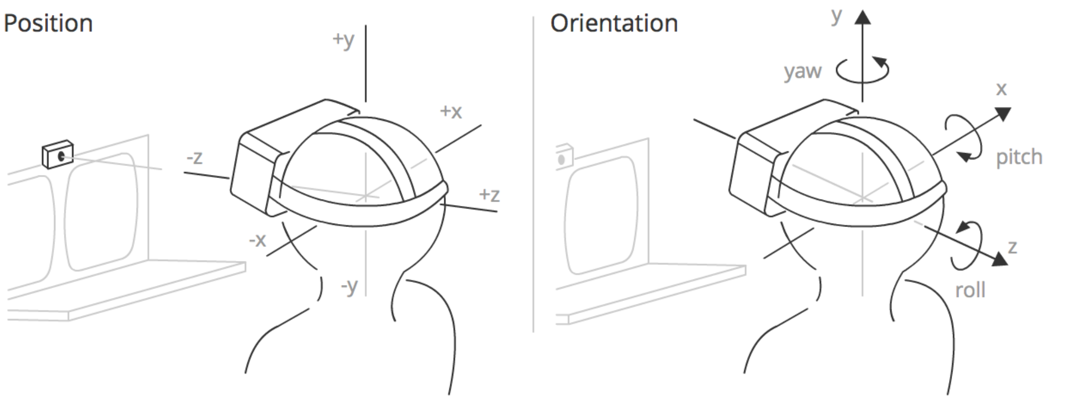


Figure 3: Position and Orientation of VR [7]

The technology with which these values are tracked are different in each system. The Playstation VR works with the same technique as Playstation Move: it uses a single camera on the front. This camera tracks the movement of the HMD and the controllers with visible light. The Oculus Rift is working with two infrared cameras which are placed on both sides of the PC monitor. This system is called the *Constellation Tracking System*, where the two cameras register several infrared LEDs embedded in the headset[17]. Both systems do have the problem that they lose the tracking of the controller when they are not in the view area of the cameras (e.g. when holding them behind the back). The HTC Vive with its Lighthouse system avoids this problem. Two cameras are placed diagonally opposite from each other. Thanks to infrared lasers and photo-sensors, it has the most accurate tracking inside a defined play area[10]. Because of the precise tracking of the HTC Vive and the indispensable need of an area, in which the user can navigate, this system is chosen for the following experiments.

2.1.2 HTC Vive Virtual Reality System

With its development since 2012 and its announcement in 2014 the HTC Vive quickly became a competitor to the Oculus Rift. In contrast to the Oculus Rift, which was only available with the HMD when released, the HTC Vive came with trackable controllers with included gyro-meters and acceleration sensors. One of the unique features of this system is its distinct tracking technology, the *Lighthouse* system, that is able to track photo-sensors with its infrared lasers within an area of 4m x 4m. Trackable objects inside this area are, in contrast to the Oculus Rift or the PlaystationVR, always tracked as long as they are visible to the base stations[3].

Figure 4: The whole HTC Vive set[1]

At this juncture the Lighthouse system is working with two base stations with a field of view (FOV) of 120 degrees. They are placed diagonally from each other and are therefore able to see the square area in between them. The base stations scan the area 60 times per second with vertical and horizontal lasers. For position tracking the vive uses IMUs which are scanned by the lasers and update at several hundred Hz[2]. With this system, the HTC Vive delivers one of the most precise positional tracking, and as long as the photo-sensors are visible, the user can move freely inside the play area.
The HMD of the HTC Vive has a refresh rate of 90 Hz. Applications (which are programmed for this) should aim for a framerate of 90 fps to reduce motion sickness and visual disturbances like tearing.

2.2 Surrounding Conditions

Unity3D as Development Environment

Unity3D is a game engine, which was first released in 2005. It has further developed and improved its functionalities of scripting, animation, UI and more since then. It is one of the most used engines for 3D and 2D game and mobile development. Over one third of 1000 most popular free mobile games on the market are made with Unity3D[5]. This shows how popular this engine is amongst developers.
With the first releases of the Oculus Rift and the HTC Vive, Unity3D quickly added the possibility to develop VR applications. Together with its good accessibility, it now is a very popular game engine to make games and other software as well as 360° movies for the virtual reality devices. Because of the engine's included physics system and its accessible virtual reality integration, a quick implementation of the wanted functionalities for the conducted experiments is easy, thus resulting in the usage of the engine.

C# and .NET as Programming Language

When working with Unity3D, the choice of which scripting language to use is essential. Unity versions after 5.0 offer the possibility to program with *C#* or *UnityScript*. Which language to use differs from user to user. For most developer *UnityScript* is easier to learn because of the strong similarity to *JavaScript*, but most users prefer *C#* due to the known *C* conventions and better documentation. For this project, *C#* is used. It has the possibility to import the *.NET* class library which delivers many useful functionalities. For the needed platform, which is the Windows operating system, it runs with the scripting backend *Mono2x* and has the api compatibility level of *.NET 2.0 Subset*. For development in Unity, the most personal experience with this framework is given.

Available Space - Room setup / Space requirements

Both experiments have the same requirements in the physical room setup. The base stations of the HTC Vive are placed in opposite corners of the room. The distance between the base stations is about 5.5m, which gives us a square play area with an approximate space of 30m^2. The setup can be seen in figure 5. These values are used by the Redirected Walking experiment (explained in section 3) to determine its needed walking values. For the dynamic space experiment (carried out in section 4), this space also represents the outer border of the accessible space inside the virtual environment. Both experiences require that there is no other object inside the measured play area.

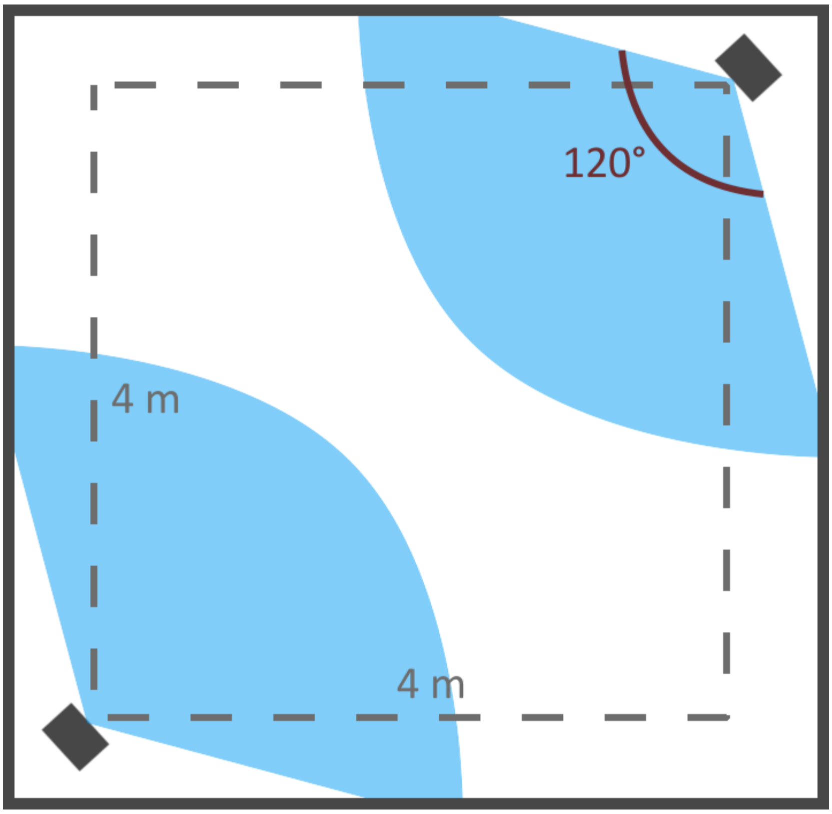


Figure 5: Room Setup

2.3 Movement in VR

The demand for great immersion for virtual reality applications is high. One big step to achieve this is the implementation of movement inside the virtual environment. Two possible ways to accomplish that is either the use of **movement metaphors** or the implementation of **real walking**.

Movement Metaphors

Movement metaphors are used when real walking is not possible. For instance, many conventional videogames use the input from the keyboard or a controller to move the player inside the game. For virtual reality this input method can lead to motion sickness. I researched four different metaphors, which can be used to move inside a virtual environment[18]. The result indicates that teleportation is the most comfortable way to move around. This could be a reason why other games and experiences in VR use this metaphor, like "The Lab"[5] from Valve or the upcoming "Doom VR"[6] from Bethesda. Movement metaphors are especially needed in commercial applications where large tracking spaces or expensive additional hardware is not coercively available.

[5] http://store.steampowered.com/app/450390/The_Lab
[6] http://store.steampowered.com/app/650000/DOOM_VFR

Real Walking

A more natural way to move around is real walking, which is limited by the trackable play area. To raise the immersion, the illusion of infinite space has to be generated. The user should have the possibility to endlessly move inside the virtual environment while doing the same in the real world.
One idea is to adapt the real movement of the user inside the VE while remaining in the same location. The *cyberith virtualizer* for example is a mechanical device in which the user is fixed and can walk on the spot[22]. This simulated movement is transferred into the VR application. For real walking inside the room, two approaches are chosen exemplary and serve as a base for the distinct experiments and will be explained in detail in the following sections. One is called *Redirected Walking* which was first introduced in 2001 by Razzaque[20]. The other one was an approach by Hannes Kaufmann from the Vienna University of Technology who examined flexible spaces for real walking inside virtual reality[14]. These methods are examined and own approaches are deduced from them.

3 Redirected Walking

The following section examines the experiment regarding Redirected Walking. The first section gives a definition for Redirected Walking and introduces some existing implementations of this system. The following part presents the own approach, implementation and setup. Lastly, this chapters shows the results as well as possible improvements of the conducted experiments.

3.1 The Technique

With Redirected Walking it is possible to move through a virtual environment, which is significantly larger than the real world walking space. It allows the user to move endlessly straight forward inside the VE without surpassing the borders of the trackable space or running into walls. It was firstly introduced in 2001 by Razzaque[20].
The idea is to steer the user on a straight line inside the Virtual Environment for a distance bigger than the actual real world space. While moving, an algorithm continually rotates the scene around the user. If the rotation is not too strong this can exploit the human perceptual system. And the user is therefore walking in circles in real life without noticing it. It has to be found out, how strong this rotation can be for a pleasant experience. This remapping of the user movement away from the physical borders is called Redirected Walking.

Different approaches and improvements were made in the past. For instance an enhanced steering algorithm for Redirected Walking was presented in 2014[16], which was a theoretical approach on how to calculate the parameters for Redirected Walking to minimize breaks from reorientation. In 2016 a team published the unlimited corridor[13], where the Redirected Walking was extended with visuo haptic interaction. Figure 6 shows this concept. A wall was built on the circumference of the walking path. This represented a virtual wall inside the VE and improved the immersion and the exploit of the human perceptual mechanism.

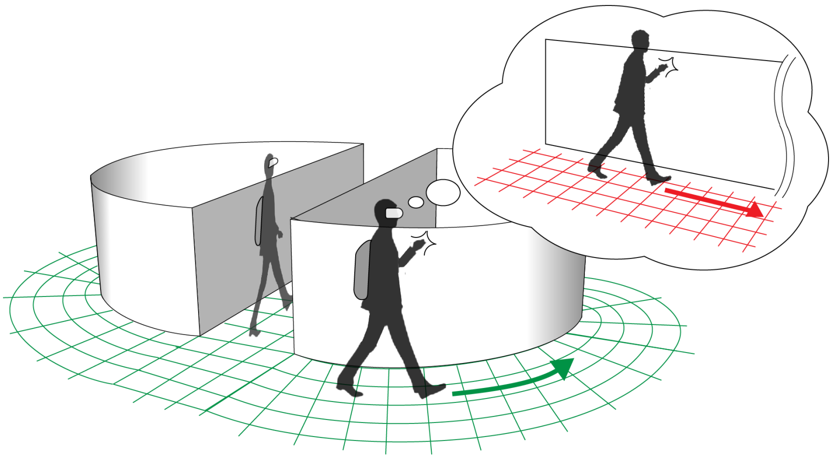


Figure 6: Concept of the unlimited corridor[13]

But not only in movement manipulation is such remapping possible. Azmandian presented a haptic re-targeting[15] in virtual reality which uses similar techniques as the ones in Redirected Walking. The virtual environment presents the user three cubes. His task is to grab every cube one after the other. In reality there is only one cube on the table. By remapping the orientation of the world without the user noticing it, he grabs differently located cubes inside the VE while always taking the same cube in real life. This approach shows that remapping the environment can be used in many ways to trick the human body to improve the immersion of the virtual environment.

3.2 Own Approach

For the experiment, the given tracking system of the HTC Vive is used. It can track a space with the possible area of 4m x 4m. The Redirected Walking uses the area of 3.5m x 3.5m. This provides a walking radius of 1.75m with a circumference of approximately 11m and gives the user some space on the edges so he doesn't accidentally runs into the wall. In this field, the base stations of the Vive can be used for room tracking and the HMD to calculate the user's movement inside the trackable space. Based on the original Redirected Walking experiment by Razzaque[20], the user is walking in a circle in real life while believing he is walking a straight line in the virtual environment. The circular path the user takes in reality can be seen in figure 8, while figure 7 represents the remapped path the user takes inside the virtual environment. There is no need for the trackable controllers since the user only performs walking. For the implementation, a virtual environment, visually represented as a dungeon, is developed in Unity3D. This dungeon consists of three large corridors and short connections between them. This setup is loosely based on the unlimited corridor experiment[13]. The physical wall is left out and the radius is smaller, but the circular motion is the same.

3.2.1 Objective

The goal of the experiment is to determine the general usability of Redirected Walking without the use of enlarging the maximum trackable space of the Vive. Because this technique requires reorientation of the environment and the aim is to trick the human perception system, the influence on the user's behavior is observed.
Five testers with diverse ranges of experience in VR have to perform the walking task. The influence of different environmental changes are taken into account which include:

- Change of real walking direction
- Change of virtual walking direction
- Switch between direct movement mapping and redirected movement

The transition between these changes are made on specific spots inside the environment and are therefore predetermined. The goal of the user is to reach the end of the environment, which demands a walking route of approximately 60 meters.

3.2.2 Setup

As against conventional software, which is only dependent on the specifications of the running hardware and used on a definite position, for example a desk, virtual reality applications can additionally require a certain real world environment. These conditions are met for the Redirected Walking experiment. A specific room setup is required as well as a software implementation tailored to the hardware and environment. The user has to navigate through the tracking area on the path shown in figure 7. This path guarantees all environmental changes stated in section 3.2.1. These can be seen on the changes of the dotted lines in figure 7.

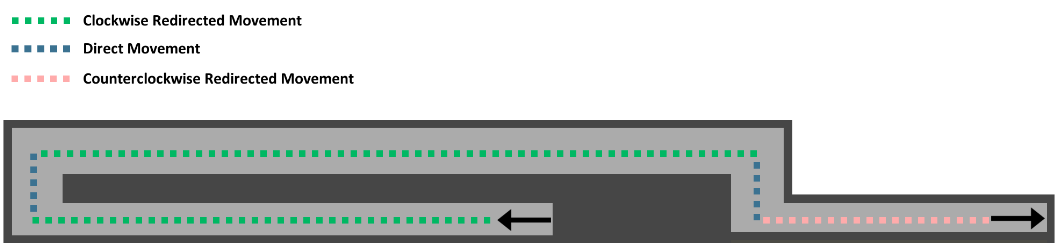


Figure 7: Redirected Walking Path

To ensure the best possible walking experience and avoid stumbling, no other objects are put inside the trackable area. Because the HTC Vive requires a permanent connection to a computer and to electricity, it is inevitable to have these cables inside the tracking space. By walking carefully, stumbling can be avoided.

Installation and Environment

As stated earlier, the wanted walking radius of 1.75m is achieved by a trackable room with an area of 4m x 4m. These dimensions are chosen for the experiment, because thats the highest possible measurements the HTC Vive delivers with its Lighthouse system. Theoretically, this area can be enlarged at will, dependent on the available space, the possible tracking space and the length of the cables connected to the HMD. A sketch of the setup from above can be seen in figure 8.

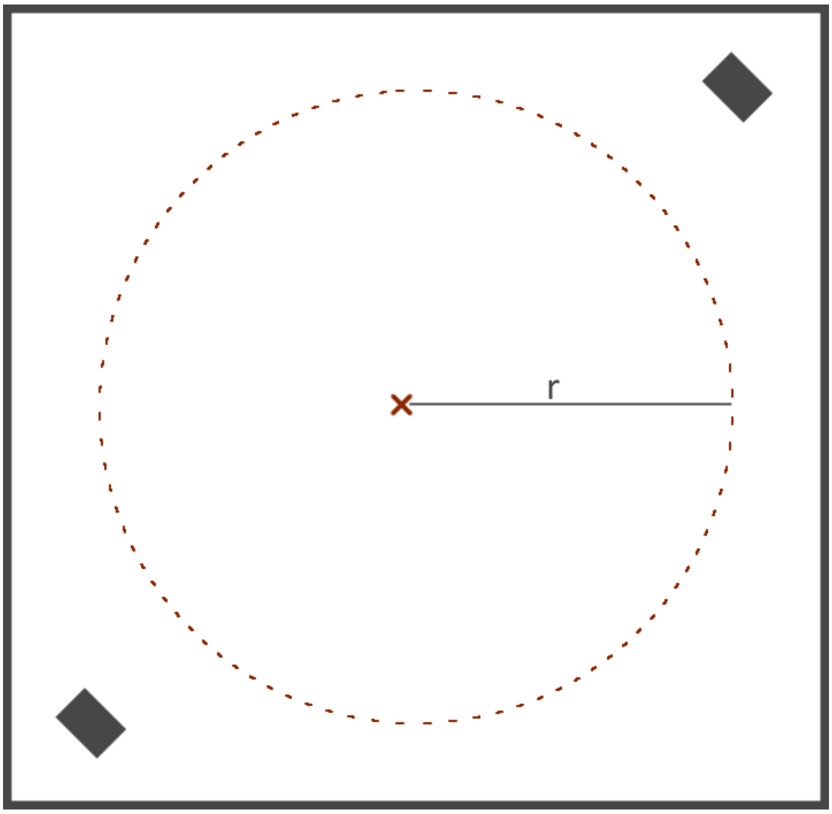


Figure 8: Redirected Walking Setup

The base stations are positioned diagonally at an approximate distance of 5.5m. The dotted line indicates the Redirected Walking path of the user with the radius **r**. As against the unlimited corridor[13], no physical obstacles are positioned inside the tracking area. To avoid possible fall hazards, the whole area is left empty. Only the connection cable between the computer and the HMD are present. These are enlarged to prevent possible tugs and provide free movement inside the tracking area.

The top view of the scenery can be seen in figure 7. The dotted lines show the path the user takes during the whole experiment. The different colors of the line state how the user has to walk in reality to maintain a straight line. The green and light red lines on the long straight paths imply a real movement in a clockwise and respectively a counterclockwise direction. In contrast, the blue lines are a link between the long routes. On these the Redirected Walking algorithm is deactivated and the user has to traverse the play area until the Redirected Walking algorithm is activated again. The connection points, where the dotted lines intersect, function as a transition between the different movements. The dark areas in figure 7 are spaces where the user is signaled, that this area is unaccessible, either by a wall or an abyss and therefore keeping him on the designated walking path.

Implementation

Redirected Walking requires reorientation by rotating either the player or the whole environment, depending on the users movement. Because the position and rotation of the HMD is tracked and set by the Lighthouse system every frame, it is not possible to programatically change its position or orientation. This affects only its local and not its world position in Unity3D. Therefore, to avoid this effect, the externally tracked player is parented to an empty game object which can be turned and therefore rotates the player. As for this, the players position is also set respectively to the play area. To move its position inside the world space, the play area is moved forward and backward, depending on the players movement.
To determine the amount of the reorientation, one has to calculate the movement changes of the player to adjust him accordingly to these changes. Based on the size of the play area, the circumference of the walk circle is calculated, which is used to determine the needed adjustments. These calculations can be found in the equations 1 and 2. Not the whole body of the user is tracked, but only the head. That is the reason why the forward and backward movement of the HMD is used to calculate the changes.

$$c = d \times \pi \tag{1}$$

$$\Delta a = (\Delta m \div c) \times 360 \tag{2}$$

Where:

c: is the circumference

d: is the diameter

Δa: is the adjustment of the rotation

Δm: is the last walked distance

To optimize a fluent experience, these calculations are made to adjust the orientation and position based on the user movement every visible frame of the desired rate of 90 frames per second. The reorientation is also dependent on whether the user is moving forward or backward. If the user is moving forward, the algorithm rotates in the opposite direction as when the user is moving backward.

With the Lighthouse system providing the position of the HMD, one has to determine whether the user is walking forward or backward. Listing 1 shows some code on how to determine in which direction the user is moving and how to adjust the orientation based on this.

```
/// Adjust the orientation of the user depending on his movement
void AdjustOrientation(float deltaAngle, float deltaMovement)
{
    Vector3 moveDir = (HMD.position - lastHMDPosition);
    float dot = Vector3.Dot(moveDir.normalized, Head.forward);
    int dir = (dot > 0) ? -1 : 1;

    User.Rotate(Vector3.up, deltaAngle * dir);

    PlayArea.position += PlayArea.forward * deltaMovement * dir;

    lastHMDPosition = HMD.position;
}
```

Listing 1: Determine adjustment for forward and backward movement

To determine the direction the user is walking, a normalized Vector is spanned between the current HMD position and the position in the last frame. The dot product between this Vector and the current look direction is calculated. Assumed that the look direction states the forward direction, the dot product depicts a forward movement if it is positive and a backward movement otherwise. Together with the calculations from equation 2, the user can be rotated and moved correctly. The last HMD position is cached after these adjustments so it can be used in the next calculation. To include every change respective to the orientation of the HMD, this remapping is made every possible frame.

3.3 Conclusion

The experiment was carried out under circumstances, which every owner of the HTC Vive can reproduce at home. No additional hardware or tracking enhancements were used to improve the tracking and enlarge the play area. Under these conditions, the testers feedback and experience depict that the size of the trackable space and the changes listed in section 3.2.1 are influencing the immersion and experience.

It is possible to have an overall good working Redirected Walking with the chosen radius of 1.75m. The feedback shows that the user needs some time to accustom himself to the reorientation and that the circular movement is not sensed as strong as it really is. Nonetheless, the perceptual system is not fully tricked. Because of the narrow angle, the illusion of walking a straight line is not fully accomplished. Most testers state, that they don't fully notice a circular movement but feel very shaky while practicing it. Walking slower stabilizes the user, but also feels as a constraint in the movement. As Steinicke found out, the radius for Redirected Walking should be greater or equal to 22m for the user not noticing the reorientation[11]. This radius being more than 12 times greater than the tested one, the latter works comparatively well. The circular movement is noticed but works good enough to give a relatively stable and consistent movement with a little swaying, which could be infinitely long.
One big problem, which occurred during the experiment, is the cables of the setup. The HMD is permanently connected to a computer and a power supply. The user has to cross the cables lying on the floor, leading to a possible risk to stumble. A wireless setup would be preferred for safety and immersion.

The change of the direction of real and virtual walking does have some effect on the behavior of the user. While it seems that it has no impact on the user when the direction of the virtual walking is reversed, it does have a great influence on him, when the direction of the real walking is changed. It leads to dizziness and disorientation. One reason for this could be the inner ear, which can not respond fast enough to the new reorientation, while being accustomed to the previous redirected movement. It can be recommended to only have one walking direction during the experience.

Concluding, it can be said that the illusion of infinite space with great immersion is not easily achieved with Redirected Walking within a standard setup. An infinitely big environment with some restrictions is possible. Reorientation is mostly noticed during the experience and the freedom of movement is limited. But while this is perceived, an almost natural movement inside a virtual environment, which is much larger than the tracked space, is possible and applicable without strong cybersickness. A larger walking radius however is recommended.

4 Maze Walking with Dynamic Spaces

In the next section a different approach for infinite walking disparate from Redirected Walking for infinite motion is presented. It uses dynamic architecture for the virtual environment. The structure of this chapter is similarly to the one in section 3. First, the general idea and other approaches in dynamic architecture and flexible spaces inside a virtual environment are presented. The executed implementation and its peculiarity are shown after that. At the end of this chapter, the expected results are compared to the actual ones and analyzed afterwards.

4.1 Idea

Redirected Walking is a promising approach for infinite motion inside a virtual environment. But Razzaque already figured out in 2001[20], that this technique is limited to certain aspects. The first one is the human perception. The body is tricked to walk in circles while thinking it is moving straight ahead. Depending on the subject, this can lead to motion sickness or the awareness of the rotating room. Based on this, a bigger available space is necessary. The lower the available walking radius, the higher the possibility for the user to perceive the rotational movement. For that to be achieved, Steinicke concluded in an experiment, that a radius equal or bigger than 22m is necessary[12].

To countervail these effects, another approach can be executed. This one uses flexible spaces and by contrast remaps the environment by switching different settings and not by reorientating the user. The team around Khrystyna Vasylevska present a procedure where they relocate virtual rooms procedurally inside the virtual environment[14]. Figure 9 shows how their approach works. When the user leaves a room, a corridor to the next room is generated to reorient the user inside the trackable room. Thus the user can move more freely and the risk of motion sickness because of rotating rooms is not existent.

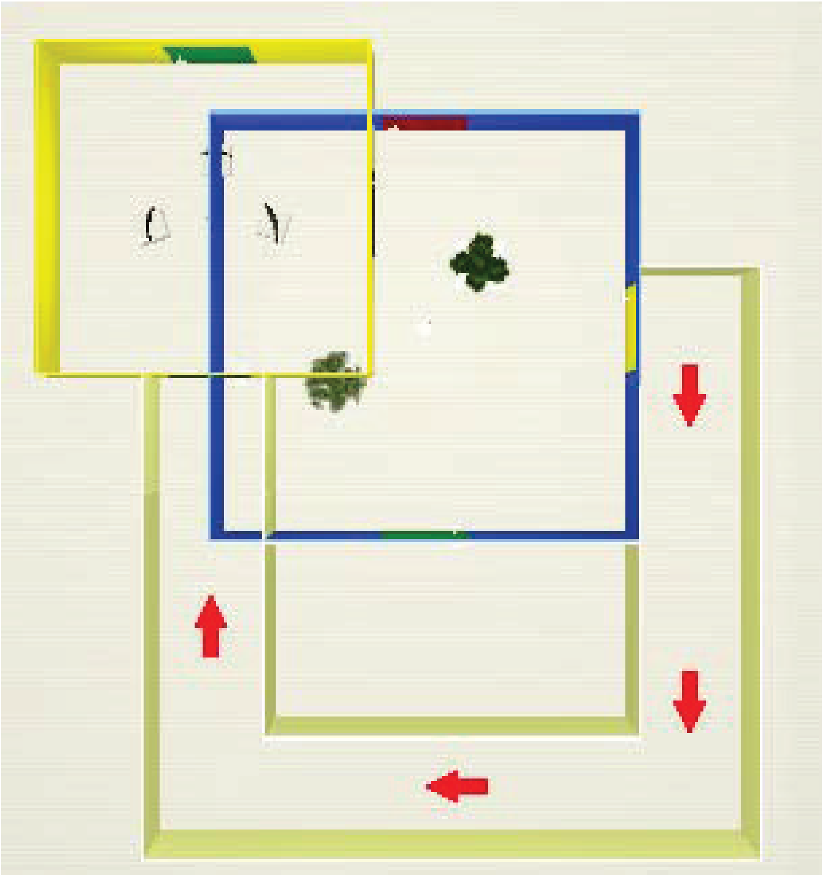


Figure 9: Connection of two rooms with flexible space from Vasylevska[14]

This approach requires a trackable area, which is at least as big as the available room inside the virtual environment. But it provides interesting projections for dynamic virtual worlds with the possibility of giving the user the deception of an infinitely big world.

4.2 The Experiments

As for the Redirected Walking experiment, the HTC Vive is used and the play area is calibrated to approximately 4m x 4m. This allows a walking area of roughly 16m^2 where a dynamic environment can be built. To avoid a possible collision with the walls, the VE is built within a little smaller area. In the previous experiment the movement of the user was remapped. With the used play area size this leads to a little swaying and did therefore not feel fully natural. The following experiment tries to countervail this effect by directly transfering the user's movement without redirecting it. It does not try to improve the previous experiment by eliminating its disadvantages. It is rather an independent approach to achieve a similar goal: to try to use real walking to simulate an infinite big virtual environment while remaining in the trackable space.

The idea is that certain parts of the environment are dynamically switched and thus creating consistently new environments in which the user can navigate. Because the accessible area for the user is limited to the maximum available trackable space of the virtual reality system, two experiments are conducted. While both share the same method of dynamically switching parts of the environment inside the movable area, they differ in the surrounding environment. The first one is an enclosed maze surrounded by high walls, while the other one shows an open world in which the surroundings appear to be accessible.
One trackable controller is needed for the inner maze experiment to serve as a virtual torch to light the environment. This is to prevent the user from noticing lighting artifacts and the changing environment. The different parts of the environment would otherwise be lighted separately, which would lead to changing of overall lighting and shadows when switched. The user could possibly notice that. This is why the torch, which also fits well in the maze setting, is used for this experiment. As for the experiment with a wide outer area, the torch is not needed. A general area light illuminates the world and shadows are turned off. In terms of illumination, dynamic exchange of the environment does not make a difference.
The positional record of the user is done by the tracking the HMD by the Lighthouse system. Like with the Redirected Walking, these experiments use only the hardware and capabilities the HTC Vive delivers. These approaches do not fully reimplement an existing method, but are made of own ideas combined with the ones of Vasylevskas experiment.

4.2.1 Goal

Like in the previous experiment, this idea tries to create a theoretically possible, infinitely large virtual environment. It is to be found out how the user responds to the change of the setting respective the dynamic exchange of parts of the environment. How the human mind can be tricked in terms of their orientation system and expectant attitude will also be determined. For this purpose, the same testers as in the last experiment go through the experience and give feedback on their walkthrough. It is also observed how they react to different environmental situations and if this is promotional for the immersion. The environment is used to demand specific movement tasks from the user, which will be explained in more detail in section 4.2.2. No endless experience is created, but a finite environment in which the users have to reach the end. With this method a possibility is shown, on how to create an arbitrary big world in which the user can navigate. To research the effect of different settings on the user, two experiments are conducted: one with enclosed walls and one with a wider setting around the user.

4.2.2 Implementation

The implementation is divided into two important aspects. One is the logic, that is working in the background and is responsible for displaying the right environment at the right moment. The other one is the design of the virtual environment. Both parts working together create the experiments to achieve the wanted immersion.

The experiments require changes of the environment depending on the position of the user. The idea is that certain parts of the area are made visible and other ones are made invisible when reaching specific points of the level. For this the Unity3D game engine provides a trigger system that prompts when two collideables hit each other. Thus one collider is set to to the position of the user (respectively the HMD) and other collider trigger to every position where environmental parts are switched. Listing 2 shows the class responsible for this functionality.

```
/// Class to handle De-/Activation of certain level parts
public class CaveTrigger : MonoBehaviour
{
    public GameObject[] ObjectsToActivate;
    public GameObject[] ObjectsToDeactivate;

    public void TriggerEnter()
    {
        foreach(var obj in this.ObjectsToActivate) obj.SetActive(
            true);
        foreach(var obj in this.ObjectsToDeactivate) obj.SetActive(
            false);
        this.gameObject.SetActive(false);
    }
}
```

Listing 2: Logic of the change of the environment

This class is assigned to every environment trigger and contains all objects, which should be activated and deactivated in a dynamic list. When the player hits such a trigger, this activation is called and a new environment is built. To avoid that the user walks again inside this trigger and the method is called again, the object is deactivated and no further collision detection can occur with it again.

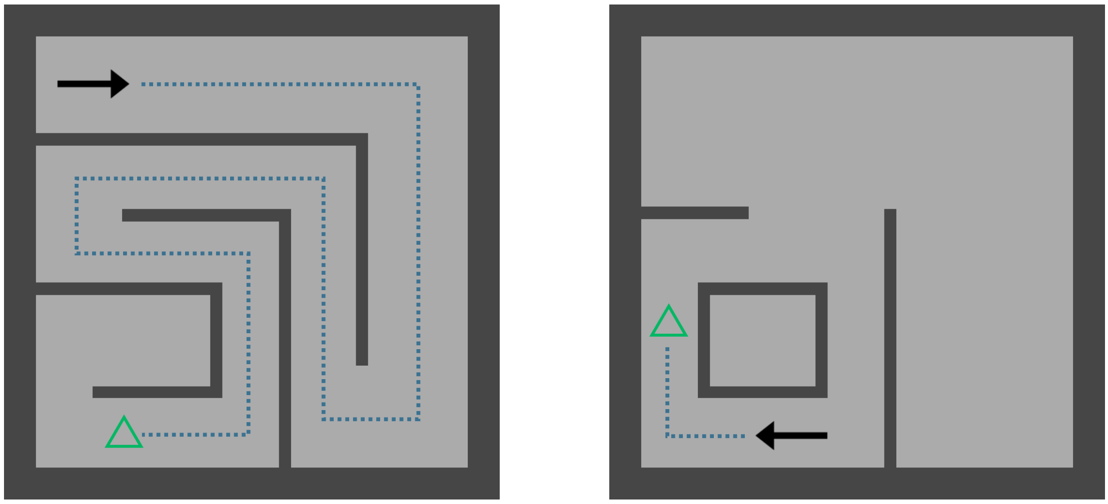
4.2.3 Environmental Design

A big part of this experiment is the design of the environment. To promote the immersion, the user should not notice the adjustment, that is done every time he reaches a trigger. One can work with the environment as well as the current orientation of the user. The following sections shows possibilities, which describe the used methods and environments, to achieve this. To research the effect of different settings, two environments are created: one inside an enclosed maze and one in an outside environment.

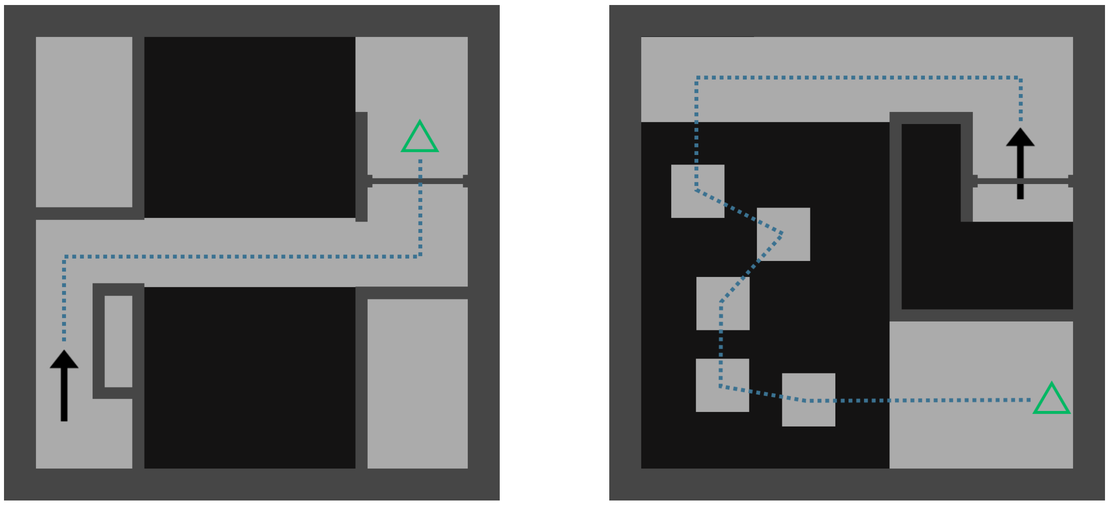
Maze System

The maze is an enclosed environment which is at most as big as the available tracking space. Figure 10 shows all rooms in the order they are changed. The light gray background indicates where the user can walk. The darker gray lines are high walls and the black areas are abysses where the user could technically walk, but is not supposed to go inside the VE. The arrow shows where the user is standing when the environment is activated and the green triangles indicate the goal of the area and therefore the position of the prementioned trigger.

As one can see, the starting point is on the same location as the goal of the previous section. Furthermore, the direct surroundings on these locations are the same for both sections. Only the parts the user can't see are deactivated and activated. This averts the noticing of the environmental changes and promotes the illusion that the user is moving inside a bigger area than he really is.



(a) Left: Starting room; Right: Second room for transition



(b) Left: Third room with bridge and obstacle; Right: Last room with pillars and abyss

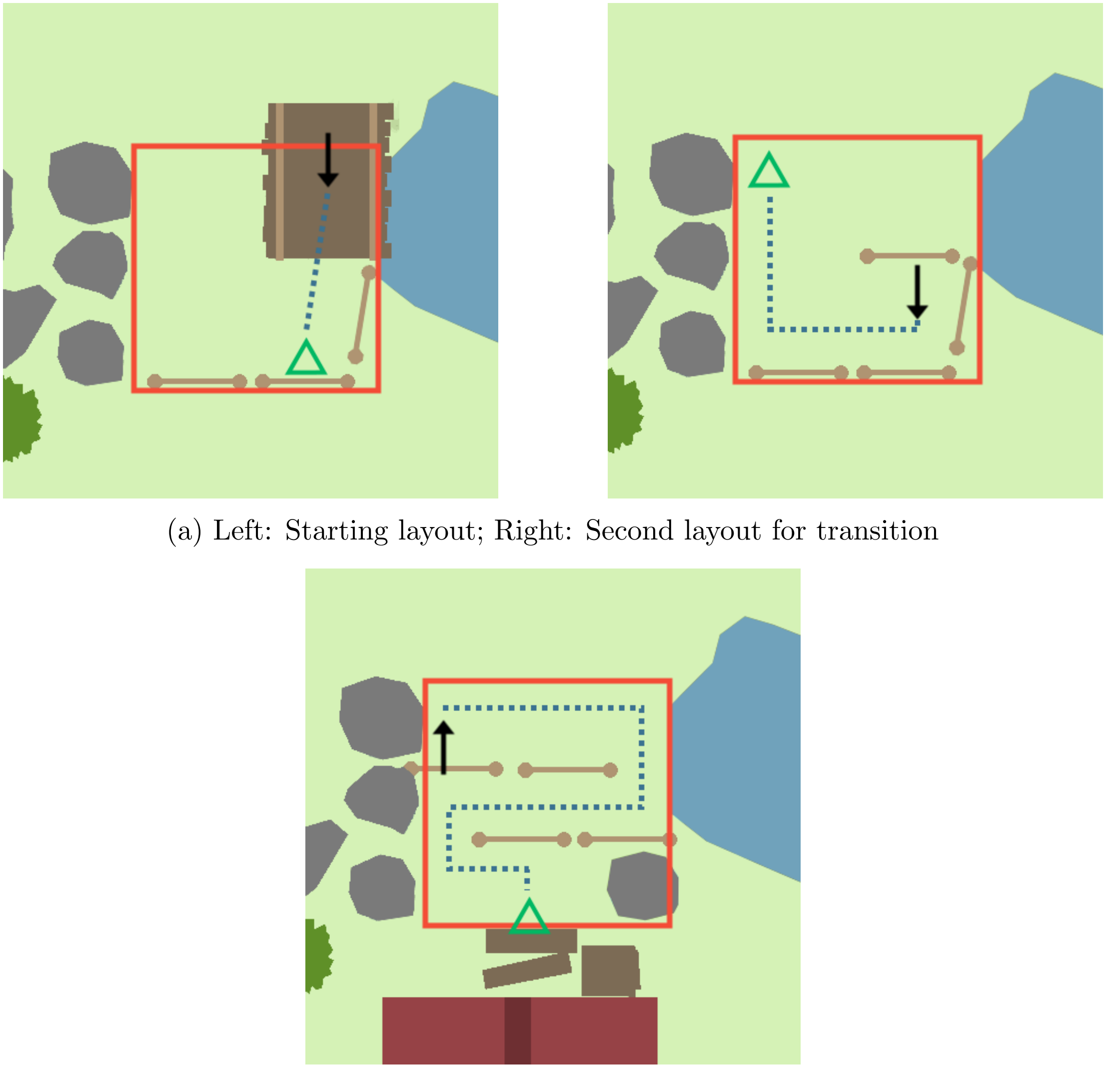
Figure 10: Layout of all rooms of the maze system

During the experience the user is holding one trackable controller, which is replaced with a torch inside the VE. Due to the fact that certain parts of the environment are separately lighted and are dynamically turned on and off, the torch serves as the only light source. The user does thereby not notice the change of environment lighting when the surroundings are changed. This is done to prevent such noticing and raise immersion and enhance the illusion.
Because the user has more freedom in its movement compared to Redirected Walking, one has to assure, that the user stays on his designated path. One reason for this is that the user should not see parts of the level he is not supposed to see and him being on the correct position when the environment is changed. Preventing him from running into physical walls outside the trackable walking space is another reason. To ensure that the user stays on the path, different actions are

implemented which can be seen in figure 10. One are simple walls, which depict virtual borders of the environment. Corridors in which the user navigates can therefore were built. It would be physically possible for the user to walk through the walls. Another action is creating abysses, like shown in room 3 and 4. The user would again be able to walk over it, but because he would not do that in real life, the abysses are supposed to prevent him from going there, holding him on the designated path.

Outer World

In contrast to the previous experiment, this approach uses a wider world around the user. Although he only has the same moving area as in the previous experiment, the view shows a much bigger world, which seems accessible. Figure 11 shows the layouts of the different environments. In contrast to the inner maze, one can see that the environment is not constrictive to the play area, but is expansive and shows a world which is not accessible by the user.



(a) Left: Starting layout; Right: Second layout for transition

(b) Last layout with house as goal

Figure 11: All layouts of outer dynamic space

The red square represents the play area in which the user can move. To assure that he does not want to go outside the play area, obstacles in the form of stones, hills and fences are set on the borders of the walking space. Similarly to the walls in the inner maze, the fences are also used to lead the user through the environment. Because those are not as high as walls, the users view cannot be blocked. Another method to dynamically switch the environment, so that the user does not notice it, has to be applied. For this the general view direction of the user is used. As the paths in figure 11 indicate, the walk direction points away from the changing environment. The intention is that the environmental changes are only performed behind the user. So when he turns around a different environment from where he came is revealed.

4.3 Conclusion

Changing the orientation without user input or changing the movement speed can lead to motion sickness [9]. Because the real movement of the user is exactly reflected inside the experience and no reorientation is done, no tester does suffer from motion sickness. The movement is stated as very natural and the design of the environment as explained in section 4.2.3 also leads to the wanted results.

In the maze no tester perceives when the non-visible environment changes and because the torch is the only source of light, the brightness of the level does not change either and is therefore not noticed. In combination with the chosen models and background sound, a highly immersive atmosphere is created. Because of this and of the convoluted corridors, some users are not able to say in the end where they are standing in the real room. The walls and abysses also worked as expected. Although it is possible, almost no tester goes through walls or walks over an abyss. So they stay on their designated path.
As for the experiment in the outer world, the change of the environment is easier to notice. Although the exact moment the environment is changed is not always noticed by the testers, the influence of the adjustments is detected. The non-accessible area outside the tracking space does not change that much, which is supporting the perception of a changing dynamic space. The world is not perceived as credible as the maze where the user loses orientation much easier and the outer world is delimited by high walls. One can hypothesize, that because the user always has the whole overview over the play area, changes are noticed more easily and orientation loss is more unlikely. From this it follows, that the disorientation inside a maze is promotional for a more believable world. Nonetheless, infinite dynamic environments can be created within the play area.
One can see that the environmental design is very important to lead the user to believe being in a coherent world which can be infinitely big. The chosen experiment has a definite start and end point, ergo a finite world. But a connection could be possible, whereby one room leads to the first starting room which then leads to an infinite tour.
As with the Redirected Walking experiment, the cables of the VR system are a big problem, because they could again lead to a possible risk to stumble. A wireless setup would be promotional for an improved immersion.

Concluding, the maze system with dynamic architecture is a promising approach to create infinite environments while allowing real movement. The reactions are mostly positive and show a good immersion. A disadvantage is that the accessible environment is limited to the physically available walking space and that it has to be designed so that the user does not notice the changes. With these restrictions considered, it is a good way to create an illusion of an infinitely big virtual environment with natural movement inside it.

5 Combination of the Walking Methods

The following section describes the approach to combine the previous two walking experiments into one experience. First, the closure of the last methods is summarized and hence the goals for the combined approach is derived from that. The execution of the experiment is described after that. This includes the hardware and software implementation as well as the characteristics of the environmental design of the world. Lastly, the outcome of the experiment is analyzed and checked against the previously stated goals.

5.1 Closure and Goals

Because the Redirected Walking and dynamic space experiments have distinct methods to generate the illusion of an infinitely big virtual environment, a combination of both approaches could lead to a better experience and immersion. The idea is that the virtual environment is made more accessible.
As concluded in section 3, Redirected Walking is suitable for walking on long straight lines inside the virtual environment. But because of the permanent reorientation, another movement than the circular one is not possible inside the trackable area. Oppositional to this is the dynamic space approach, which provides a free movement in this area but does not allow one to leave the designated play area. The idea for the following experiment is to combine these prospects. The goal is to minimize the stated disadvantages.
To achieve this, several dynamic spaces are placed in an environment and will be connected with straight paths. To get from one dynamic space to another, Redirected Walking is used to walk on the paths. So the reorientation is dynamically turned on and off during the experiment when it is desired. Thus, a more accessible virtual environment will be created in which the user can navigate more freely.

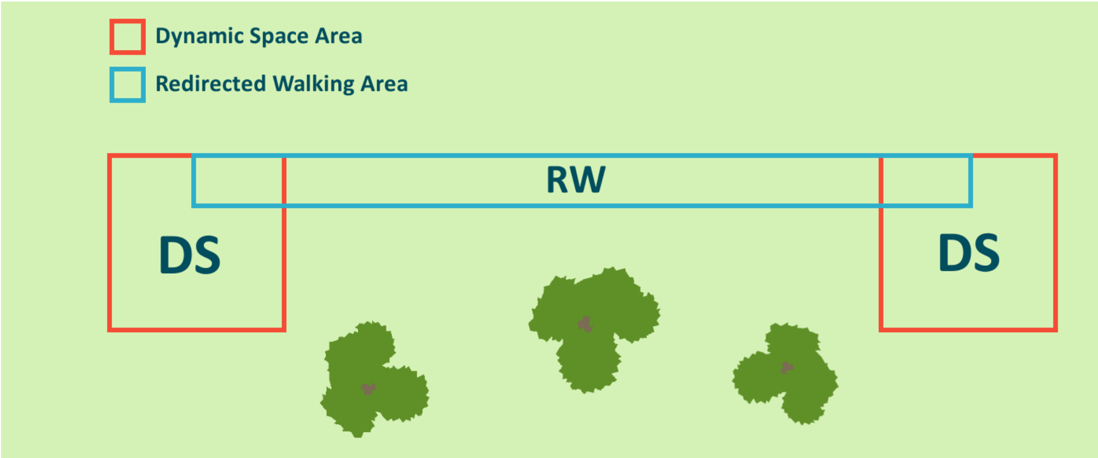


Figure 12: Concept of Combined Areas

It is to be found out how the user responds to the implemented changes of the environment, as well as the transitions between Redirected Walking and a non-reorientated movement inside a dynamic space. The influence of certain environments, which should help to lead the user through the virtual environment, is also taken into account. The combination of the experiments shall also show, whether disadvantages of the distinct methods can be minimized or if new problems arise.

5.2 Execution of the Experiment

As with the previous approaches, this one only uses the available hardware and tracking scope of the HTC Vive. The available space for a dynamic room is again 4m x 4m and the diameter for the Redirected Walking radius is 3.5m. To grasp the concept of the movement methods, the subjects did conduct the experiments explained in section 3 and 4 beforehand. Thereby the users know what to do and can give feedback in comparison to the previous methods. In the conducted experiment, a user has to traverse three dynamic spaces which are connected with two paths. The goal for him is to reach the end of the movable environment. Because those paths lie outside the play area, Redirected Walking is used to traverse these. So the user has to do both movements: one with and one without reorientation.

5.2.1 Setup and Implementation

To ensure a continuity in the experiments the combined walking has a similar setup. The maximum available tracking space of 4m x 4m is used. Everything besides the unpreventable cable of the system inside this play area is cleared. This enables a free movement inside this area.
The experiment has a distinct start and end point inside the virtual environment. To reach the goal, the user has to walk across three rooms in which he can move freely. The first room does not have a dynamic architecture but shows a path

to the first transition point. The second room has multiple trigger where parts of the inner and outer environment are changed. This enlarges the walking path and gives the user visual feedback of something changing. The last room only changes the outer environment. A design element is used to steer the users view. Section 5.2.2 goes into more detail considering the design elements as well as the outer and inner environment used in the experiment.

A straight path in the virtual environment leads to the next dynamic space. That's where reorientated movement is taking place. On specific interaction points the Redirected Walking is therefore turned on and off. To have the biggest possible radius for the move circle, one has to assure that the user is on the border of the play area when the reorientation is activated. Also they have to be in the middle of the corresponding area side and not in the corner to prevent the user from leaving the trackable space. Should they be on a corner, the circular movement would force him to go outside this space. When he reaches the next dynamic space inside the VE, the reorientation is deactivated and free movement inside this new surrounding is possible. This can be seen in figure 12, where the Redirected Walking starts and ends in the specified location inside a dynamic space.

5.2.2 Environmental Design

This experiment is set in the same environment as the outer world described in the dynamic space method in section 4.2.3. Although the changes of the environment in this setting are more noticeable than inside a maze with high walls, a more open world is simulated. The layout of the created world can be seen in figure 13. The red squares show areas with dynamic environments, while the blue outlines indicate areas where Redirected Walking is activated. The user has to get from the space in the upper right corner to the area in the lower left corner.

In the dynamic spaces, multiple design elements are used to steer the movement of the user. To show him, where he should walk, fences with the height of approximately 1m are used. As in the experiment in section 4, certain trigger on specific locations in the world change the environment. When the user reaches them, the layout of the fences is changed to make new paths available. Also objects like trees and houses outside the users reach are changed, which are supposed to simulate a dynamic world to him. To minimize the detection of the changes, the triggers in the environment are set, so that objects behind the user are switched. This presumes that the user is walking inside the dynamic space at will of the level designer. Thus, when not doing this, a perception of the environmental changes is possible. To try to prevent the user from undesired movement, one additional element is used. In the last dynamic space a sign with text on it is used to try to draw the users attention to it. When he tries to read the sign, the environment behind him is changed. The last element that is used to manipulate the motion of the user are natural barriers. Stones and logs are placed in the world to convey that the user is not supposed to go there. For example when reaching a new dynamic space, a log is placed behind him to prevent the user from going back, which is not possible. Together with the fences, they create the desired path the user has to take.

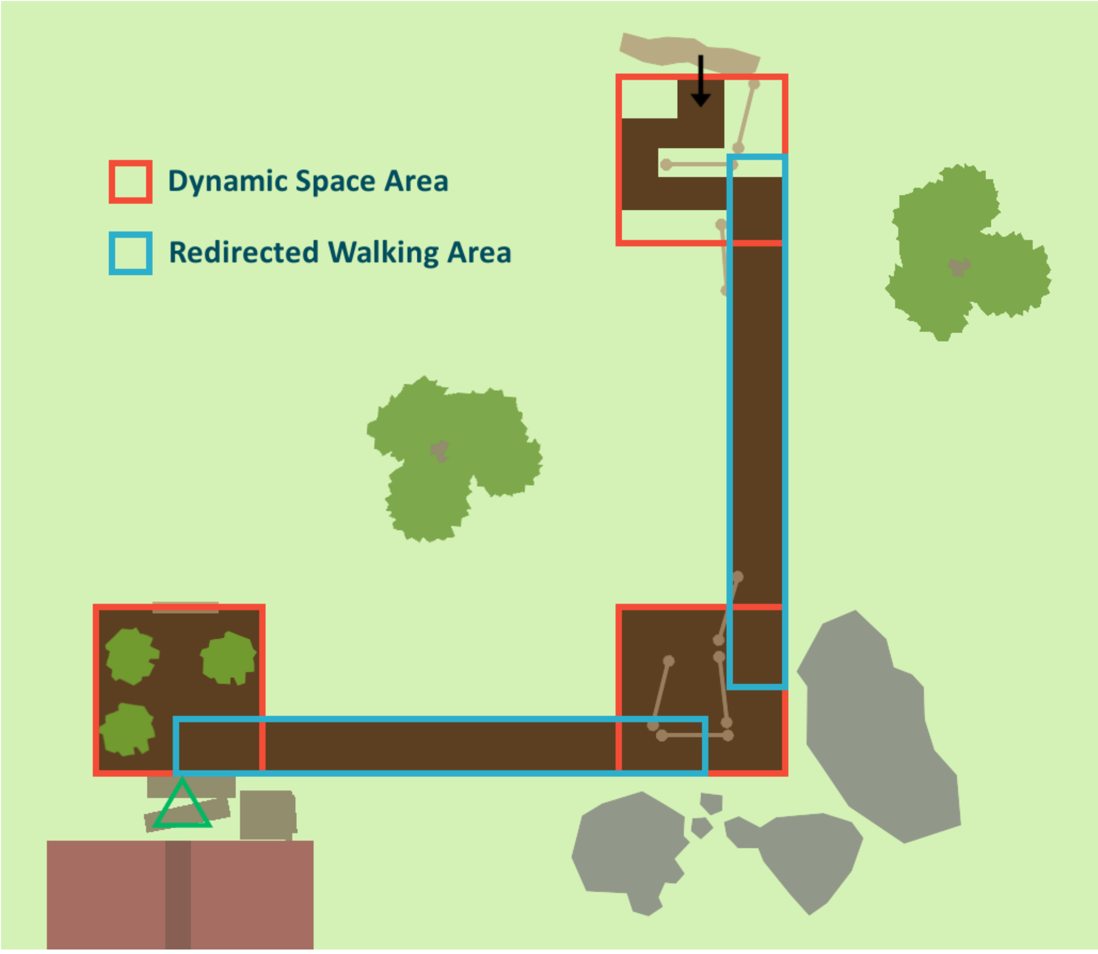


Figure 13: Overview over the Environment for Combined Movement

To get from one dynamic space to the next, Redirected Walking is used. To tell the user where he is supposed to walk in the VE, a road is drawn on the ground. As stated earlier, the reorientation is activated when the user reaches specific points in the dynamic space, which are on one border in the middle. After activating the Redirected Walking, he has to walk a measured distance to the next space. Because all dynamic areas are designed to fit inside the available tracking space of 4m x 4m, one has to assure that the play area is on the correct location after the reorientation phase. For the reason that the play area gets rotated when applying Redirected Walking, it revolves around 360 degrees after the user has completed one circle iteration in its movement. Because the play area is square, one can state, that after every 90 degrees turn (180 degrees if it isn't square) the play area has the same orientation as in the beginning. Thats why the paths between the dynamic spaces have to be of a specific length. To assure that these areas are orientated correctly and with a walking circumference of 11m, the length of the path has to be a multiple of 2.75m (5.5m for a non square play area). The dynamic spaces have a spacing of 11m in the experiment, which equates to a fully walked circle in the real world. A correct mapping of the trackable space onto a dynamic space is therefore assured.

5.3 Outcome

When observing the different parts (Redirected Walking and dynamic spaces) separately, they get the same feedback as previously stated in section 3 and 4. The users comments depict that the radius for the Redirected Walking is too small for an unnoticed reorientation, although a slower movement is sensed as promotional for less swaying. The dynamic space walking is again stated as more natural and easier to move. Nonetheless, new findings are gained with this experiment.

One thing the subjects stated is that the transition between the movement methods generates a short stumble in the movement, assumed the user is in a continuous walk. Although the users accustomed themselves fast to the changed movement, one can observe and deduce that standing still during these transitions is promotional for the users stability. They have a short period where the movement changes, which they do not coercively notice, leading to a better adaptation to the new maneuver.
The used environmental designs mostly leads to the wanted results regarding the users reactions. The drawn paths on the ground, as well as the stones, logs and fences, steered them through the environment as desired. The design of those paths worked mostly as planned. Although the certainty that the user does always look in the desired direction is not given, most users did not notice the exact moment when the environment is changed. Especially the sign works well. The users are focused on it, which makes a veiled change possible. Because of different located dynamic spaces, the world feels more open and accessible for the users. This openness though can also lead to the user wanting to walk outside the play area. To avoid this, all walking borders should be distinguished in the environmental design. The user's feedback also state, that the changed environment is still noticeable after some time. This leads to the suggestion, that convoluted corridors inside a delimited room are promotional for the immersion. However, because of the combination with Redirected Walking and the open world, which is set outside, a bigger world than the real environment is simulated. Creating a maze, like described in section 4.2.3, which combines the movement methods would therefore not be promotional. The environment would not enable a bigger

accessible world and Redirected Walking would only lead from one maze to another. Connecting different rooms on the other hand, like Vasylevskas approach, could be a more promising approach for delimited settings inside an enclosed room[14].

In summary, this method can lead to an improvement compared to using the earlier experiments separately. Several different placed dynamic spaces allow a more diversified environment. A more accessible world can therefore be created. Although the problem of a too small radius for Redirected Walking remains, a slower movement is promotional for decreasing motion sickness. The experiment and the users feedback show that a movement without reorientation is preferred, but using Redirected Walking to get to new places outside the trackable space is well received. When the Redirected Walking part is improved so that the dizziness and cognition of the circular movement is not existent, the combination of the method can be seen as an improvement. For the available tracking space of 16 m^2, the single dynamic space is still preferred by the users.

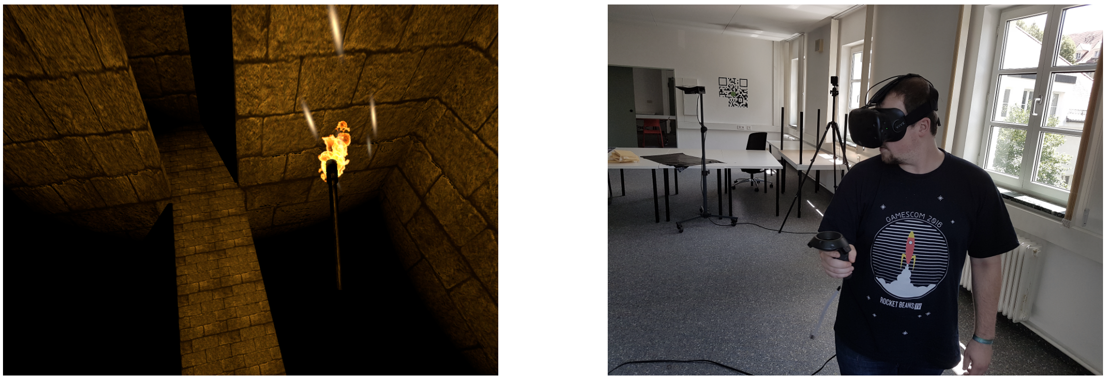
6 Result

The following section takes the first two examined methods separately and brings out their different advantages and disadvantages. They are compared in terms of their results and their distinctive areas of applications are carved out. The executed combination of these methods will be also taken into account. With the current results of the experiments, a section on how these movements can be improved is presented together with the future development of the techniques. Lastly, a conclusion about the whole project is given and what worked out good, what didn't pan out as expected and what could have been avoided.

6.1 Comparison of Redirected and Maze Walking

Two different ways of maneuvering in virtual reality applications were presented in section 2.3. Both conducted methods relinquish the use of movement metaphors and aim to transfer real walking into motion inside a virtual environment. While doing this, the user should experience the deception of being inside a world which is not bound to the physical room limitations. The two experiments have different courses of action to achieve the same goal. The Redirected Walking method manipulates the rotation to distort the users perception, thus letting him walk in circles while believing he is moving straight forward. Different from that, the maze uses a small room with interleaved architecture to trick the user's orientation, allowing to dynamically create new rooms in which he can navigate. Therefore they have different advantages and disadvantages in their application. The two are compared in two aspects: the environmental requirements and the physical applicability.

(a) Redirected Walking with path and in-game view



(b) Maze with dynamic architecture; environment with bridge

Figure 14: The experiments with real and in-game view

Real Environmental Requirements

While the possible tracking space of the HTC Vive with 4m x 4m is enough for a good application of the maze with dynamic environment, Redirected Walking requires much more space for unnoticed circular movement. The maze does not require much room, but its layout is highly dependable on it. The outer perimeter has to be adapted to the tracking area. This requires a specific design of the virtual environment and the size of this space cannot be changed afterwards. On the other hand, this method gives much freedom in designing the level inside this available space, because it is possible for the user to move freely inside of it. Tricks like abysses, drawn paths, walls and obstacles help to keep the user on designated paths and lead him to points, where parts of the level can dynamically be switched.

For Redirected Walking, the size of the environment can be much bigger than in the maze system. This is possible due to the fact that the user infinitely walks in a circle, never reaching the end of the trackable area. The size of the VE is therefore not dependent on the size of the play area. But compared to the maze, the movement inside the VE is very limited, because only forward (respectively backward) movement is possible. For a more free movement, the reorientation

algorithm would have to be turned on and off dynamically, as was done in the combination of both methods. Another disadvantage of this method is that much physical space is required. The tested walking radius of 1.75m was enough to have the user assimilated to the movement, but not enough to have him not notice the reorientation. The recommended radius of at least 22m[11] is not feasible for home use and with the standard hardware of the HTC Vive.
Because the combination of both methods implements the Redirected Walking as well, this approach also is not practical for experiences with the basic hardware. By dynamically switching between real and dynamic walking, the movement is no longer restricted to only a forward or backward direction and can enlarge the accessible area in the VE. But the user can notice these transitions which can lead to a short dizziness.

Virtual Environment Design

It was shown that the design of the virtual environment has big influences on how the user perceives the world and how the developer can steer his movement. Elements like obstacles, paths and walls can be a good way to direct the user to the desired goal. They can be used to create paths and to block ways where the user is not supposed to go.
Additionally to that, the environment is jointly responsible in how the user is immersed in the world. The experiments showed that for the dynamic spaces, an enclosed world with convoluted corridors are superior to a big outer environment, regarding the noticing of environmental changes and user's feedback on immersion. Because the outer area does not change as much when creating new paths in the play area, the users do perceive the changes more easily, what can be interpreted as a loss in experiencing a coherently infinite big world. In the inner maze the walls block the users view, preventing him from seeing outside the walking borders. Together with the convoluted corridors, one can assume that this leads to a harder retaining of the orientation. The illusion to move inside a greater world than available in reality could benefit from this effect.
As for the Redirected Walking, the feedback shows almost no difference between an outside or inside world. One can assume, that this is because Redirected Walking is used to reach places outside the play area. Therefore, a big world around the user makes sense for a coherent environment.
One can conclude, that for a highly immersive experience, the environmental design can be an important part of the development. It can affect the user's perception of the world as well as the ability to keep him on the compulsory paths.

Physical Applicability

The methods do have several impacts on how the movement is perceived and how strong the immersion is. With the used radius for Redirected Walking, fluent navigation was not easily possible. As stated before, the reorientation was noticed and a little motion sickness did arise. This feeling strongly increased when the direction of walking was reversed during the experiment. The vestibular system was not able to adapt to the new condition with such a small radius fast enough, which lead to dizziness. Nevertheless, when having only one direction, a stable walking is feasible. This allows a movement free from motion sickness after a short adaption to the reorientation. But with the given conditions of the experiment, accidents are still possible and a second person to supervise the movement is recommended.

The maze with dynamic environment however doesn't need this adaption. The absent reorientation is conducive to the general perception. Motion sickness is not promoted with this method. One reason for this is that the real movement is transfered directly into the program. The user does therefore not experience a movement he does not expect, leading to a better immersion and a more steady walking. The limitation of the walkable space yields a smaller environment compared to Redirected Walking and narrow architectures inside this area can lead to claustrophobic feelings.

The combination of the methods can enlarge the accessible environment of the dynamic space by using Redirected Walking as a connection between several rooms, but comes with the new problem of a more complex level design and the unpreventable transition between reoriented and natural movement. Therefore, this combination is not able to zero out the distinct disadvantages.

Besides that, when conducted right, all experiments can have a high immersion, leading to a suppression of the outer world and a loss of the real world orientation.

	Redirected Walking	Maze Walking
Advantages	– Large environments possible – Infinite forward walking	– Free movement – Diversified environment – Direct motion transfer
Disadvantages	– Possible motion sickness – Restricted movement to one direction – Much space needed	– Complex level design needed – Accessible environments can not exceed trackable space

6.2 Area of Application

Due to the disparate requirements the methods have, they can be used for different use cases.
Redirected Walking is useful to map a comparatively big environment onto the smaller available tracking space. This should be a good use for applications which use big environments and are dependent on the navigation through those, like video games. However, this technique needs a much larger space than the HTC Vive is capable of tracking for the best possible experience. So because of the need of additional setup and hardware, this is not feasible yet for commercial use at home. Experiences who are using this method to create large environments should aim for users who can definitely provide the necessary space.
The presented maze on the other hand is viable with the given hardware. Therefore, a usage for commercial home applications is possible. The only limitation this method has is the required space set in the program. But every user who can provide this space has the possibility to use such an application. But also when additional tracking hardware is available, this method can be applied for much larger areas. It can be used to have different dynamic rooms, which are at most as big as the available tracking space, but not larger. This means that not all visible areas inside an environment have to be accessible for the user. While a large world can be rendered outside the trackable space, the user can only navigate inside the available area.
The experiment, where both methods are combined, can counteract this effect. As found out, it provides a good method by having more than one dynamic space, leading to a greater accessible world with more variety in the setting. Because the reorientation is used, the radius was again too small for these parts to not notice the redirection. But because it combines the possibility to go to locations

outside the trackable space with the opportunity to move freely and natural in an environment, this could be the most promising method to create large explorable environments with minimized motion sickness and need of reorientation.

6.3 Improvements

As stated earlier, each method has its advantages and disadvantages. The goal of future works would be to countervail these detriments. The motion sickness, which arised during the Redirected Walking, can be countered by a large enough area to accomplish an unnoticed reorientation.
The methods have antithetic problems. While the Redirected Walking can reproduce large worlds, but is limited to movement in one direction, the maze with dynamic environments allows a more free movement, while the environment is limited to the available tracking space. One idea was already implemented by combining both methods. One problem which arised was the noticing of the changes. Additional to the used sign and obstacles to call the users attention, other methods to steer his movement and view could be researched. The goal would be to make the whole reorientation and change of the environment unnoticeable.
Another idea is to test, if certain additional equipment is beneficial for the reorientation of the Redirected Walking and therefore allows a smaller radius to walk. This could be, for example, the use of weights or disparately high shoes to naturally force the user to walk in a circle.

6.4 Conclusion

The experiments show a good alternative for movement metaphors inside a virtual reality application. But they also illustrate, that with the demand of real walking inside a VE, certain limitations have to be considered. The available space is too small to create a pleasing experience. Especially the Redirected Movement requires a significantly larger area. Nevertheless, they have great potential for a future usage in virtual reality applications. The experiments were tested by a small group of persons with different ranges of experience in using virtual reality headsets. Their feedback and cognition when conducting them point out, that the dynamic space inside a cave is the most pleasant experience. The Redirected Walking suffers from the too small radius, while the dynamic space in an outside world has the problem of a perceivable adjustment of the environment and an outside world which is not physically reachable. Although the combined experiment shows, that some of these disadvantages can be reduced, the inner maze is stated as the most immersive and fun experience to be in.
Thats also why environmental design turned out to be an important part in conducting these methods. Wrong design can also lead to a loss in immersion. Thats why some thinking should go into this, when creating an application which uses

one of the conducted experimental approaches. Different objects can be used to steer the user in a wanted direction. This works in an outside environment as well as in an interior room. Merely the world outside the trackable space makes a big difference in perceiving a credible world. While the outer environment depicts a mostly non-developed world, the inner dynamic space uses its branched environment to feel like a plausible maze within a coherent world.
All presented methods do not provide a perfect solution for movement inside a virtual reality application, but they can create the wanted illusion of an infinitely big world. Although not all preconditions were ideal, the feedback from the testers can be concluded, that the methods can lead to a high immersion. A future research as well as improvements and enhancements of these methods promise more feasible movements inside virtual reality with still higher immersion.

Glossary

Cybersickness / Motion Sickness Symptoms which occur during the use of 3D applications, like headache, disorientation and dizziness.

FOV FOV is short for field of view. It describes the field of vision in degrees one can see at any given moment of the observable world.

FPS FPS is short for frames per second. It describes the amount of provided images every second from the system.

GameObject A GameObject is the base class for all entities in a Unity scene. They have a position, rotation and scale in the three-dimensional room and act as a container for Components, which implement the real functionality for this object.

HMD A head mounted display, or short HMD, is a visual output device, which is worn on the head. With screens directly in front of the eyes, it is mostly used for virtual and augmented reality.

Immersion Immersion in virtual reality describes the effect, that the cognition and consciousness of the user is tricked to let him believe, that the virtual environment is real.

IMU An internal measuring unit consisting of accelerometers, gyroscopes and magnetometers to measure the velocity, orientation and gravitational force of a device.

Kickstarter Kickstarter is one of the biggest crowdfunding platforms. Companies and persons can publish projects, which can be funded by many private persons, until a specific financial goal is reached and the project is realized.

Play Area The Play Area is the area, which is configured as walkable space in the HTC Vive setup.

Scripting Backend A scripting backend in Unity3D is a framework that powers scripting. Depending on the target platform, there are three backends in Unity: Mono, .NET and IL2CPP.

VE VE is the short form for virtual environment. It describes the setting and world in which the virtual reality application is set.

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