

Development and Evaluation of a Virtual Reality Adventure Game for the Virtualizer

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Kurzfassung

Diese Arbeit beschreibt das Design, die Implementierung und Evaluierung eines Virtual Reality (VR) Abenteuerspiels für den Virtualizer, den PrioVR und die Oculus Rift. Zuerst wird ein Überblick über den aktuellen Stand der Technik in den Bereichen Head-Mounted Displays (HMDs), Motion Capture Suits, Bewegungscontroller und Technologien, die das Gehen in einer virtuellen Realität ermöglichen, gegeben. Anschließend wird ein Überblick über derzeit existierende VR-Spiele gegeben. Cybersickness ist ein großes Problem in VR-Spielen. Diese Arbeit beschreibt die drei existierenden Theorien die den Entstehungsprozess dieser Krankheit beschreiben. Weiters werden Faktoren, die die Wahrscheinlichkeit cybersick zu werden erhöhen, beschrieben, sowie Ansätze erwähnt, die das Auftreten von Cybersickness reduzieren können.

In VR ist es für den Spieler/die Spielerin notwendig, dass er/sie in der Lage ist in der virtuellen Realität ebenso zu interagieren wie in der wirklichen Welt sowie seinen/ihren virtuellen Körper, welcher den wirklichen Bewegungen folgt, zu sehen um ein Gefühl der Anwesenheit in der virtuellen Welt zu erzielen. Neueste Technologien sollen diese Form der Interaktion für den Spieler zu Hause ermöglichen. Bis jetzt wurde noch kein Spiel entwickelt, welches die Kombination aus Oculus Rift, PrioVR und Virtualizer verwendet. Deshalb beschreibt diese Arbeit die Entwicklung eines VR Spieles für diese Technologien. Benutzerstudien wurden gemacht um herauszufinden wie gut die Interaktion mit diesen Technologien funktioniert und ob die Testpersonen cybersick werden. Weiters werden Richtlinien für den Entwurf sowie technische Probleme die während der Benutzertests aufgetreten sind, beschrieben.

Abstract

This thesis describes the design, implementation and evaluation of a virtual reality (VR) adventure game for the Virtualizer, the PrioVR and the Oculus Rift. First an overview is given about the state-of-the art in terms of head-mounted displays (HMDs), motion capture suits, game motion controllers and technologies for walking in virtual reality. Further, an overview is given about already developed VR games. Cybersickness is a major problem in VR games. There are three theories that try to explain the process of becoming cybersick, which are described in this thesis. Further, factors that can influence the possibility of getting cybersick are mentioned and approaches that can reduce the occurrence of cybersickness are described.

In VR it is necessary to be able to interact in the virtual world like in the real world as well as seeing your own virtual body that follows your real-world movements to create a feeling of presence in the virtual world. Recent technologies enable this kind of interaction for the casual player at home. Up to now, no game has been developed that uses the combination of the Oculus Rift, the PrioVR and the Virtualizer. Therefore this thesis describes the development of a VR game for these technologies. User tests were conducted to find out about how good the interaction with these technologies is working and if the participants get cybersick. Further, design guidelines are discussed and technical problems that occurred during the user tests are described.

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1 Introduction

Virtual Reality (VR) is a new form of human machine interaction that uses input technologies that are beyond casual input devices like keyboards or mice [1]. It enables an immersive experience that can be applied in different fields such as engineering, entertainment, education or flight simulations [2].

Because of the fact that virtual reality tries to replicate the player's experience in the physical world, users often have the expectation that they are able to interact in virtual reality like they do in the real world [3]. Therefore it is important to show the user's virtual body corresponding to his real body. This gives the feeling of presence in the game and thus provides a higher immersive game experience [4]. Therefore full-body tracking is needed. Usual technologies came with high costs and high complexity of operation, but recent technologies, like the PrioVR [5], Perception Neuron [6] and ControlVR [7] enable body tracking at an affordable price for the casual gamer.

Apart from motion tracking, locomotion is also an important interaction technique in virtual worlds, because it gives the user the feeling of presence [8]. Walking is the most intuitive way to explore the real world and it is important that the user gets a sensory input as well as a physical input to reduce cybersickness in virtual environments [9]. Former locomotion devices were expensive and were hard to use and some of them needed a lot of space, but recent technologies like the Virtualizer [10] and the Virtuix Omni [11] enable the casual gamer to actually walk in the game for an affordable price.

HMDs (Head Mounted Displays) are used to display the virtual experience and provide a 360-degree image of the virtual space [12]. This gives the user the feeling of being in the virtual world [13]. Recent technologies such as the Oculus Rift and the Sony Project Morpheus enable a virtual experience at low cost [13].

This thesis describes the implementation of a VR game using the PrioVR, the Virtualizer and the Oculus Rift, which should enable an immersive virtual experience for the player. The VR game is an adventure game, where the user controls the movements of a virtual avatar by the PrioVR and the Virtualizer. The Oculus Rift tracks the head rotation and displays the game. User tests were conducted to find out about user interaction and if people get cybersick. Factors that might influence the possibility to get cybersick, such as gender or wearing glasses, were identified. Within the game the user had to solve different puzzles by interacting with different game elements. This was used to find out how difficult it is for the player to navigate in the virtual world with the used hardware. Up to now, no game has been published that combines these novel technologies. The contribution of this thesis, from a research perspective, is to design and implement a new

game which integrates these technologies, and to perform user studies, investigating presence, cybersickness and other factors.

Section 2 of this thesis gives an overview of the state of the art in locomotion interfaces, motion input devices like motion tracking and video game motion controllers, head mounted displays and cybersickness. Section 3 describes the game design and section 4 describes the hardware and software implementation for the developed game. Section 5 describes the execution of the user tests. Section 6 describes the results of the user tests as well as technical issues. Further it describes design guidelines that should be regarded when developing a VR game.

2 State of the Art

2.1 Walking in Virtual Environments

Walking in VR is challenging because in many virtual reality applications the virtual environment is larger than the available physical space. Different devices exist to enable walking in virtual environments that are described in this chapter [14].

2.1.1 Locomotion Interfaces

A locomotion interface is defined as a device that simulates an artificial sensation of walking in a virtual environment. An ideal version of such an interface should provide three key functions:

- Creation of a sense of walking while the true position of the user stays the same.
- Possibility to change walking direction: Omni-directional displacement has to be cancelled for allowing the user to change walking direction.
- Possibility to simulate uneven surfaces.

Locomotion interfaces can be classified in four different categories that are described in this section. Prof. Iwata worked on locomotion devices since 1985 and summarizes them in [15].

2.1.1.1 Sliding Shoes

In this section three examples of Sliding Shoes are described: the Virtual Perambulator, powered shoes and the String Walker.

Virtual Perambulator

The Virtual Perambulator [16] was the first locomotion device. It was developed in 1988 and allowed the user to change walking direction. Figure 1a shows the first prototype. The user wears omni-directional roller skates and his torso is fixed to the device by a parachute-like harness. The user had to skate over an omni-directional sliding device. The framework enables a free movement of the user's feet in any direction. The harness was later replaced by a belt around the waist because users felt uncomfortable due to the pressure of the harness. Further a break pad was attached to the roller skates to enhance the friction force and hence increase the stability of the user.

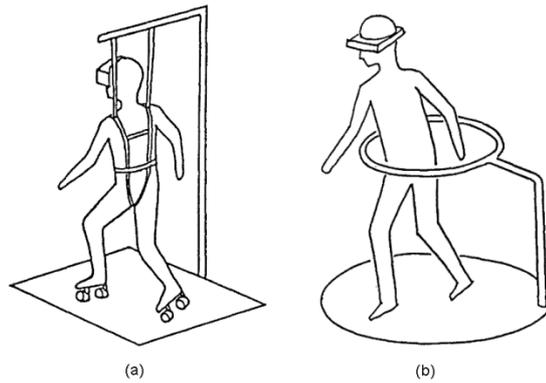


Figure 1: (a) First Prototype of the virtual perambulator, (b) second prototype with hoop frame [12]

Iwata et al. [12] enhanced their system by replacing the waist belt by a hoop, in which the user can physically walk and turn around (see Figure 1b) and the roller skates were replaced by special sandals that were equipped with a low friction film in the middle of the sole and rubber at the tip of the toe region as a breaking pad [12]. In this second prototype of the Virtual Perambulator also a 6 DOF platform was integrated to simulate uneven surfaces.

Powered Shoes

Powered Shoes [17] is an interface that uses motorized roller skates that have a drive mechanism underneath the sole. The motor is separated from the roller due to the large force that is required to move the user. The motors and the batteries were put in a backpack because of their weight. The major limitation of this system was that the user is restricted to walk in a straight line because the direction of the traction force generated by the rollers is identical to the shoe.

String Walker

The String Walker [18] is a device where the user stands on a turntable. The device is based on eight strings, four connected on each shoe for pulling the shoe in the opposite direction of walking. The position and orientation of the shoe is measured by the motor-driven mechanism. The String Walker enables omni-directional walking by rotating the turntable with the direction of the user.

Recent Technologies

The Omni [11] and the Virtualizer [19] are newer technologies that both use a low-friction surface to walk on. The surface of the Omni is curved. It has additional grooves on the base-plate and special shoes with pins that fit into these grooves to stabilize the user. The shoes have a higher friction coefficient on the toe to additionally stabilize the

player. The player's hip is fixed by a belt that is attached to a supporting rig. This enables vertical movement and prevents the player from falling down or slipping [11].

The Virtualizer has a flat base plate that should allow more natural walking. The player's hip is fixed by an adjustable harness that is attached to a ring that is mounted on a moveable rig that allows vertical movement as well as sitting. Instead of using special shoes the player wears socks in the Virtualizer. The prototype has a metal construction of the ring and the pillars, but the consumer version will be made of solid plastic instead to enable the use of additional sensor solutions. These solutions use magnetic fields to calculate the position data, and should not be distorted by the used material. 3 sets of optical sensors in the base plate, the rig and the 3 pillars track the movement of the user's body and feet. Further, vibration units are integrated in the base-plate to enable haptic feedback. The optical sensors in the base plate detect the player's feet movement whereas the ultrasonic sensors inside the pillars detect the vertical position of the player. The player's angle is detected by sensors in the ring construction. The Virtualizer has an additional "arm" that guides cables of HMDs, headsets or other devices to the user's head so that he does not struggle himself with the cables while playing. The consumer version of the Virtualizer will have optical sensors instead of ultrasonic sensors inside the pillars to collect more reliable data and to have a lower latency [10].

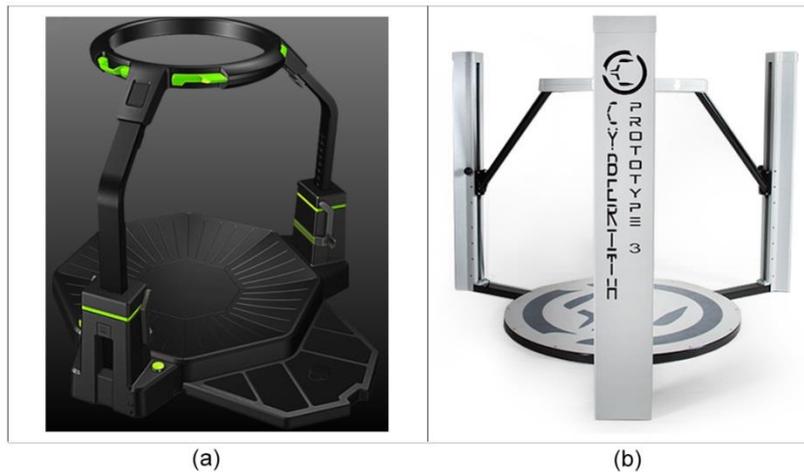


Figure 2: (a) Omni [11], (b) 3rd prototype of the Virtualizer [19]

Both the Omni [11] and the Virtualizer [19] translate the real motion data to key strokes. Both technologies enable natural walking, running, jumping and crouching. The technologies are affordable and easy to use. Figure 2 shows the Omni and the Virtualizer for comparison.

2.1.1.2 Treadmills

A treadmill is a simple device that is normally used as fitness device, but can also be used to enable virtual walking. The problem with simple treadmill-based interfaces is the

change of direction. One possible solution to enable omni-directional walking is the use of rollers to move the user in perpendicular directions. The omni-directional treadmill [20] contains two perpendicular treadmills, whereas one of them is inside the other. Another example of a similar treadmill is the Ball Array Treadmill [21], that contains small balls which move the walker in the requested direction. The problem with the mentioned omni-directional treadmills is that the rollers or balls are dangerous when the user falls down.

Another method to enable omni-directional walking is to use a large sphere in which the user is standing. Accordant to the user's step the sphere is moving around. The problem of this approach is that when a user walks too fast, he cannot stop.

A newer approach for realizing an omni-directional treadmill is the torus treadmill [22]. For creating an omni-directional infinite moving floor the shape of a torus is used because it can be easily implemented by a group of belts connected to each other that form a plane surface. Figure 3 shows the first prototype the "Torus Treadmill" that consists of twelve treadmills that move the user along the x-direction. These treadmills are connected side by side and driven in a perpendicular direction for moving the user along the y-direction. The major limitation of the torus treadmill is that it cannot simulate uneven surfaces.

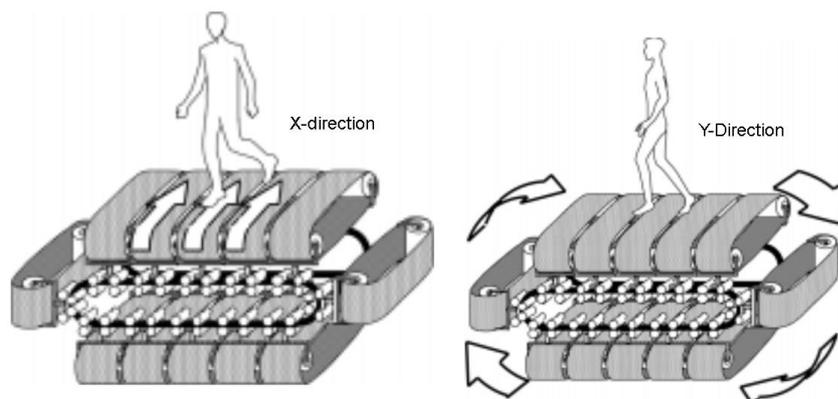


Figure 3: Structure of the Torus Treadmill [22]

The same approach as the Torus Treadmill is used in the CyberWalk Platform [9], which was constructed at the Max Planck Institute.

2.1.1.3 Foot Pad

Foot Pads use platforms to apply displacements to the user's feet. Foot Pad-based devices can therefore fulfill the third key functionality of locomotion devices, the simulation of uneven surfaces.

The pedaling device is the easiest form of a foot pad-based device. A more sufficient device is the GaitMaster [23], which is a device that was developed in 1999 and can simulate an omni-directional uneven surface. It consists of two 6 DOF motion-bases that are mounted on a turntable. The user stands on the top plate of the base. Figure 4a shows the structure of the GaitMaster. The two bases trace the position of the feet and cancel the motion by moving to the opposite direction. The turntable traces the orientation of the user and rotates accordant to the rotation movement. Figure 4b shows the prototype of this device.

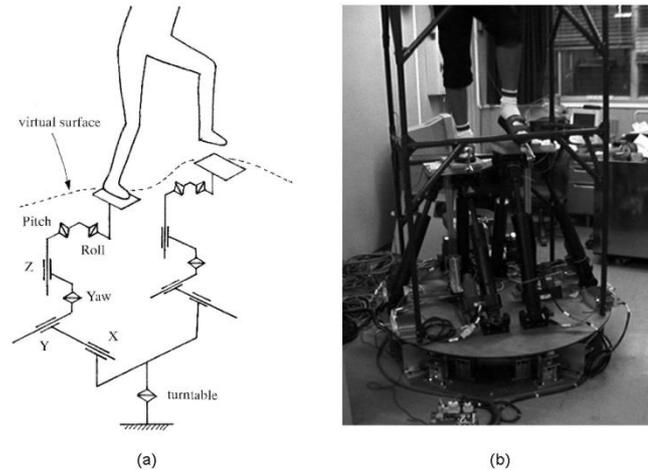


Figure 4: (a) Basic Design of the GaitMaster, (b) Overall View of the GaitMaster [23]

Due to the not sufficient tracking speed, the practical use of the Gait Master was limited, but a simpler form of this device is used for walking rehabilitation.

2.1.1.4 Robotic Tiles

The CirculaFloor project [24] was started to combine the advantages of the Torus Treadmill and the GaitMaster. The goal was to develop computer hardware that is more compact than the hardware of the Torus Treadmill but still create an infinite surface with this hardware.

Omni-directional moveable tiles, so-named robotic tiles were used to achieve this goal. Each of the tiles is equipped with a holonomic mechanism to achieve omni-directional movement. The simulation of an infinite surface was achieved by the circulation of the robotic tiles. In Figure 5a a prototype of the CirculaFloor is shown. The movement of the user's feet is measured and the robotic tiles move opposite to the user's walking direction to cancel his motion. With this principle it is possible for the user to freely change walking direction like in the Torus Treadmill. Uneven surfaces can be simulated by an up-and-down mechanism attached to each tile. The combination of tiles offers a sufficient walking area. Figure 5b shows the simulation of stairs by a combination of robotic tiles.

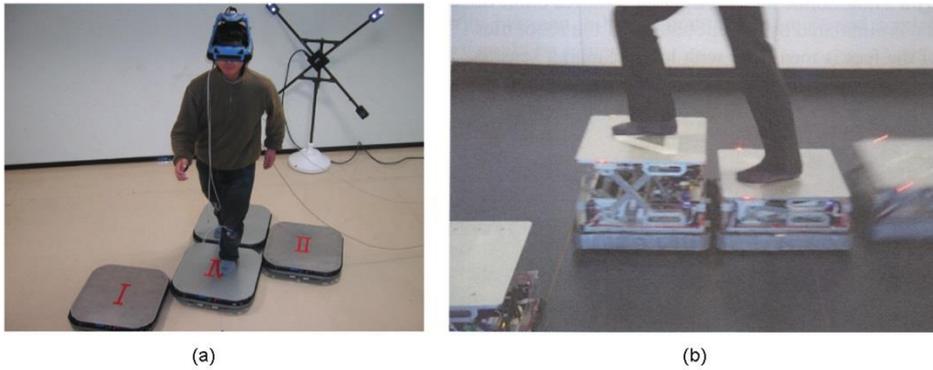


Figure 5: (a) Overall View of the CirculaFloor [24] , (b) Robot tiles simulate virtual staircases [15]

The system only offers a low walking speed. Therefore a higher circulation speed would be needed to enable natural walking.

2.1.2 Stepping-Driven Locomotion Interfaces

Locomotion interfaces that employ stepping movements are the ones that offer the most natural walking and therefore the users have a feeling of higher immersion. Whitton et al. describe different types of stepping-driven locomotion interfaces [25].

Stepping-driven locomotion interfaces are interfaces that are driven by the actual stepping motions from a user and do not include any mechanical devices. The speed and direction of a user's movement is calculated and converted to a movement in the virtual environment (VE) between several frames. There are two different kinds of stepping-driven locomotion interfaces: walking-in-place interfaces and real world locomotion. The two principles differ in how movement in large VEs is enabled. Walking-in-place interfaces constrain the user's movement to a small area whereas real-walking techniques transform the virtual environment so that the user's physical path stays within the available physical space of the laboratory. While in walking-in-place interfaces the user stays in place and does not move forward, real world locomotion allows the user to go both physically and virtually forward.

The challenge in both technologies is to control the user's speed so that it is responsive and smooth. In real world locomotion a major task is to transform the environment to lead the player in a desired physical direction in a way that keeps his path through the VE within the lab space. There are two ways to achieve this goal, either using scaled rotation and translation or re-center the user with redirection techniques. In real-world locomotion the virtual direction and speed is controlled by the physical walking speed and moving direction of the user.

There are different requirements on stepping-driven interfaces:

- They should be easy to learn and easy to use

- The hands of the user should be free to be available for other task-related interactions
- Users should not be able to run into real-world obstacles
- No increase of simulator sickness
- The supporting infrastructure like tracking devices should be minimized
- Strain should be minimized: it should be easy to don and doff; equipment should not interfere with other gear that the user is wearing

There are also different goals in terms of setting speed:

- The start and stop latency should be minimized: movement of the user should start on the first step and end on the last step.
- Users should be able to adjust their walking speed continually during a step like they do in real walking.
- The virtual walking speed should stay constant to avoid variations in optical flow.
- Fine positioning and maneuvering steps should be possible.

Further, there are goals in terms of setting direction:

- The system should offer the user to move in any direction (forward, backwards, sideways, ...)
- The direction of the walking movement should be independent of the view direction or body orientation of the user.
- The direction setting should be working without using the hands, so that the hands can be used for other task-related interactions.

2.1.2.1 Walking-in-place interfaces

In WIP (walking-in-place) interfaces a stepping-in-place gesture is used to control the speed. Different techniques and input devices exist to set the direction of the player. In this section techniques for setting the speed of the movement and the direction of the player are described.

Setting Speed

Repeated stepping gestures have different observable motion phases. Figure 6 shows a six-phase WIP gait cycle. As can be seen, there are three events for each step of a leg: first the foot gets off, then the foot reaches the maximum step height and then the foot strikes back to the ground. Sensors can be used to detect these events. Measurements are made and certain time-stamps are attached.

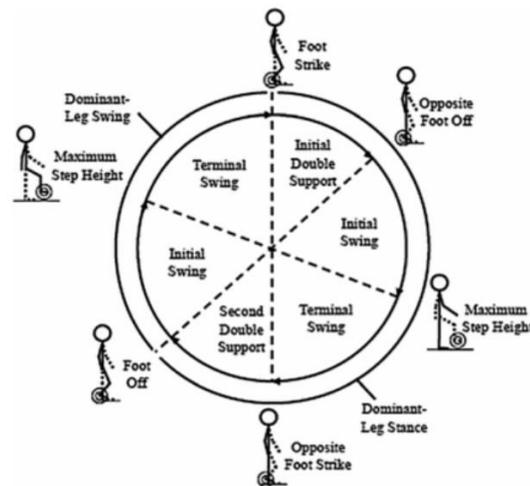


Figure 6: Six-phase walking-in-place gait cycle [25]

The earliest WIP interface detected foot-strikes. When a foot-strike was detected, the viewpoint moved forward. The faster the foot strike was the faster the player moved through the virtual world. Another system, called the virtual treadmill [26] applied a neural network to the delivered head tracker data to detect local maxima in the vertical head-bob. Whenever a step was detected, an amount of forward movement was applied over several frames.

Other systems used pressure sensors on shoes [27] or on the floor [28] or used head-worn accelerometers [29] to detect foot strikes.

A major problem was the starting latency. The step was counted when the foot lifted and went back to the ground. Therefore maneuvering was not possible, because the system has to ignore small foot movements. This requires the need of additional data about the stepping motion to continuously measure the leg position. For this, tracked devices can be attached to the front or back of the leg. These trackers provide a continuous stream of time-stamped tracker data for detecting the six events of the gait cycle.

The Gaiter WIP system [27] offers locomotion with limited real-space maneuvering. In this system, the knee excursion in the horizontal plane is measured by trackers on the shin. The system can differ between a virtual and a real step.

Yan et al. [30] developed a system where the walking speed is measured based on the leg speed during the period of high-leg acceleration. The motion begins when the leg-lift speed is exceeded. The system prevents false steps and allows slow maneuvering steps.

Different techniques can be used to smooth the speed between foot strikes and to offer maneuvering and therefore enhance the explained systems.

Setting direction

Setting the direction to the forward direction of the body or of the head is not difficult. The challenge is to allow the user to move in any direction independent of the view direction or the body orientation. The direction can in general be set with or without hand-held devices.

Hands-free direction settings:

- Head-directed motion: the user's forward direction is equal to the forward direction of the head. In this case looking around while moving is not possible.
- Torso-directed motion: A tracked device is located on the torso or hips of the player and he walks forward in the forward direction of the body. This enables looking around while walking, but moving backwards or sideways is not possible. Therefore a decoupling of motion from the direction of the player's body would be needed.
- Gesture-controlled direction: Trackers can be attached to hands, legs, feet or the head. The tracked movements can be interpreted and special gestures can be detected. In the Gaiter system for example sideways walking is interpreted when the leg swings to the side of the hip.

Hand-Held Direction Setting devices:

- Wands pointing: Wands can be tracked and can support other input devices like buttons. The forward direction can be defined by a combination of a hand-held 3 DOF (Degree of Freedom) tracker and the arm gesture by measuring the position of the wand relative to the user's head position. If a 6 DOF tracker is used, the coordinate system of the wand itself can be used to define the forward direction.
- Joysticks / Game Controllers: The player can move in an arbitrary direction with the help of game controllers. The body-centric coordinate system can be defined by a 6 DOF tracker on the user's body.
- Integrated tracker / joystick and task tool: Hand-held interfaces can be integrated into task tools. An example for this are raffles with integrated thump-operated joysticks used in military training systems.

The mathematical modelling of walking in WIP interfaces is still not suitable enough with the mentioned methods. The shape of the velocity profile during the walking phases is not addressed yet. Also the changing of speed is not suitable enough. Due to newer affordable devices like the Kinect as well as small inexpensive wireless sensors like accelerometers, gyro meters or magnetometers more input can be collected to enhance the simulation and modeling of natural walking. In the past these data could only be delivered by expensive full motion suits and hence were too expensive to integrate in affordable WIP interfaces.

2.1.2.2 Real-Walking Interfaces

Real-Walking interfaces enable natural walking like in the real world. Therefore the user is tracked in a laboratory. The easiest case is when the lab and the virtual space are of same size. Then a one-to-one mapping between the real walking speed and the virtual walking speed as well as between the real moving direction and the virtual moving direction can be applied.

The challenging case is when the size of the virtual environment is bigger than the size of the tracked area. Then a transformation of the scene or of the user's motion has to be applied by manipulating the ratio between the real and virtual speed and between the real and virtual direction of the user.

Early redirected walking methods [14] manipulated the user's motions by scaling the rotation and/or translation of the player to keep him inside the tracked space. The problem with these methods is that the ability of the human perceptual system for tolerating a mismatch between the visual and vestibular system is limited, which makes the manipulations noticeable for the user.

Manipulating Speed

One approach to enable natural walking in large virtual environments is to apply a transformation between the real walking speed and the virtual walking speed. The ratio between the virtual and the real walking speed can be increased to enable the user to travel greater distance with the same number of steps.

Problems occur when this scaling factor gets very large, because then the user will recognize the discrepancy or even worse it can give him the feeling of teleporting or disorientation. Bruder et al. [31] use change blindness techniques to solve that problem. In this approach the user is moved forward while the user is unaware of it. This is based on the fact that users are unaware of changes in their view when these changes appear during saccadic eye movements. The user is moved while a blank screen is displayed in

the HMD for about 60-100 ms. With this method the user is less aware of changes that have occurred.

Manipulating Direction: Redirected Walking

Redirected walking increases or decreases a component of the user's physical movement to exploit imperfections in the human perception of self-motion [32]. An example of using such imperfections is the following principle: The head rotation of the user is measured and scaled by a factor to get the virtual rotation. The result is a gradual rotation of the virtual environment around the user's head that results in a change of walking direction. This rotation is applied when the head turns if the user is standing still or if the user turns his body when the user is walking around. When the rotation is slow and gradually it will not be noticed, because the player compensates this movement. In the physical space he is walking in curvature while he is walking in a straight line in the virtual space.

Redirected walking is working because the vision tends to dominate over the vestibular sensation when they conflict. Redirected walking is used to prevent the user to leave the tracked area. With this technique the user can walk in a circle in the real world but has the feeling to walk normally through the virtual environment. Redirected walking enables physical walking in large virtual environments.

There are reorientation techniques that only rotate the virtual scene and techniques that also rotate the user physically so that his next path-direction is inside the tracked area. There are techniques that stop the user and some that do not stop the user at all when rotating the scene. The use of reorientation techniques should not interfere with the virtual experience.

There are different interfaces that use redirected walking. One of them is the Motion Compression [33] [34] that rotates the virtual environment around the user and remaps areas of the scene that are outside of the tracked lab space into the lab space. The underlying algorithm predicts the target location of the user based on points of interests in the environment. The straight line of the path between the user and the target location gets then mapped to the largest possible arc that fits in the lab. [25] Redirected walking used in motion compression does not stop the user when turning the scene around his position, but has to use large rotations so that the user gets the feeling that the scene is spinning around.

Another method uses headphones [35] [36] [8] that support reorientation. The user is asked to stop, turn his head around and to continue walking in the same direction as before. During the head movement the virtual scene is rotated so that the next walking path lies inside the tracked area.

The method developed by Hodgson et al. [37] stops the player physically and turns him back to the tracked area when he is about to leave the tracked area. The user can continue walking in the scene in the same direction as before. The HMD is virtually frozen during the turn of the player.

Circular algorithms [38] keep the user inside the laboratory by keeping him on a circular trajectory. He is either kept in the inside of the circle or returned from outside of a circle.

Razzaque's environments [35] [36] [8] use static waypoints, which define the user's route through the virtual space so that the goal locations of the user are predetermined. Due to this knowledge the part of the scene that has to be rotated can be determined. The waypoints also make the player to look around and therefore moving his head. The system redirects the user's path to the next waypoint into the tracked space. Waypoints are a good solution for predicting the user's direction which is one of the most challenging parts of redirected walking. But this answer also comes with the throwback that applications have to have predefined paths and reasons for the player to look around.

A further support for redirection techniques are distractors. Distractors are defined as virtual objects or sounds in the virtual scene that stop the user and provoke head rotations. This makes the users less aware of scene rotations. Avatars are a good example of distractors.

Examples of further techniques are the use of virtual barriers to mark physical borders in the tracked area, or using a joystick to move unreachable parts of the virtual scene into the tracked area. Newer techniques use a combination of different techniques to guide the user.

It was found out that there are limits for the magnitude of the conflict between the visual and vestibular sensation. Excessive manipulation can become noticeable and in the worst case can lead to disorientation or cybersickness [32]. To overcome this problem further approaches have been developed, like change blindness illusions or self-overlapping architectures.

Recent research developed a different approach for redirected walking that does not require the rotation of the virtual environment around the user's head position. The approach is known as change blindness redirection and reorients the user by changing parts of the virtual environment that he is not looking at. Sumo et al. [39] for example managed this by changing the physical orientation of doorways, because such minor changes are difficult to detect. In their user tests, only one out of 77 participants noticed the change of the door position. Figure 7 shows an example where a door is moved to another wall while the user is not looking at it.

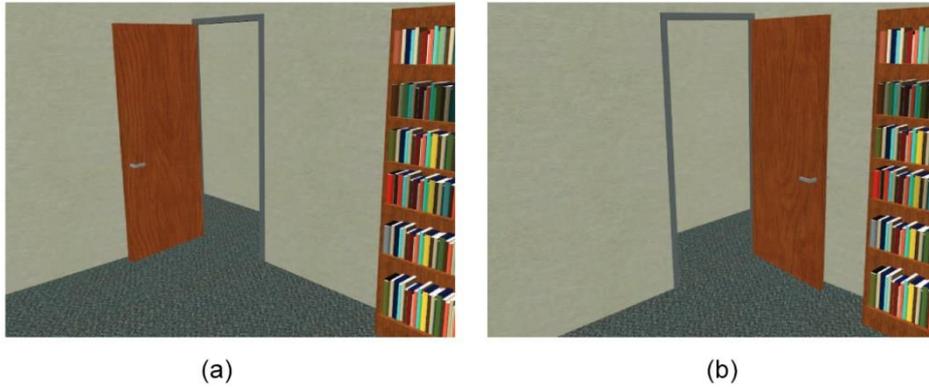


Figure 7: Example of a scene change where a doorway with the adjoining corridor are swapped when the user looks away; (a) before the scene change, (b) after the scene change [39]

Another method to enable walking in large virtual environments are impossible spaces with overlapping geometry [40]. When the user walks from one room to the neighboring room, the shared wall between the two rooms is translated so that the visited room gets bigger. The percentage of the overlap is bigger for smaller rooms and smaller for larger rooms. Figure 8 shows an example.

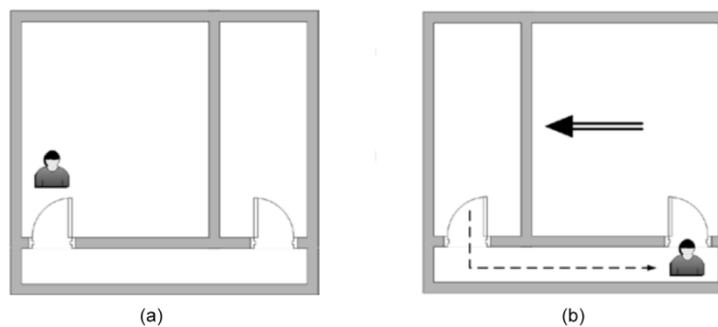


Figure 8: Impossible spaces with overlapping geometry, (a) User is standing in room 1, (b) When the user walks from room 1 to room 2, the wall between the rooms is moved to increase the size of the target room [40]

Flexible Spaces

It is not always necessary to have an architectural structure that is consistent within a single virtual environment. There are two types of virtual environments: structural virtual environments, where the spatial layout represents the key information and informational virtual environments where the particular layout is not critical. Here the focus lies on the content in the virtual environment. Informational virtual environments are used for applications like entertainment, virtual therapy and educational applications. In informational virtual environments there is no need to copy the spatial layout of real existing environments. Instead they can be represented as non-physical virtual environments that visually correspond to the real world but underlie different laws.

Flexible spaces [14] are defined as impossible environments that violate the real world constancy and provide the experience of unrestricted walking in large virtual environments. The method of flexible spaces is a dynamic self-overlapping layout generation algorithm that reconstructs parts of the virtual environment to fit in the tracked space of the laboratory and executes dynamic relocation. Figure 9 shows an example with two rooms. The user can walk from one room to another following a route and eventually walks back with a different route.

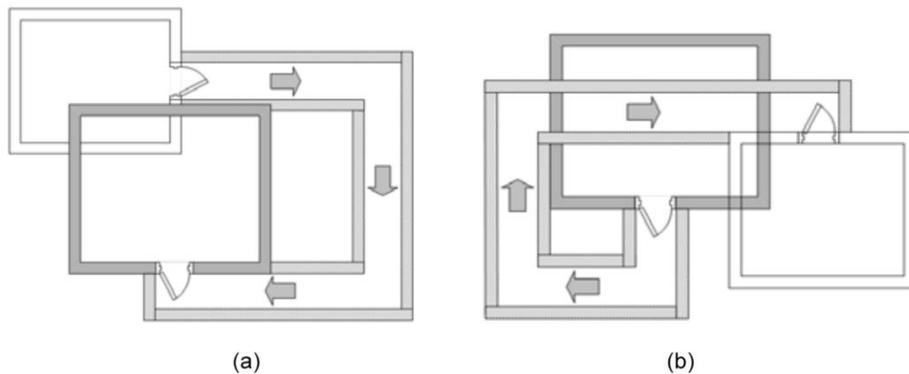


Figure 9: (a) The corridor from one room to another gets generated, (b) The corridor is regenerated with a new shape whenever the user walks from one room to another. [14]

Flexible spaces enable a user to explore a virtual environment with less physical restrictions. The used test environment by Vasylevska et al. is a complicated building, which includes two subtypes of environment architecture: the informational part, which consists of rooms with features and content inside and the transitional parts that are formed by corridors. The informational part underlies minimal changes for enabling orientation cues. The changes are done before the player enters the room so that the changes are unnoticed by the user. The transitional part as well as the position of the target room is procedurally generated. Dynamic reconstruction of the layout is transformed with random factors.

Flexible spaces enable infinite walking. The room positions and the door positions change randomly, which makes it possible to enter a room from each direction. The connection between two rooms does not change. This means that a bidirectional connection is offered to the user so that he can return to a previous room. The doors provide information for orientation by providing different wall colors (see Figure 10b).

The length of the corridor depends on the location and size of the rooms it connects. The variability of the corridors is reduced so that corridors do not intersect with the room at a point that is close to the target door. Flexible spaces support an unlimited number of rooms as well as multiple exits/entrances. Only part of the virtual space is rendered dependent on the user's position and movement direction, which provides a consistent view despite of overlaps. Flexible spaces enable an infinite walking without limitations so

that the user has the freedom to decide where to go. The throwback of flexible spaces is the limitation to individual spaces connected by walkways. The size of the tracked area has to be at least the size of one room plus a corridor reserved space of approximately one meter width.

The Flexible spaces algorithm [41] avoids the natural manipulation of the player's motion parameters and does not use visual-vestibular conflicts imposed by other redirection methods. Further it enables an intuitive navigation through large virtual environments. Figure 10 shows the used test environment.

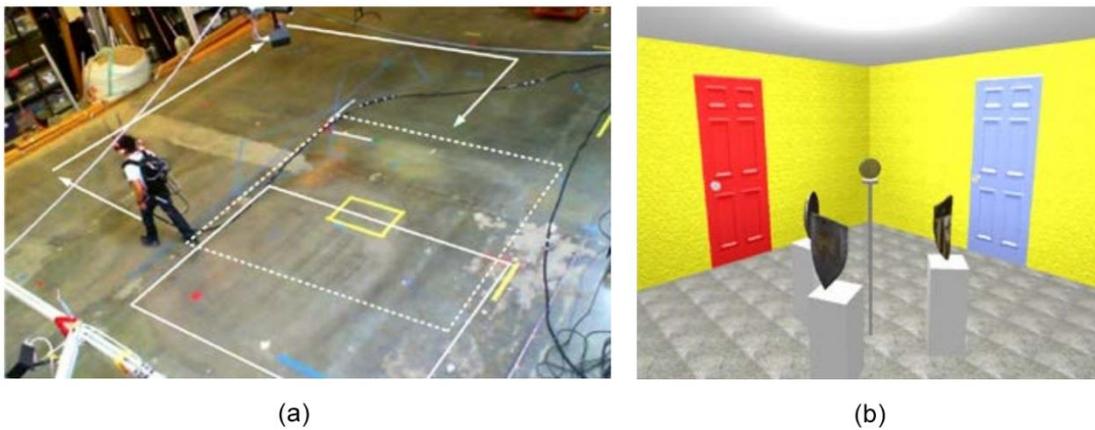


Figure 10: Test environment: (a) The user walks from one room to another in the tracked space, (b) virtual room with multiple doors [14]

2.2 Motion Input Devices for 3D Interaction

For the last 20 years natural interaction in VR was a major goal for 3D user interfaces, but full-body-locomotion that is needed to track various points of the body required expensive hardware. Due to the demand in the gaming industry these technologies got affordable and can track parts of the body or even the full body of the user [42]. This chapter describes motion tracking technologies in general as well as different motion input devices.

2.2.1 Motion Tracking

To provide a correspondence between the physical and the virtual environment, which is important for 3D interaction in VR, an accurate tracking has to be provided. There are different motion tracking systems that include optical, magnetic, acoustic, mechanical, inertial, and hybrid tracking [43]. Each of these tracking technologies has critical parameters like accuracy, jitter, range and latency.

Magnetic Tracking

A magnetic tracking system consists of a transmitter and receivers. The transmitter emits a low-frequency magnetic field, whereas the receiver is a small sensor that determines its position and orientation relative to the magnetic source. With this tracking technology a range of about 1-3 meters can be tracked. An accuracy of 2.54 mm in position and 2.54 degree in orientation can be reached. The disadvantage of the system is that ferromagnetic and conductive objects distort the magnetic field and thus reduces the accuracy of the tracking system.

Mechanical Tracking

A mechanical tracking system includes interconnected mechanical links and electromechanical transducers like shaft encoders or potentiometers. One end of the system is attached to the tracked object, whereas the other end is fixed in place. The linkage move when the tracked object moves and the measurements of the transducers provide the position and orientation of the tracked body part. Mechanical tracking systems are very accurate and come with low latencies but are also bulky, which limits the mobility of the user.

Acoustic Tracking

Acoustic tracking systems consist of a source that emits high-frequency sound and microphones that receive that sound. It can be distinguished between outside-in tracking, where the microphones are located in the environment and the source is attached to the tracked body part and inside-out tracking, where the source is located in the environment, and the microphones are attached to the tracked object. Time-of-flight duration of ultrasonic pulses is the dominant tracking technique in acoustic tracking. The time the ultrasonic pulse needs from the source to the receiver times the speed of the sound gives the distance between the source and the receiver. From this distance the position of the tracked body part can be derived. When using more receivers the orientation of the body part can also be determined by using triangulation. The advantage of inexpensive and light wave tracking comes with the drawback of a short tracking range and a low sampling rate. The accuracy of the tracking system gets reduced when acoustically reflecting surfaces are present in the tracked environment. External noises cause interference with the tracked signal and therefore reduce the accuracy as well.

Inertial Tracking

Inertial tracking systems use a multitude of inertial devices like accelerometers or gyroscopes. These devices deliver derivative measurements. The gyroscopes measure

angular velocity whereas the accelerometers measure the linear acceleration. In combination they deliver the position and orientation of the tracked body part. The drawback of the inertial tracking system is that the tracking range is limited to the length of the cable between the sensor and the electronic unity, but wireless solutions are also possible. Inertial tracking systems provide high sampling rate but the error accumulation from sensor drifts, noise and biases are the major limitation of the system. The error accumulation is a big issue with linear accelerometers, therefore most systems only track the orientation of the sensor, because the error accumulation of the gyroscopes can be compensated and thus is less problematic.

Optical Tracking

Optical tracking derives the position and orientation information of a tracked body part from measurements of reflected or emitted light. Optical tracking uses computer vision techniques, IR emitters, optical sensors like cameras, or lateral effect diodes. The systems generate signals that are proportional to the position of the incoming light. There are two different approaches: the outside-in tracking, where the sensors are mounted in the environment and active or passive landmarks like colored gloves or retro reflective markers are attached on the tracked body part and the inside-out approach where optical sensors are attached to the tracked object and the landmarks are attached to the environment. Different landmarks are used with different optical tracking systems. For instance passive fiducials like cards with recognizable patterns or active LED beacons can be used.

The example device shown in Figure 11a includes a scanner that reflects laser beams, which get picked up by the sensor. Then the signal gets send back to the DSP electronics of the scanner. Another example is the HiBall system [44] that includes a set of high-speed cameras mounted on the user's head and LEDs mounted in the environment (see Figure 11b). The LEDs flash at high speed and the position and orientation of the tracked body part can be calculated by triangulation.

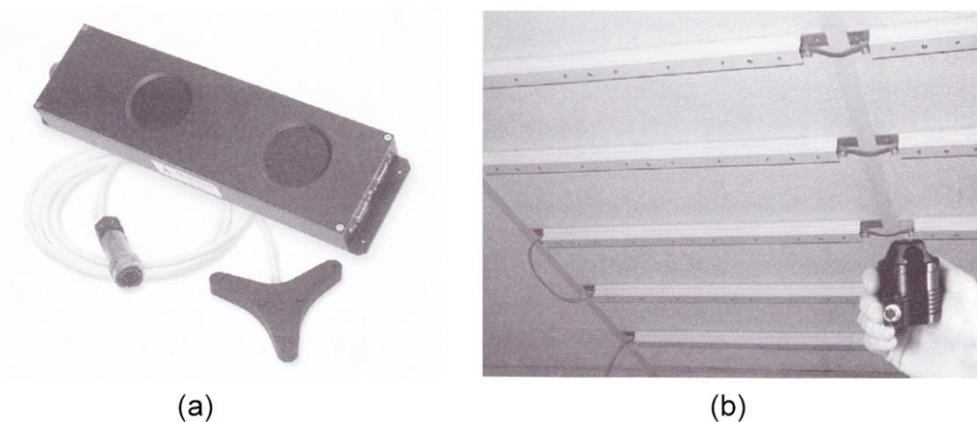


Figure 11: (a) Example of an optical tracking device; (b) HiBall tracking system [43]

The advantage of optical tracking is the fact that it can be an untethered solution but huge drawbacks of this technology are occlusions that occur when body parts occlude other body parts. To prevent occluded markers from not being tracked, additional landmarks are needed which makes the tracking system more complicated.

Hybrid Tracking

Hybrid tracking systems include more than one tracking technology with the goal to increase accuracy, reduce latency, and to compensate weaknesses. An example device [45], shown in Figure 12, combines inertial tracking with ultrasonic tracking. The inertial sensors provide the orientation and the ultrasonic component measures the position of the tracked body part. Thus a 6DOF tracking is provided by the system. Another example is a system that combines video cameras and structured light projectors. Such a tracking device can provide color, depth and surface reflection. Another approach, used in large-space outdoor environments, is the combination between GPS and initial sensors like gyroscopes and accelerometers.

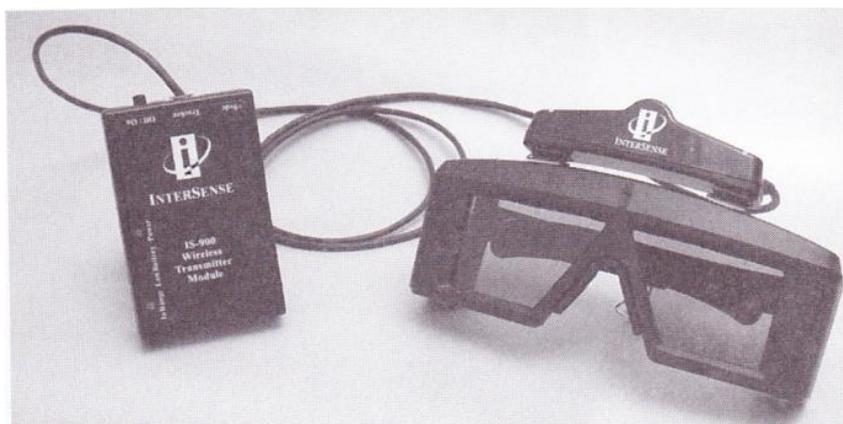


Figure 12: Wireless inertial / ultrasonic tracker [43]

2.2.2 Motion Capture Suits as Video Game Controllers

In the following, different examples of current affordable MoCap (motion capture) suits that are designed as input controllers for VR games are described. In virtual reality it is important to see your own virtual body corresponding to your real body, because this gives you the feeling of presence in the game and therefore gives you a higher immersive game experience [4].

The usual technology used for marker-based optical full-body MoCap uses a motion capture suit with retro-reflective markers on it that get tracked by cameras in real-time with mm accuracy. However this technology comes with high costs and high complexity of operation and hence was not used in many applications. Schönauer et al. [46] developed a flexible marker-based optical full-body MoCap system for the use as input

device for a serious game used for rehabilitation for patients that suffer from chronic pain of the neck and the lower back. The patients should perform different exercises to improve their physical conditions and their mobility and coordination. Such a system has to have a high accuracy because the capabilities and progress of a patient have to be determined for medical evaluation. Therefore Schönauer et al. [46] [47] used a passive marker based IR optical MoCap system, named iotracker [48]. To reduce the costs commodity hardware was used. The iotracker cameras are shutter synchronized and equipped with IR strobe lights and optical band pass filters to make the passive markers visible. The iotracker server application calculates 3D positions from camera images. The measurements can be done with low latency, submillimeter location resolution and minimal jitter. The absolute accuracy of the measurements is ± 0.5 cm.

Recent developed motion capture suits for the casual gamer are Perception Neuron [6], Control VR [4] and PrioVR [49]. All of them are still in development. Perception Neuron [6] is a light-weight modular MoCap system based on an inertial measurement unit named Neuron that consists of a 3-axis accelerometer, a 3-axis gyroscope and a 3-axis magnetometer and is only 1x1 cm big. It can output data at up to 120 fps and provides high-speed on-board calculation with embedded data fusion and calibration algorithms. The data stream of the sensors is channeled wirelessly to the hub, which collects, synchronizes and transmits the data. The hub can transfer the data to the PC in 3 different ways: over USB, WiFi or via a micro-SD card. Perception Neuron generates smooth and true motion with minimal latency and provides a static accuracy of ± 1 degree for the pitch and roll angle and ± 2 degrees for the yaw angle. The system is powered by an external USB power pack. With Perception Neuron up to 32 neuron sensors can be placed on the user's body in different configurations. With 32 neurons a full-body motion tracking including also an accurate finger tracking is provided. The system comes with wrist, hand and finger straps and with gloves. The overall system is shown in Figure 13b.

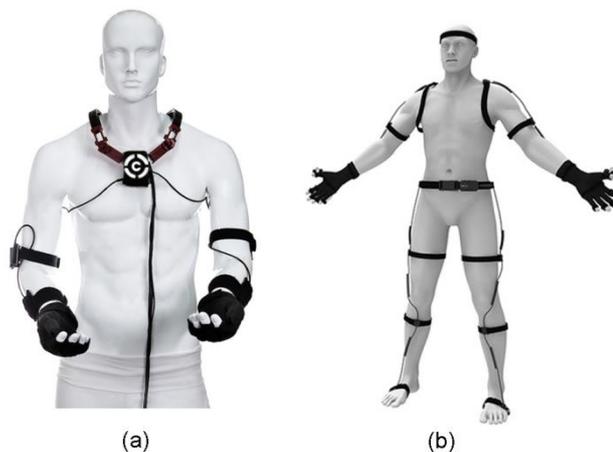


Figure 13: (a) Control VR prototype [7]; (b) Perception Neuron [6]

Control VR [4] is a MoCap suit that was originally designed to track the hands and upper body and provide detailed finger movement, but is planned to provide full-body motion capturing in the future. The technology that is used is a hybrid between optical and inertial motion tracking. It uses military grade small inertial sensors with an accuracy of 0.1 degree and additionally an optical system that includes one camera on the body. To calibrate the system you have to take an inertial pose that maps the avatar to this default position. Additionally the user can use the secondary optical system to see his inertial skeleton in comparison to his real-world position to make calibration easier. The motion capture system is not limited by any range. Control VR is also designed to recognize hand gestures. This happens without being confined to the camera's line of sight and the user is not limited to specific lighting conditions. The overall system provides ultra-low-latency by using wired sensors. The Control VR can be seen in Figure 13a.

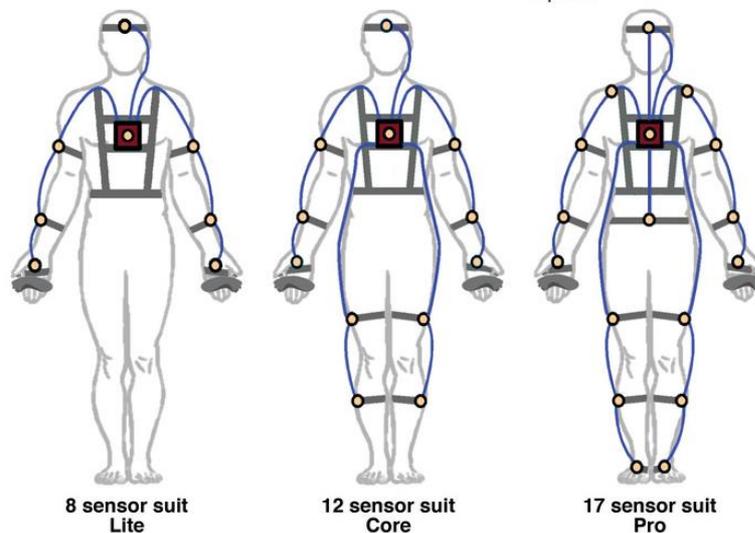


Figure 14: Different versions of the PrioVR [5]

PrioVR [49] is a motion capture suit that is available in three different versions: the light version that provides upper-body motion capture with 8 sensors, the core version that provides full-body motion capture with 12 sensors and the pro version that provides full-body motion capture with 17 sensors (see Figure 14). The system uses high-performance inertial sensors with low latency. The transmission to the computer happens over Wi-Fi. The suit also uses two hand controllers. Currently Wii Nunchucks are used in the prototype, but the consumer version will be delivered with new designed hand controllers with buttons, triggers and joysticks. The sensing element of the suit is an inertial sensor with a 3-axis magnetometer, a 3-axis accelerometer and a 3-axis gyroscope. The sensors are coupled with a high-performance 32 bit processor that takes data from the component sensors and applies calibration and sensor fusion algorithms to produce a single accurate drift-free orientation output that corresponds to the human's motion in real-time. The sensors are configured as sensor chain and connected to the wireless hub. The hub contains an embedded sensor unit, a chargeable battery and a

high-performance 32 bit processor that collects data from the sensor array and the hand controllers. The data are then compressed, packetized and sent wirelessly to the base station that is attached to the computer. The wireless technology is optimized for low latency real-time communication and large capture spaces. Multiple suits can be used simultaneously in the same space due to the optimized wireless technology. The overall latency of the suit is less than 10 ms. The suit can be used in a space of 30.5 meters radius to the computer.

2.2.3 Video Game Motion Controllers

Former video controllers had only buttons and analog or digital controller. Electromagnetic, inertial or vision based tracking systems were too expensive and thus were only used in expensive VR or AR applications. In the last years sensing technologies became available to an affordable price. Therefore new game controllers using these technologies were developed for the casual gamer. The three most common video game controllers are, arranged accordant to the release date, the Nintendo Wiimote, the PlayStation Move and the Microsoft Kinect. They can determine the player's position as well as his movement in the 3-dimensional physical space. Williamson et al. describe them in [42].

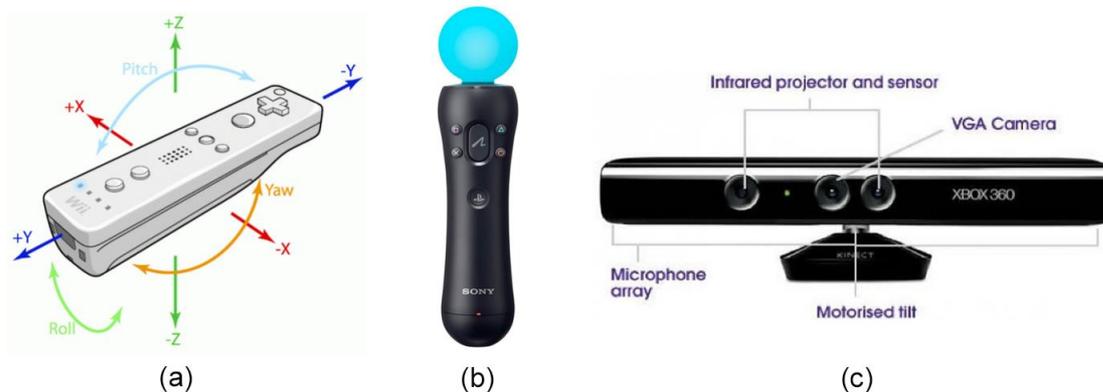


Figure 15: (a) Wiimote, (b) PlayStation Move, (c) Microsoft Kinect

2.2.3.1 Nintendo Wiimote

The Wiimote contains apart from the integrated tracking technologies, several buttons, programmable LEDs, a speaker and a rumble device. The Wiimote tracking system consists of two inputs: an accelerometer and an intermittent optical sensing via an additional infrared sensor bar.

The sensor bar (see Figure 16) emits infrared light blobs by LEDs that are attached on each side of the sensor bar. The Wiimote contains an infrared optical camera that tracks this light blobs when pointing at the sensor bar. The x and y-coordinates as well as the

blob's width in pixels get determined by the camera. The LEDs are spread in a slight arc to improve the tracking distance.

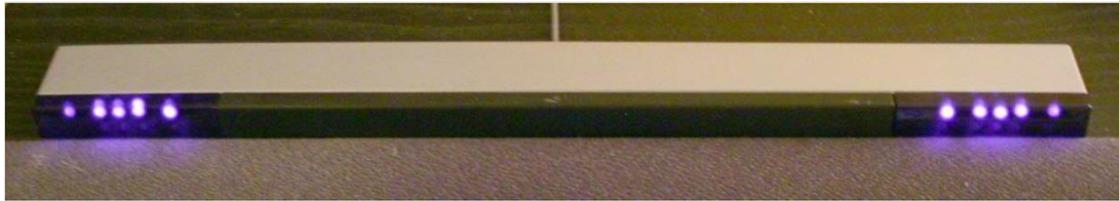


Figure 16: Wiimote sensor bar contains two groups of IR LEDs arranged at fixed widths [42]

The second input of the Wiimote is the 3-axis accelerometer. The acceleration data caused by the user and the earth's gravity gets detected in the x-, y- and z-direction. The gravity vector in the FOR (frame of reference) of the earth can be used to determine parts of the Wiimote's orientation.

The 3-axis acceleration data, provided by the system, do not require a particular FOR. The Wiimote tracking system works with three frames of reference: the personal FOR (see Figure 15a) consisting of the x-, y- and z-axis as well as the roll, pitch and yaw rotations, the earth gravity that gets detected by the accelerometers and the relationship of the Wiimote to the sensor bar. Each frame of reference captures different incomplete information about the spatial position and rotation and therefore all of them have to be considered.

Further an extension called the Wii MotionPlus can be added to the Wiimote. The Wii MotionPlus contains two MEMS (micro-electromechanical system) gyroscopes that measure the angular velocity along the x-, y- and z-axis.

2.2.3.2 PlayStation Move

The PlayStation Move system consists of 1-4 Move controllers and a PlayStation Eye camera. It combines the advantages of motion sensing, camera tracking and traditional buttons. The PlayStation Move system reaches better results than the Wiimote. The PlayStation Move controller (see Figure 15b) is equipped with several MEMS sensors: 3-axis gyroscopes and 3-axis accelerometers. Further the controller has a glowing sphere on top with a RGB LED inside that is tracked by the Eye camera. This makes tracking also in dark room possible, because optical lighting is not needed. The color tracking is rotation invariant because of the spherical shape, which makes recovering of the 3D position easier. The move state of the controller gets determined in 2 steps: image analysis and sensor fusion.

The image analysis consists of 2 steps: First the sphere gets found in the image and then a shape model gets fit to the sphere projection. The sphere gets found by color segmentation which is separated in 2 steps: segmentation, where every pixel that

belongs to the object gets labeled and pose recovery, where the 2D image data gets converted to the 3D object pose.

The results of the inertial sensors and the results of the image analysis have to be combined, because each sensor has an essential contribution for computing the complete pose. The camera tracking delivers the absolute 3D position, whereas the accelerometers provide information about the absolute pitch and roll angle because they determine the direction of gravity when the controller is not moved. The gravity can be subtracted from the accelerometer data when the orientation is known to determine the acceleration of the controller. The accelerometer data can in turn be used to reduce noise in the 3D position and to determine the 3D velocity. The data provided by the gyroscope can be used to determine the 3D rotation and further on to derive the angular velocity. The absolute yaw can be determined by comparing the motion direction computed by the camera-related image data to the one computed from the body-relative inertial data.

2.2.3.3 Microsoft Kinect

The Microsoft Kinect is an equipment for the XBOX 360 and enables using the body as a controller. The Microsoft Kinect can detect multiple bodies at the same time and can take their movements as inputs. The hardware of the Microsoft Kinect (see Figure 15c) contains a multi-array microphone to detect voices of the players, a color camera, a depth camera and a motorized tilt platform. The RGB camera can be used for facial recognition. It detects features of the user and the space by detecting RGB colors. The depth sensor consists of a CMOS (complementary metal-oxide semiconductor) sensor and an IR laser projector. The laser projector sends out a multitude of IR dots that the CMOS sensor can detect independent of the lighting conditions of the room. The software interprets these data and can reconstruct the depth information by using stereo triangulation. This is done in real-time with 30 fps. The CMOS sensor is an active pixel sensor that consists of a 2-dimensional array of pixel sensors whereas each of them has a photo detector and an active amplifier.

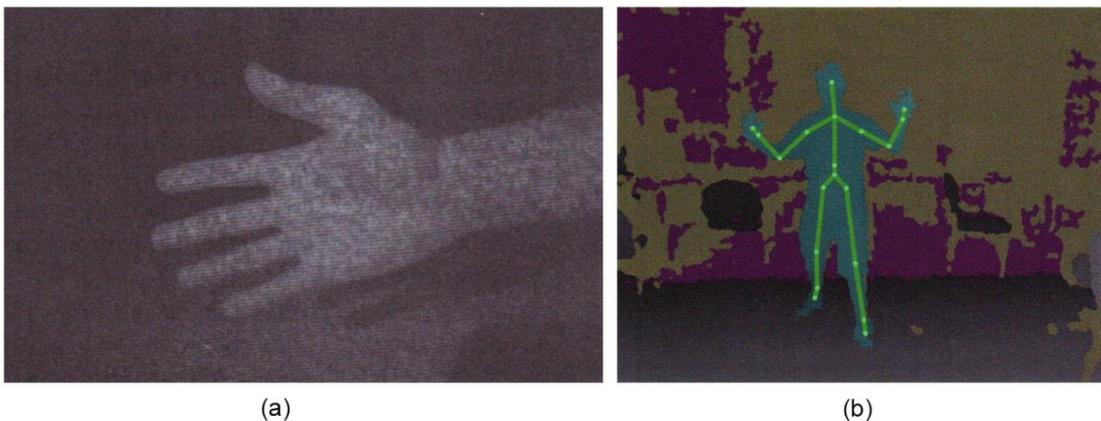


Figure 17: (a) structured light pattern, (b) skeleton representation of a user [42]

The depth information and the knowledge about the kinematics of the human body are used to track the skeleton of the user. When the user steps in front of the Kinect, the depth data is used to create a 3D shape. A point cloud of the user gets created and a starting guess about the player's skeleton is made. By using the kinematic data the Kinect can determine different parts of the body and thus find a skeleton that fits these body parts.

2.3 Head Mounted Displays

Virtual Reality simulates the real world and creates an experience in the 3-dimensional virtual space. To enable an interaction with the virtual environment this experience has to be displayed in a convenient way. Therefore screens in front of the user have to be used that provide the feeling of being in the virtual world [13].

HMDs are visual displays that are attached to the user's head. HMDs include optical, mechanical and electronic components. Some of them even include audio components to provide surround sound. Different HMDs have been developed over the years to place images in front of the user with one or two screens. HMDs use a combination of mirrors and/or refractive lenses to present the rendered images on the screens. Most HMDs are equipped with CRT (cathode ray tube) displays or LCDs (liquid crystal display). An alternative to these displays are head mounted projective displays (HMPD) that include small LCD projectors to project the rendered images into the real environment. Retro-reflective materials reflect back the light in the direction it came from. These materials are placed in the environment enabling the user to see the rendered image reflected off the material. This display method is used in mixed reality, because it provides correct occlusion cues for the real and virtual objects [50].

HMDs provide monoscopic and motion parallax depth cues. Stereoscopy can be provided by using two screens where two separate images are shown at two separate screens so that each eyes sees a different image. This enables full immersion, because the user always sees the virtual world without seeing the real environment. Therefore HMDs are the most important output device in virtual reality. In mixed or augmented reality on the other side it is desired to also see the real world. Therefore see-through displays or cameras that are mounted on the HMD are used to see the real world as well. Tracked HMDs provide a 360° field of range, but only provide small field of views (FOVs) of around 30 - 60° horizontal. This leads to perception problems. It reduces the user's ability to perceive correct spatial information and distorts the perception of distance and size. Another problem in the last decades was the fact that stereoscopic HMDS have been expensive because they needed multiple graphics engines. Stereoscopic HMDS have to regard the interocular distance, defined as the distance between the user's eyes, because this distance is different for every user. However, many HMDS do not provide the

possibility to adopt this distance. A further problem is that the images rendered at the screens are always in focus and have the same focal depth, which leads to convergence and accommodation cue conflicts when objects are placed at different depth. This leads to discomfort and eye strain. Omura et al [51] incorporated moveable relay lenses that continuously adjust to the user's gaze direction into a HMD to reduce this problem and thus provide accommodation and convergence cues [50].

An important design guideline for HMDs is their weightiness, because heavy HMDs can lead to strain in the neck muscles. Therefore small lightweight displays with low resolution provided by LCDs are preferred against higher-quality, but heavier CRTs. The shape is also a criterion, especially because each user has a different head shape and size and it is hard to find a shape that fits every user. HMDs also limit the selection of input devices, because the user cannot see what he is holding in his hands. Further it is important for the user to see his hands to be able to interact in virtual reality [50].

In the last view years new HMDs have been prototyped. The two most promising HMDs are the Oculus Rift and the Sony Morpheus. These devices will make VR available for the general public to an affordable price [13].



Figure 18: (a) Oculus Rift DK2, (b) Sony Project Morpheus [13]

Oculus Rift:

The Oculus Rift is a ski-masked shaped HMD. Most headsets suffer from motion sickness and dizziness. The Oculus Rift solved this problem. Currently two developer versions (DK1 and DK2) of the Oculus Rift were released [1].

The screen of the Oculus Rift displays two images, one for each eye, adjacent to each other. The combination of two lenses above the screen enables re-shaping of the rendered image for both eyes and thus creates a stereoscopic image. The Oculus Rift adjusts the image to the measured head motions of the user. The head movement is measured by an embedded sensor that includes a gyroscope, an accelerometer and a magnetometer. This enables the player to look around like in the real world. The

included sensors provide sampling rates up to 1000 Hz. This sampling rate is equal to a lag time of 2ms from detecting the head movement to receiving the data at the game engine. The Oculus Rift determines the head movement by combining the data of the accelerometer, gyroscope and magnetometer by sensor fusion. Afterwards the sensor data get translated from head movement to camera movement. By producing a translation at the user's eyes to create a motion parallax, depth perception and the uncomfortable feeling usually associated with VR during head rotation are solved. [13]

Figure 19 shows an inside few of the Oculus Rift. The Rift is equipped with three lenses. One for normal eyes and two suited for users that have problems with near sightedness. However these lenses only correct minor vision complications, but the Oculus Rift can be used with non-huge glasses [1].

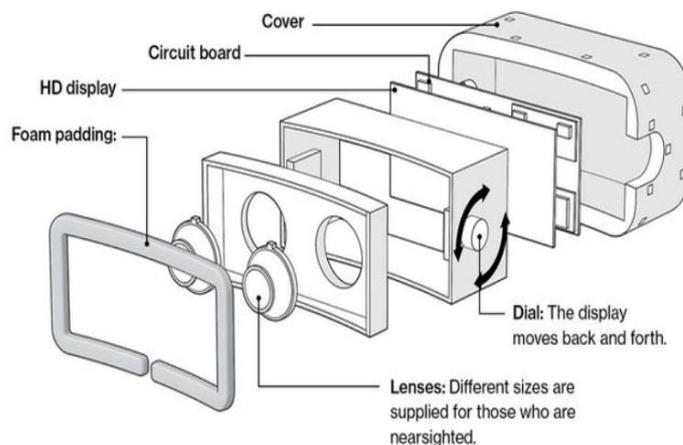


Figure 19: Inside view of the Oculus Rift [1]

The latest version, the DK2 (see Figure 18a), is equipped with an external 6 DOF positional-tracking device that tracks the head motion more accurately. For this the Oculus Rift is equipped with an array of IR micro-LEDs underneath the IR translucent outer casing that is tracked by an included IR camera mounted on the PC / laptop. Positional tracking reduces dizziness and offers new possibilities in VR games, like moving out of projectiles' way or looking around the corner with a subtle shift of the body. Only updated frames coming from the GPU are displayed to the user [13].

The display resolution of the DK2 is 960x1080 per eye. The DK1 used a LCD display, whereas the DK2 uses a low-persistence OLED display to reduce smearing and ghosting, which is the effect of faded trains behind moving object due to a slow pixel switching time that results in a blurring of the scene [1]. The OLED display eliminates judder and motion blur, which can cause cybersickness. As a result the scene looks visual stable. Although the DK2 has a full HD display, the so called screen door effect is still a problem. The screen door effect is a distracting phenomenon where file lines between individual

pixels become visible due to the fact that the projective optics have a higher pixel density than the projected image. It gives the user the impression that he watches pixels through a mesh. This is caused by the empty space between pixels known as the pixel fill factor (see Figure 20). Most displays using real pixels have an amount of space between the pixels. In an LCD display for example each pixel contains of 3 sub-colored pixels (RGB) that are lit with different intensities to create a colored pixel. A higher pixel pitch, which indicates the distance between sub-pixels, leads to a higher pixel fill factor.

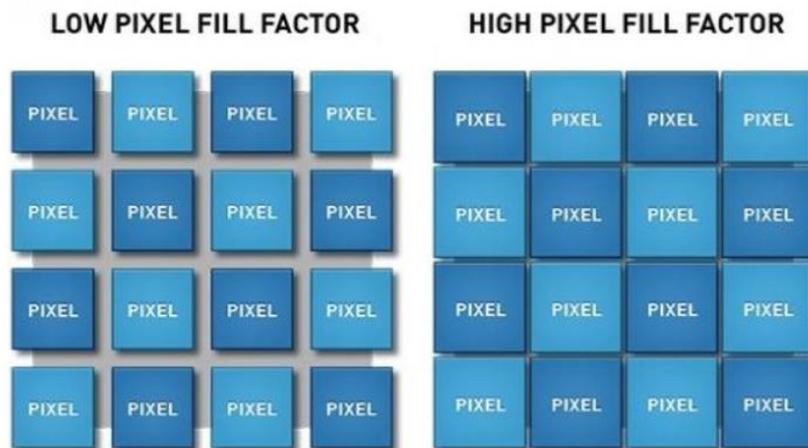


Figure 20: Pixel Fill Factor [1]

The goal for the consumer version is to reach a lower latency of under the sub-20ms range and to reach greater resolutions. The overall latency is defined as the time between the user's head movement to the image displayed on the screen. The DK2 has a lower latency head tracking than any other competitors. Further it offers a wide horizontal FOV of 90°, has a weight of 440g and offers a refresh rate of 75Hz.

Sony Project Morpheus

In comparison to the Oculus Rift, where developer versions were sold and so the specifications are known, only a few things about the Sony Project Morpheus are known, because there are no developer versions available. The Project Morpheus is an HMD using a LCD display and will work exclusively with PlayStation 4, so the Oculus DK2 has the higher compatibility in terms of software libraries, because it is compatible with most popular VR games. Project Morpheus uses the PlayStation camera for tracking and the PlayStation Move for motion control. Currently the Project Morpheus comes with a 5m cable, but it is planned to be released wirelessly. The DK2 in comparison is planned to be wired in the consumer version. Project Morpheus provides the user with 3D sound that changes with the head orientation in real-time. The Project Morpheus has a more attractive design than the DK2 as shown in Figure 18b, but the Oculus is easier to use because it just has an elastic band, whereas the Project Morpheus requires a two-step

process to get it on the head and then the depth of the display has to be adjusted. Project Morpheus has less screen-door effect as the DK 2, but the image persistence is better in the DK2. The DK2 is uncomfortable to use for people with glasses whereas the Project Morpheus is more ergonomically and easy to adjust.

2.4 Cybersickness

Cybersickness describes symptoms that occur during or after immersion in a virtual environment. These symptoms are similar to that described when experiencing motion sickness. The user in a virtual environment is often stationary, but experiences a moving visual imagery that causes a sense of self motion [2]. This leads to a conflict between the visual, vestibular and proprioceptive sensory systems [52]. Experienced symptoms can be headache, eye strain, sweating, pallor, disorientation, fullness of stomach, dryness of mouth, ataxia, vertigo, vomiting and nausea. The main difference to motion sickness is that motion sickness can be caused by a vestibular stimulus alone, but vision also can be a contributing factor, whereas cybersickness occurs without vestibular stimulation and only by visual stimulation. Cybersickness is a normal physiological response to an unusual or non-habitual stimulus. At least 60% of the users that experience VR for the first time get cybersickness symptoms.

The dangerous problem about cybersickness is after-effects that can develop hours after a VR experience. They can last hours or even days. Therefore VR entertainment centers tell their customers that they should not drive in the next 30-45 minutes after a VR experience. When users are exposed to a more intense VR experience like flight simulators these after-effects are even more dangerous. Therefore the air force for example prohibits pilots to fly within the next 12-24 hours after such a simulation. Cybersickness decreases the usage of VR, because people do not want to get sick and in case of professional flight simulators, where pilots should be trained, some users adopt behaviors to avoid various symptoms, which can affect the flying of the real vehicle.

The exact cause for cybersickness is unknown, but there exist three theories that try to explain it. To understand these theories first some physiological basics and the sensory systems have to be explained.

2.4.1 Sensory Systems

There are two main components relating to self-motion: The visual perception and the vestibular system [2] [52]. Further the proprioceptive system plays a major role in regard to cybersickness.

Vestibular System

The vestibular system can be seen in Figure 21. It provides information about the orientation and the movement of the head in 3D space. It consists of the saccule, the utricle and the non-acoustic portion of the inner ear that consists of three semicircular canals. The utricle and saccule detect the linear acceleration whereas the non-acoustic portion of the inner ear detects the angular acceleration of the head. Each semicircular canal detects one dimension of motion. For this it is filled with endolymph, which is a fluid that flows through the canal when the head experiences angular velocity. The fluid deflects small hair-like cells named cupula and sends signals to the brain. Figure 22 shows the cross-section of a semicircular canal.

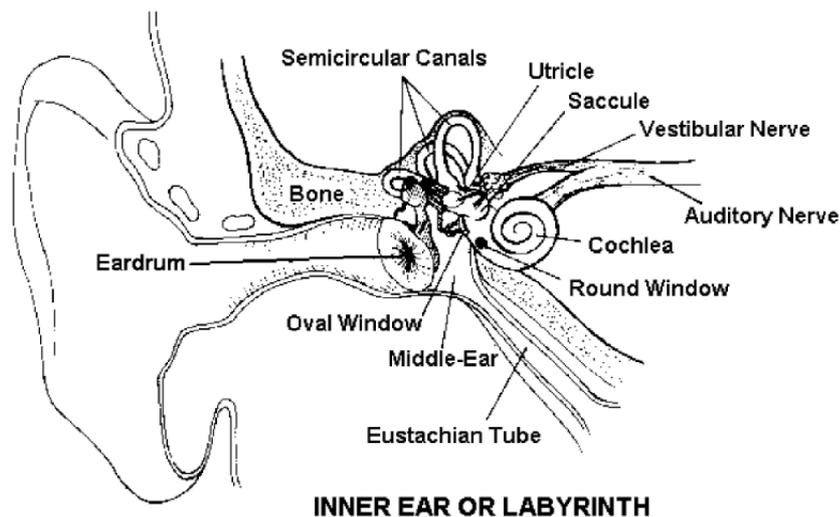


Figure 21: Components of the vestibular system [2]

The human body consists of two vestibular components that are mirrored. It is important that both agree with each other. Under normal operation one side of the head should be pulled when the other side pushes. Otherwise vertigo will occur. The utricle and saccule contain a sheet of hair-like cells, named mocola. The mocola contains cilia that are embedded in a gelatinous mass, which contains otolith that are clumps of small crystals, which provide inertia that is required to drag hair cells from one side to another to percept motion. At a constant speed the otoliths stabilize and no motion is perceived. The hair cells of the saccule and utricle are polarized. They are arrayed in different direction. Each mocola provides two directions of motion. The saccule is oriented vertically and detects forward, backwards, up and down movement. The utricle is located horizontally in the ear and detects motion on a horizontal place. The saccule and utricle detect vertical orientation with respect to gravity.

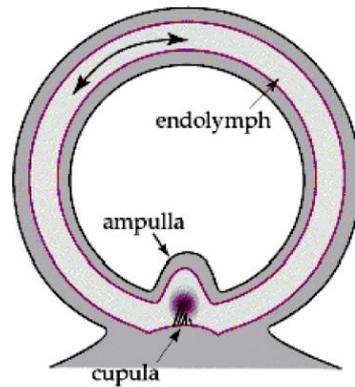


Figure 22: Cross section of a semicircular canal [2]

Stimulation of the vestibular system in VR influences a variety of behaviors:

- Gaze Stabilization: The eyes have to stabilize in relation to the viewed object to maintain a proper vision. This requires the positional information of the head in relation to the environment provided by the vestibular system. When the head is moving while being in VR a time delay can occur between the displacements that are perceived by the vestibular system and the visual information transmitted by the PC. This delay can cause nausea and disorientation.
- Balance and Control: The vestibular system influences control, balance and posture. Other sensory systems like vision, touch or hearing also influence balance and posture. In a VR experience the vestibular system and other sensory systems can be stimulated. When the interaction between these systems does not perfectly agree cybersickness symptoms can occur.
- Hand-eye coordination: People have the tendency to point to objects that are out of their reach. The sense of vision verifies this pointing behavior. Changes occurring in the vestibular and other sensory systems and the interaction between them influence the precision of this guided vision. Changes in the vestibular adoption produce an error and thus can lead to cybersickness symptoms.
- Other influences: The vestibular system can influence other autonomous functions and thus can create diverse physiological sensations. Problems in the vestibular system can lead to panic disorders.

[52]

Visual System

Humans have a stereoscopic vision, which allows evaluating distances and situating objects in space when they are near to the observer. Stereoscopic vision requires coordination of the eyes and a convergence of the eyes onto the observed object.

Under certain conditions someone can get the impression of self-motion while being in a stationary position. This impression of self-motion is known asvection. In real life someone can get this feeling for example when he is sitting in a stationary vehicle when another vehicle begins to move. Wide FOV displays of optical flow patterns can producevection. Optical flow can give the sense of self-motion. Normallyvection is accompanied by vestibular information, but in VR the vestibular information is not present, because the user is stationary. This leads to a sensory conflict based on the visual-vestibular relationship and thus can lead to cybersickness. The FOV is a major factor in terms ofvection. The larger the FOV the more retinal periphery gets stimulated. The optical flow is another important factor, because the faster the flow rate the higher the perceived motion speed is. Also the depth of objects in VR plays a major role. When thevection is limited in a virtual environment where the user is not moving, but only observing things he will percept lessvection than being in a flight simulation, because of less motion.

In VR ocular problems can occur because the user wears an HMD and therefore the screen is close to the eyes. However these are temporary effects that can be limited when the player makes a break after every 20-30 minutes of playing. The delay between the image projected on the HMD and the movement of the user can also cause cybersickness because this delay affects the coordination of eyes. A conflict between the convergence and accommodation of the eyes can also lead to side effects. Efforts of the eyes to accommodate and converge can cause symptoms like nausea, headache and dizzy spells, especially when the user is moving and a delay between the movements occurs.

Proprioceptive System

The proprioceptive system is related to the human body's motor system. Internal signals that are related to the control of movements contribute to spatial and proprioceptive vigilance. The human's perception of control and movement depend mostly on the proprioceptive system. When a user gets set in a virtual environment he will make perceptual and motor errors until he has adapted to the new environment. This can take 30-60 seconds and can still continue after the virtual experience. When the user will return after the virtual immersion, he will continue making the same movements in the real world. This behavior is an after-effect of the virtual immersion. Such after effects can be proprioceptive errors, wrong estimation of external forces experienced by the user, derived executions of a limb or wrong sense of auditory or visual localization. When the

user is back in the real world, he has to undergo a kind of rehabilitation to get used to the real environment again.

2.4.2 Theories about the Cybersickness

There is no unified overall theory about the cause of cybersickness. Instead there are three theories about why and how cybersickness occurs [2] [52].

Sensory Conflict Theory

The sensory conflict theory is the oldest, but most accepted one. It is based on the conflict between the vestibular and visual system. The conflict occurs because the user expects a stimulus based on his experience that is not the same as the sensory information he gets. This can occur when the optical flow patterns tell the visual system of the user that he is moving, but the vestibular sense does not provide this sense of motion. In a normal case e.g. while physically driving in a car the perception is the same as the user expects, because both the vestibular and the visual system provide the same information. When the user does not get the expected perception, cybersickness can occur. Although the sensory conflict theory is the most accepted one, it cannot predict if cybersickness will occur and if so to which amount. The theory also does not explain why some people get sick and others not and there is no explanation why this cue conflict causes cybersickness.

Poison Theory

The poison theory explains cybersickness from an evolutionary standpoint. The ingestion of poisoning causes physiological effects involving the coordination of vestibular, visual and other sensory inputs. The effects act as an early warning system to enhance the survival by removing poison of the stomach. The stimulation in VR can affect the vestibular and visual system in a way that the body thinks it ingested toxic substances and shows symptoms that lead to an emetic response. The poison theory also does not explain why some people get sick and others not and also it does not explain why not all people who get sick get an emetic response.

Postural Instability Theory

The postural instability theory is based on the goal of the humans' behavioral to maintain postural stability in an environment. Postural stability is the state in which uncontrolled movement of the action system and perception are minimized. This state is constrained by the environment, because walking on ice for example is different than walking on grass. If someone would walk on ice like he walks on grass he will fall down. The natural reaction is to change the walking pattern to maintain postural stability. When the environment changes abrupt, the individual loose postural control due to lack of

experience. A control strategy will be learned to gain postural stability. According to the postural instability theory, cybersickness and motion sickness are caused by postural instability. The severity of cybersickness symptoms depend on the duration of instability. There are environmental situations that can cause long periods of postural instabilities, which can be classified in four categories: weightlessness, low-frequency vibration, changing specificity and changing relationships between surface of support and the gravitoinertial force vector. Cybersickness can be categorized in the field of altered specificity. In VR postural control strategies will not work due to optically specified rotations and accelerations unrelated to constraints on controlling the body. The postural instability theory was developed to refute the sensory conflict theory, but the theories parallel each other.

Each of the theories cannot be proven valid, because none of them can predict if and to which amount someone gets sick. Cybersickness needs a unified theory that can determine the cause of cybersickness and also has predictive power. Then perhaps cybersickness could be eliminated completely.

2.4.3 Contributing Factors

Aside from the three theories there are other factors that contribute to cybersickness. These factors are associated with the used technology, the individual and the task characteristics [2] [52]. However with current equipment there are no longer significant problems in the field of technology.

Display and Technology

Imperfections in technology, especially in displays, can lead to cybersickness. Because of the fact that technology improves with time these imperfections are almost gone. The major imperfections are position tracking errors, lag and flicker.

- Position Tracking Error: In VR an accurate representation of the user's head and limbs is important. Therefore they have to be tracked. Head tracking is important to give the user the correct perspective. If the position tracking is too inaccurate cybersickness can occur. Slightly unstable information can cause jitter and as a result cybersickness if the information is used to update the user's view. Symptoms like dizziness or lack of concentration can occur.
- Resolution: A low resolution of the screen can lead to eye fatigue.
- Lag: Lag is the time between the user initiating an action and the action occurring in the virtual environment. When the user moves his head and the display doesn't get updated instantly, objects might be not where they are expected to be. This can lead to cybersickness and a conflict between the visual and vestibular system.

- Flicker: Flicker can cause eye fatigue, which can cause cybersickness symptoms. Because of the fact that the periphery is more sensitive to flicker than the fovea, a higher FOV increases the tendency to perceive flicker. For the fovea an update rate of 30 Hz is enough, but for the periphery the refresh rate has to be much higher to not perceive flicker. The display refresh rate got higher in the last years and as a result flicker got reduced.
- Weight of HMDs: Heavy HMDs increase physical symptoms.
- Visual Stress: Stereoscopic screens can lead to visual stress. This can happen when minimal changes in the position of the HMD on the head occur, because this impacts the convergence of the eyes. Therefore stability of the HMD on the user's head is important.

Individual Factors

Because of the human complexity there are only a few individual factors identified that influence cybersickness.

- Gender: Women get more often cybersick than men, because they have a wider FOV, which results in a higher chance to perceive flicker.
- Age: The susceptibility of cybersickness is highest at an age between 2-12 years and decreases rapidly between 12-21 years. Afterwards it decreases slower and around an age of 50 years cybersickness is almost nonexistent.
- Illness: Illness increases the susceptibility to cybersickness.
- Position in the simulator: The position in the VR can play a role. People are often sitting or standing while perceiving a VR experience. Sitting is the better position according to the postural instability theory, because it reduces the demand on postural control. The susceptibility is also increased when the player is in the role of an observer instead of controlling the simulation.
- Prior Experience with VR: Appearance of cybersickness reduces with experience.
- Perception: Individual factors related to perception are degree of concentration or ability to effectuate mental rotations.

Task Characteristics

- Control of Movement: The control of movement in the VR reduces the likelihood to experience cybersickness symptoms.
- Characteristics of the visual image: Characteristics like content of scene, quality of field of vision and others can reduce cybersickness symptoms.
- Interaction with the task: Sessions shorter than 10 minutes or longer than 40 minutes can lead to nausea.

2.4.4 Reducing Cybersickness

Different approaches were suggested to reduce cybersickness, which are summarized in [2].

Motion Platforms

As mentioned above the sensory conflict theory says that people get sick when there is a conflict between the vestibular and visual system. So one approach for reducing cybersickness was to use a motion platform so that the user gets both vestibular and visual stimulation, but the users still got sick. It is not clear if the platform was not aligned correctly and thus there was still a conflict or if it was aligned correctly and people became motion sick instead.

Direct Vestibular Stimulation

Another approach would be to use direct vestibular stimulation instead of a motion platform. The user wears a device that sends electrical signals to the 8th cranial nerve and as a result the vestibular system believes that angular or linear acceleration occurs. This approach could reduce cybersickness, but is just a theory that was never tried out. The major question is if such a device can be accurate enough, because otherwise it would lead again to cybersickness.

Rest Frames

Humans have a strong perception for stationary things. A rest frame is defined as a frame that a user takes to be stationary. The nervous system has access to multiple rest frames. Normally it selects one of them for spatial judgement, but sometimes it fails to select a single rest frame. Cybersickness can result from a difficulty to select a consistent rest frame, because the user gets conflicting information about what is stationary in the virtual environment. So the discrepancies that lead to conflicting rest frames have to be removed.

Adoption

The best way to reduce cybersickness is to slowly adapt the user to the virtual environment and increase the exposure time gradually. The tasks that require high rates of rotational or linear acceleration should be gradually included to the virtual environment. The problem with this approach is that it does not help to re-adopt the user to the real world again and thus after effects can still occur.

Control Factors

Precautions can be made to reduce the intensity of cybersickness:

- Explaining differences between cybersickness and anxiety symptoms. The simulation should be stopped if cybersickness symptoms occur.
- The duration of a VR experience should be between 20-30 minutes. Afterwards the user should wait at least 20 minutes before driving home.
- The user should be seated and have the possibility to hold on to something. By positioning the HMD so that the user sees partially his own body, cybersickness can be also reduced.
- Adjust tracker to client's sensitivity: When images are changing too fast or the lag is too big, the tracker should be adapted.
- People with medical problems should not participate in VR simulations.

This control factors can reduce the immersion but increase the degree of the user's security.

2.5 VR Games

VR gaming started to get popular in the early 90s, because location-based entertainment was booming and powerful PCs and consoles were developed [53] [54] [55].



Figure 23: Left: Virtuality arcade cabinets, Right: VR Pacman

In 1992 a line of VR-equipped arcade systems, including 3D visuals were developed by a company named Virtuality Group. This so-called Virtuality cabinets were oversized units where the player has to step in and put on virtual goggles. The arcade units offered several games like a VR version of Pac Man and Zone Hunter. The arcade units were the first mass-produced multiplayer VR entertainment systems. They used headsets and exoskeleton gloves and offered the first immersive VR experience. The systems were primarily used in the UK. More than 42 million plays occurred at the systems in more than 17 countries. The arcade systems mainly offered racing and shooter games. However only certain aspects of reality were simulated. In 1998 the Virtuality Group even developed a home model powered by Philips Electronics that was sold for \$299. However only around 55 000 pieces were sold.

In 1995 Nintendo developed a red-and-black based headset named Virtual Boy, which was sold for \$180. Several 3D games like Mario's Tennis, Red Alert and Teleroboxer were released for the headset. Most of the people felt queasy when using it. Because of this and because of the red-and-black color the HMD was no success.



Figure 24: Left: Virtual Boy, Right: Mario's Tennis

Virtual reality crashed in the mid-90s. The costs of equipment stopped the hype and the VR bubble burst in the late 90s. The cheapest price for HMDs at this time was around \$15 000. A reasonable powered graphics system was available for around \$50 000. Therefore developing games on a consumer level was not possible and VR technology was only available to governments and labs. The technology got better in the following years but the price remained the same.

In the 2000s NVIDIA and ATI started developing consumer-class video cards. Modern gaming enables a new level for virtual reality due to the development of technologies like the Microsoft Kinect, the Wii Mote and the PlayStation Move, which track and send motion data to the video consoles.

A new hype for virtual reality started when Oculus VR announced the Oculus Rift, which is a HMD that is designed for games. Games like Doom 3, Hawken and Mirror's Edge were adopted for the Oculus Rift. Further technologies like the Virtuix Omni, the Virtualizer, the PrioVR, the ControlVR and the Perception Neuron offer new possibilities for VR

games. A full VR kit, which consists of five motion tracking points, a HMD and a treadmill is available now for around \$1100 and thus is affordable for the general public.

Due to the fact that the development kit of the Oculus is available for developers, a multitude of VR games were developed since its release. There are different platforms like <https://share.oculus.com/>, <http://www.theriftarcade.com/oculus-rift-games/> and <http://www.riftenabled.com/admin/apps/> where you can release and download different games.

Until now there exists only one game that combines the PrioVR, the Virtualizer and the Oculus Rift. It is named Technolust [56] and is still in development. In the next chapters the implementation and design of an adventure game using these three technologies is described.

3 Game Design

3.1 Game Description

The developed game is a first person adventure game. The user plays an Egyptian warrior who got evidence that the treasure of a pharaoh is hidden in an underground temple system. When the game starts the user finds himself in this temple. He has to solve puzzles, collect pieces of papyrus and fight against different enemies to find the treasure. The temple consists of multiple rooms and corridors. Solving puzzles by interacting with different game elements and collecting different items, takes place in the rooms. Enemies occur in both the corridors and the rooms. Because of the fact that the core game elements take place in the rooms, it is possible to port the game to Flexible Spaces by generating the corridors on-the-fly, when the user enters or leaves one of the rooms. Therefore the corridors consist of different pieces that can be put together dynamically.

The game was developed in Unity3D and the player is provided with the Oculus Rift, the PrioVR and a Dolby Surround headset. Two Wii Nunchuck controllers are attached to the PrioVR to give the user the possibility to navigate through the inventory and to calibrate the system.

3.2 Controls and Enemies

The game is controlled with the Virtualizer, the PrioVR and the attached Nunchucks. The user can kill enemies like mummies, snakes and bats and can destroy vases by hitting them with his sword. This is done by swinging the right arm. The user can kill scorpions and open treasure chests by kicking them with his feet. A player fighting against different enemies can be seen in Figure 25.

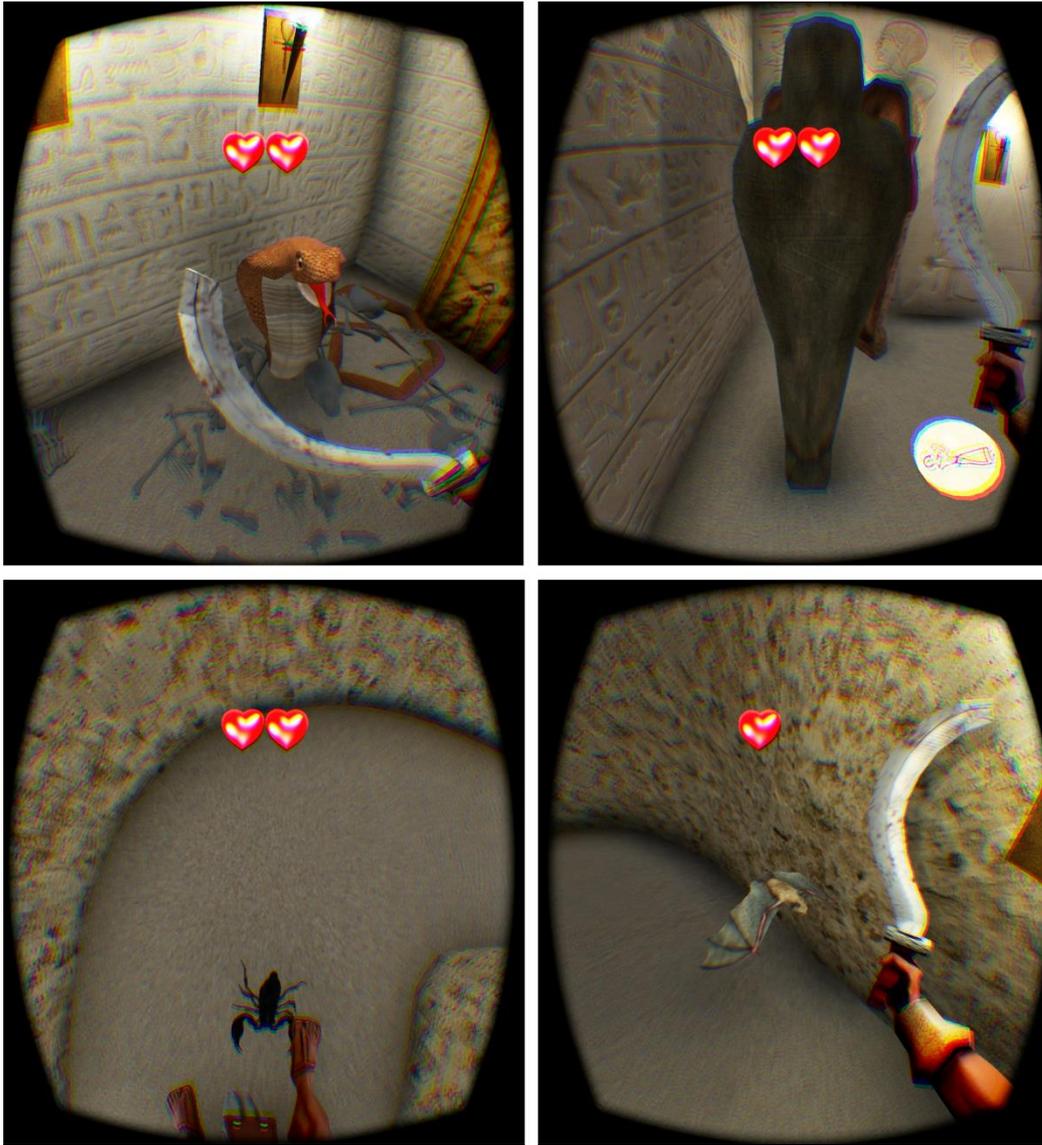


Figure 25: Screenshots of the game: The player has to fight against different enemies

The user can collect items or push stone bricks into the wall by touching them with his left hand. The player's walking speed is measured by the Virtualizer.



Figure 26: Control scheme of the Nunchucks

Figure 26 shows the control scheme of the Nunchucks. With the c-Button of the left Nunchuck the user can re-calibrate the character whenever he notices that the position of the body or limbs are not where he expects them to be. During the re-calibration process the player has to stand in T-pose. With the Z-Button of the right controller the user can open or close the inventory and with the analog stick he can navigate through it. The c-Button of the right controller toggles the visibility of the HUD. A screenshot of the inventory can be seen in Figure 27.

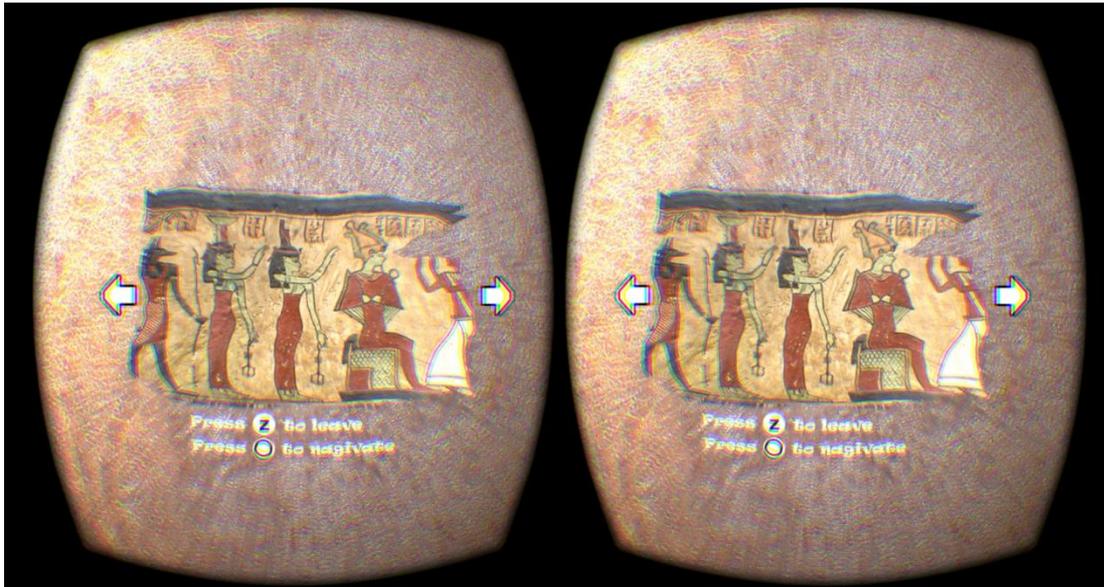


Figure 27: Screenshot of the inventory

3.3 Tasks

This section describes different tasks that the user has to overcome. Each task is created to determine how comfortable the user is when performing different interactions and how difficult it is for him to perform these interactions. As already mentioned the tasks take place in the rooms. Therefore the most important rooms are described in the following:

Room 0

At the beginning of the game the user finds himself in an Egyptian temple. A start screen welcomes the player and tells him to stand in T-pose for calibration of the PrioVR. As soon as the suit is calibrated the game guides him to the table to pick up a piece of papyrus. When he grabs it the user is encouraged to open the inventory where he can see the collected paper. After closing the inventory the user has to destroy vases with his sword and kick open a treasure chest. Then a red line appears on which the user has to walk on. When the user walks on the line it disappears and the stones that blocked the exit door fall down so that the user can pass. In this room the user should learn how to

interact in the game. Walking on the line is one of the major tasks during the user tests, because it gives information about how difficult it is for the player to navigate in the game. Figure 28 shows a screenshot of this task.

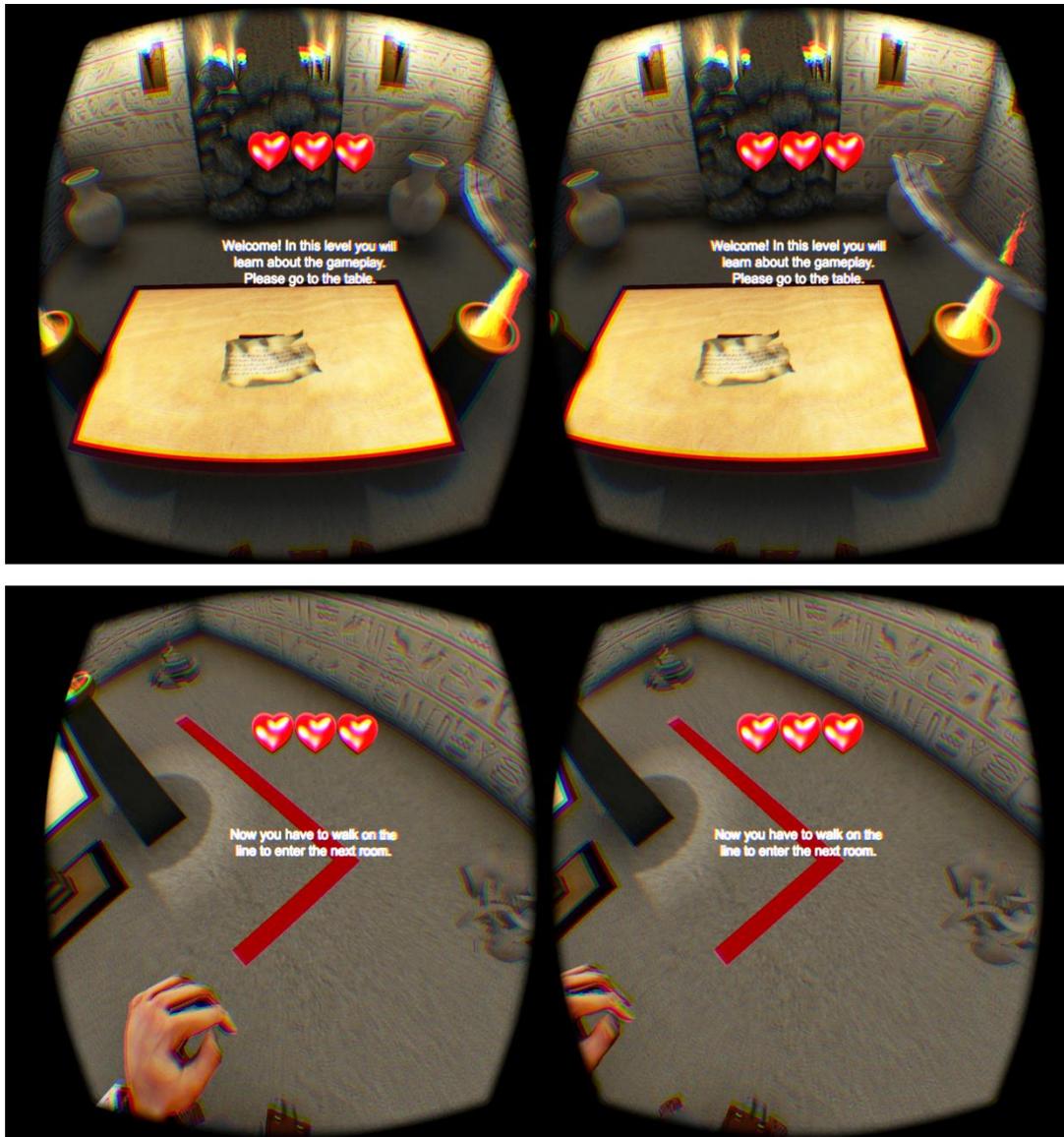


Figure 28: Screenshots of room 0. In the bottom image we can see the red line the player has to walk on. In the top image we can see a screenshot of room 0

Room 2

In this room platforms are placed on the floor. The user has to activate them in the right order according to the paper he found in the previous room. When the task gets performed correctly, two sarcophagi open and mummies step out of them. When the user kills them the exit door breaks open and the user is able to leave the room. In this room two interesting tasks are implemented. The activation of the platforms should give information about how well the player can navigate with the Virtualizer as well as with

the PrioVR, because he has to activate them with his feet without touching any other platforms. The mummies were implemented to find out if the player feels uncomfortable when enemies approach him very fast and close. The following figure shows screenshots of this room.

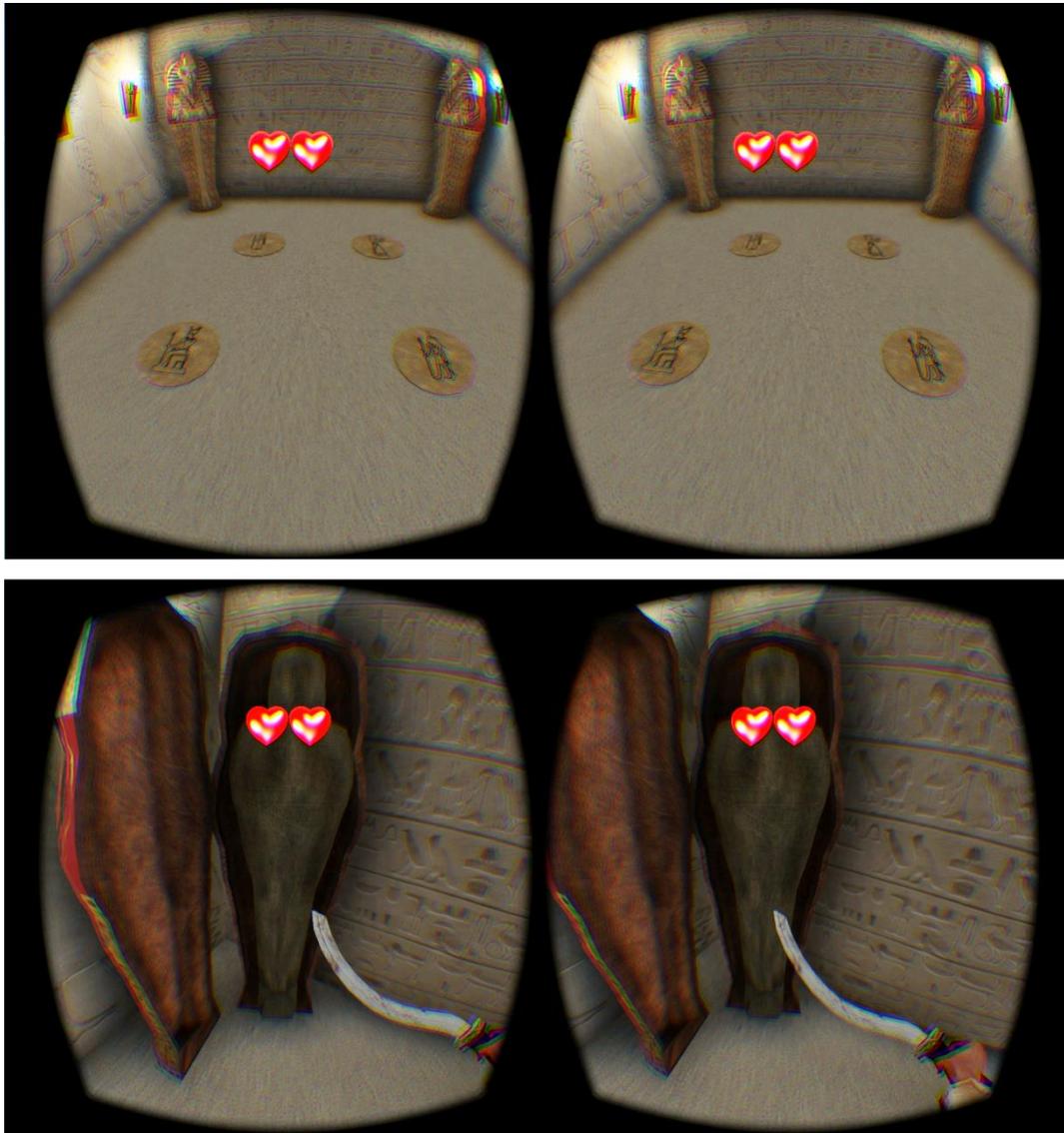


Figure 29: Screenshots of room 2. Top: The user has to activate the platforms in the right order; Bottom: Mummies attacking the player

Room 5

The player finds himself in a room with treasure chests. When he kicks them open he finds a piece of papyrus in one of them. He has to collect it to be able to solve the puzzle in the next room. Collecting the piece of papyrus in the treasure box is another important task for the user tests, because the user has to lower his upper body and depending on his size he has to bend his knees to reach it. It should give information about how difficult it is to perform such movement. Figure 30 shows the task and the player performing it.

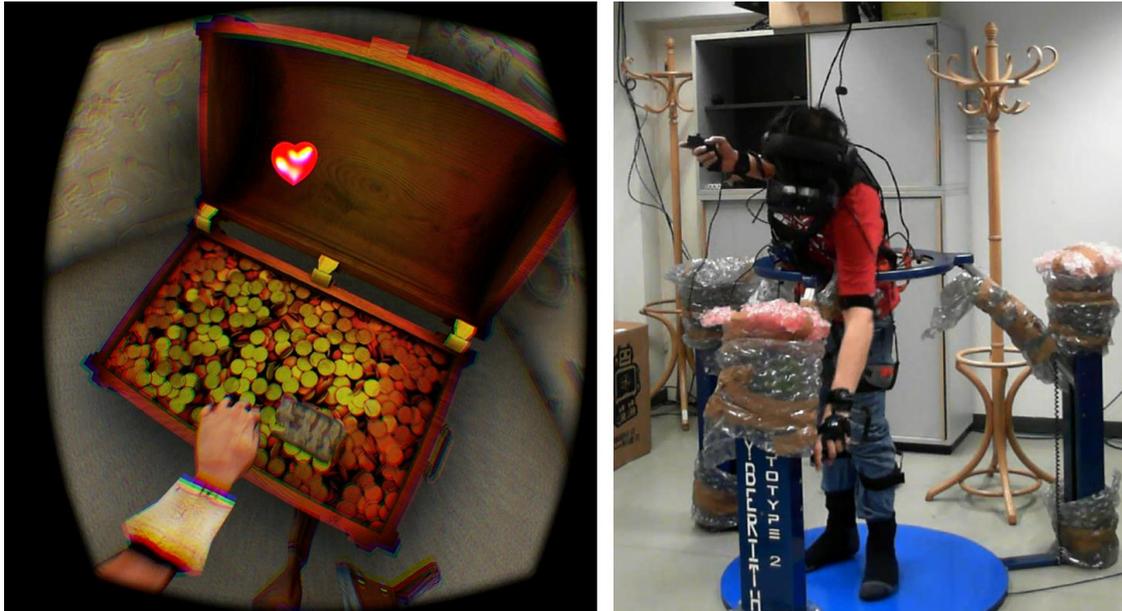


Figure 30: The player has to collect a piece of papyrus in a treasure box; Left: Screenshot from the game; Right: Player during the interaction

Room 7

In this room the user has to push stone bricks into the wall in the right order according to the paper he found in the previous room. When the bricks are activated in the right order the player can pass through the door and is led to the treasure. Moving the bricks is another major task because it gives information about how difficult it is for the user to reach certain things with his arms.



Figure 31: The player has to slide stone bricks into the walls. Left: Screenshot of the game; Right: Player performing the task

4 Implementation

The game was developed on a Schenker XMG P724 PRO Gaming Notebook equipped with a 3.10 – 4 GHz Intel Core i7-4940MX CPU, 16 GB RAM and two NVIDIA GeForce GTX 880M GPUs. The game engine Unity3D was used for rendering and handling the game mechanics. For game content creation Autodesk Maya and Adobe Photoshop were used. Some of the models were self-created with these tools and some were bought from www.turbosquid.com. The sound used in the game was downloaded from www.freesound.org.

Before programming the game, the used hardware had to be integrated. For controlling the avatar, the Virtualizer and the PrioVR were used. The Oculus Rift and a Dolby Surround headset were used as output devices. The Oculus Rift was also used as input device, because it gives us information about the rotation of the user’s head. The following sections describe how the used hardware was integrated into Unity3D.

4.1 Hardware Integration

This section describes the integration of the hardware components into Unity3d. The following image gives an overview of the hardware components that had to be integrated and the scripts that are delivered with the respective hardware component. Please notice that for the Oculus Rift only the scripts relevant for this game are mentioned. There are more scripts that are delivered with the Oculus Rift that are not relevant for this integration.

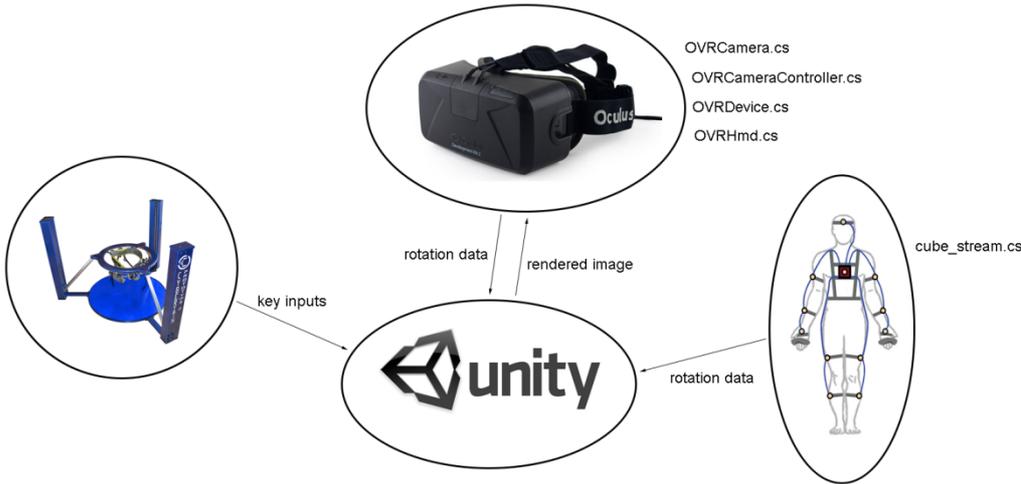


Figure 32: Hardware overview

4.1.1 Virtualizer

The prototype 2 of the Virtualizer was used for walking in the game. In this version of the Virtualizer no vertical movement is possible and it is not equipped with vibration units. The Virtualizer is attached to a notebook where a server application is running that converts the measurements from the optical sensors of the Virtualizer to keyboard inputs and sends them to the laptop where the game is running on. The laptop receives the keyboard inputs using a client application. To integrate the Virtualizer into the Unity game, only the keys WASD had to be included. Whenever a W key is received the character moves forward into the direction of the avatar's chest. Thus the head can be moved separately from the body. The A key moves the player leftwards, the S key moves the player rightwards and the D key moves the player backwards.

4.1.2 PrioVR

For integrating the PrioVR into Unity, a Unity demo is available. After installing the necessary drivers, the demo works if the PrioVR is assembled correctly, switched on and the base station is connected to the notebook. For integrating the PrioVR in the game a few modifications had to be made. First the script "cube_stream.cs" and the XML file "YEI_3Space.xml" had to be copied to the Unity project and the DLLs had to be copied to the Unity Editor folder. Due of the fact that the game uses another avatar than the demo project uses, attachments had to be made in the file "YEI_3Space.xml". The "YEI_3Space.xml" file is a file that defines which joint of the avatar is controlled by which sensor. So the file has to be adapted to every new avatar, because the joints of each avatar can be named differently. Further the file also defines which layout of the PrioVR is used. For controlling the game the core edition of the PrioVR was used, which is equipped with twelve sensors as described in section 2.2.2. After adapting the XML file, the "cube_stream.cs" script had to be adapted according to the avatar and the changes made in the XML file. The "cube_stream.cs" script was renamed to "cube_stream_warrior.cs". The script "cube_stream_warrior.cs" controls the avatar according to the sensor data. Further the calibration process was changed so that the player has to stand 3 seconds in T-pose before the suit gets calibrated. The calibration process has to take place before starting the game. It searches for the sensors and controllers and calibrates them assuming that the user is standing in T-pose.

The neck sensor of the PrioVR was not used because the head movement of the avatar is controlled by the Oculus Rift. For controlling an avatar with the PrioVR it is important that the rig of the avatar contains the necessary joints that are controlled by the suit. Figure 33 shows the used avatar with the attached rig. The joints that have to be included for controlling the avatar with the PrioVR are marked.

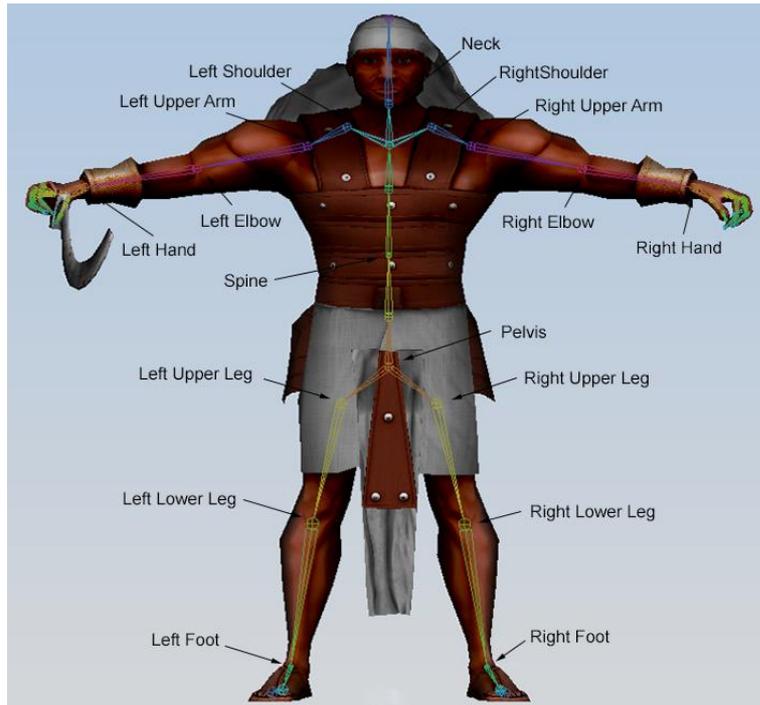


Figure 33: Joints that have to be included for controlling the avatar with the PrioVR

4.1.3 Oculus Rift

The DK2 of the Oculus Rift was used. For using the Oculus Rift in Unity3D an integration is already available and can be downloaded. To integrate it you have to import the package into Unity. When it is imported, an “OVRPlayerController” prefab and an “OVRCameraController” prefab can be seen in the OVR folder in the Asset folder of the Unity project. When you drop them into the scene and start the game, the Oculus Rift is already working and you can look around, if the DLLs are placed in the Unity Editor folder, the necessary drivers are installed and the Oculus Rift extends the main display. With the “OVRPlayerController” prefab you can also walk around. I used the “OVRCameraController” prefab and attached it to the avatar’s neck.

4.1.4 Calibration Process

As mentioned above, the PrioVR has to be calibrated. The calibration process was extended for combining the Oculus Rift with the PrioVR. The Oculus Rift delivers the global orientations of the user’s head. Thus it depends on the orientation of the Oculus Rift when it gets switched on in which direction the camera of the player’s avatar is oriented when the game is started. In the “OVRCameraController” script that is attached to the “MainCamera” the “FollowOrientation” parameter can be set to a game object to which the orientation of the Oculus should be set when being in the default orientation. Therefore the child object “ForwardDirection” was attached to the avatar game object. When the calibration process of the PrioVR is successful, the camera attached to the

avatar gets rotated to match with the orientation of the forward direction so that the camera has the same orientation as the default head orientation of the avatar. Thus during the calibration process first the avatar's joints are set to the default T-pose and then the camera is set to the default head orientation. The calibration of the PrioVR is done in the function `CalibrateSens()` of the script "cube_stream_warrior.cs". The camera is rotated to the default position in the function `SetOrientationOffset(...)` in the script "OVRCameraController.cs".

The whole setup can be seen in the right image of Figure 31.

4.2 Software / Game Integration

This section describes the most important scripts that control the game.

OVRMainMenu.cs

As can be seen in Figure 32, the Unity integration of the Oculus Rift includes this script. The script controls the GUI and HUD for the Oculus Rift. In this script some modifications had to be made in the function `Update()` and in the function `OnGUI()` and some functions were added to show the player's hearts, the inventory, the calibration screen, the win screen and instruction text.

Room2.cs

This script handles the game logic in room 2. The script contains two functions. `SetPlatform(...)` is called when the feet of the player collide with one of the platforms. The function checks if the platform is pressed in the right order. Depending on that it activates the pressed platform or deactivates all platforms. If all the platforms are activated in the right order, mummies attack the player. The `setMummyDead()` function is called when a mummy is killed. It lets the mummies disappear and breaks the wall open if all mummies are killed.

Room7.cs

This script handles the game logic in room 7. It contains the function `SetPlatform(...)`, which is called when the player touches the wall bricks with his left hand. It checks if the bricks were pushed into the wall in the right order and depending on that it slides the brick into the wall or resets all bricks.

CorridorBat.cs

This script contains the function `OnTriggerEnter(...)`, which is called when the player goes through a door and a bat should fly towards him through the corridor. A bat gets

instantiated and the waypoints set in the waypoints list get set in the script “CorridorBatFlying.cs”.

CorridorBatFlying.cs

This script controls the bats flying through the corridors. It consists of a list of waypoints that the bat should pass. When the bat gets instantiated at the opposite end of the corridor as the player is standing, the script gets activated and the bat flies from waypoint to waypoint till it reaches the end of the corridor where it gets destroyed.

CorridorScorpionWalking.cs

This script controls the scorpions walking through the corridors. It consists of a list of waypoints that the scorpions should pass. It works like the script “CorridorBatFlying.cs”, but for scorpions.

CorridorScorpion.cs

This script instantiates a scorpion when the player walks through a door. It works like the script “CorridorBat.cs”, but for scorpions.

LineHit.cs

The red line in room 0 contains multiple line parts. When the left or right foot of the player collides with one of the red line parts, the part gets destroyed. The script is attached to these line parts.

Mummy_Controls.cs

This script opens the sarcophagi in room 2 and controls the mummies so that they are always walking towards the player. If the player hits the mummy, it disappears.

Show_Gui.cs

This script handles the inputs of the controllers and controls the logic of the tutorial in room 0. It lets the rocks fall down, when the player has finished the tutorial. Further it handles the inventory and the player’s life.

Split_Vase.cs

In this script, the vases get split when the player hits them with his sword with a certain velocity.

5 User Tests

5.1 Study Design

The user tests took place in the VR lab of the Interactive Media Systems group at Vienna University of Technology. A time slot of 30 minutes was scheduled for every user. First the user had to take off his shoes and put on gymnastic slippers. He had to put on thick socks over the gymnastic slippers to lower the friction in the Virtualizer. Afterwards the user put on the PrioVR and stepped into the harness of the Virtualizer. He was informed about the controls, the gameplay and the calibration process. He was also informed about cybersickness symptoms and that he should stop when he starts feeling uncomfortable or sick. Then the player had to put on the Oculus Rift and a headset. When the player was ready he was instructed to stand in T-pose for calibration. He could also see the appropriate GUI screen for the calibration process (see Figure 34). The first calibration process had to be done from the notebook, because in the first calibration process the whole suit and the controllers get recognized. Afterwards he could re-calibrate himself whenever the whole body or parts of the body were not where he expected them to be. We can see the player standing in T-pose in Figure 34.



Figure 34: Calibration process; Left: When calibration starts, a counter starts; Middle: User standing in T-pose; Right: Screen when the calibration was successful

When the calibration process was successful the player could start with the game. First he was instructed to look around and check if his body is correctly calibrated. Then he started with the actual game. During the whole game, the user got instructions what to do and where to go. When the user reached the end of the game or when he stopped because he got sick or felt uncomfortable, he was asked to fill out a questionnaire. In total 40 users participated in the test, whereas 26 were men and 14 were women. 23 of them were between 25 and 29 years old, 4 of them were under 18, 4 were between 18 and 24, 7 were between 30 and 34, 2 were between 35 and 40 and 1 person was between 41 and 50.

5.2 Questionnaire

A questionnaire was designed to evaluate if people get cybersick, how good and intuitive interaction with the PrioVR and Virtualizer feels and how the graphics in the Oculus Rift looks like according to the users. Further, they were asked about user behavior and individual factors that can influence cybersickness. The questionnaire was created with Google Forms and thus was an online questionnaire that the users had to fill out on a laptop. It was classified in different categories:

- **General Questions:** The first questions have been general questions about the age and sex of the user and if he wears glasses in daily life and during the game.
- **Gameplay:** The user was questioned about the gameplay, e.g. how realistic the game experience has been, how uncomfortable he was when enemies approached, how difficult it was for him to perform different tasks mentioned in section 3.3, how realistic the spatial proportions are and how comfortable he felt in his virtual body.
- **Side Effects:** The user was asked about different cybersickness symptoms. The symptoms were taken from the Simulator Sickness Questionnaire described in [57].
- **User Behavior:** The user was asked about his user behavior, like how often he plays games and if the developed VR game was more realistic than the games he is usually playing.
- **Oculus Rift:** The user was asked questions about the Oculus Rift, e.g. if he has ever used it or another HMD and if he liked the graphics.
- **Virtualizer:** The user was asked if he ever used the Virtualizer before and if it was difficult for him to walk in it.
- **PrioVR:** The user was asked if he ever used the PrioVR or another MoCap suit before.

The whole questionnaire can be seen in the Appendix I

6 Results

6.1 Technical Issues

During the user tests problems with the Virtualizer and the PrioVR occurred. The accuracy of the PrioVR was not as good as promised. The drift was enormous. It was assumed that the drift occurs due to the metal ring of the Virtualizer, because as mentioned in section 2.2.2 the sensors of the PrioVR include magnetometers and thus can interfere with magnetic fields or objects made of metal. Therefore the user had to re-calibrate from time to time during the game. Another problem was the fact that cables often got disconnected during gameplay and had to be re-plugged. Also some sensors died during the user tests and had to be exchanged. It was sometimes hard to find the dead sensors, because when a sensor or cable dies the whole suit does not work. Although the first Beta version of the PrioVR was available, the Alpha version of the PrioVR was used because it turned out to be more stable.

The Virtualizer worked fine in the beginning of the tests, but on the second test day it started to work improperly. As described in section 2.2.2 the Virtualizer sends keyboard inputs to the laptop where the game is running on. While walking forward the Virtualizer started to send random inputs and as a result the character walked in the wrong direction or couldn't walk at all, because he was caught in one place. Therefore I changed the controls of the game so that every input coming from the Virtualizer moves the player forward no matter in which direction he is physically walking. Therefore the user could only walk forward and had to turn when he wanted to walk in another direction. However this was no big problem, because most of the users avoided walking backwards or sideways. The users that had troubles with the Virtualizer were excluded from the evaluation, which have been 15 people.

6.2 Design Guidelines

This section describes some of the design guidelines that should be considered when developing a VR game for the Oculus Rift described in [3] and how they have been considered within the game design process. It also describes my own findings. It is important to stick to the suggested guidelines because an improperly designed game can lead to an uncomfortable experience or cybersickness.

Stereoscopic Imaging and Depth Cues

Stereopsis is just one of the depth cues the human brain processes. Most of the other depth cues are monocular depth cues like lighting and shadows that provide us with information about the shape and position of objects. Therefore the developed game

includes a multitude of light sources implemented as torches and is rendered with shadows and SSAO (Screen Space Ambient Occlusion).

The optics of the DK2 is equivalent to looking at a screen that is around 1.3 meters away from the eyes. Therefore objects that the user is fixating for a longer period of time should be around 0.75 to 3.5 meters away from the user to avoid eye strain. Due to the fact that the player is located in rooms most of the time, he does hardly extend his focus above 3.5 meters, because every room is approximately about 5 meters long and the user focuses on objects that are next to him. Also the user does hardly focus on objects closer than 0.75 meters, except when enemies are approaching, but these are only short time events. Also the inventory is displayed 0.75 meters away from the user, which will be discussed later in this section.

In Unity3D the Oculus Rift is implemented with two virtual cameras. It is important that the render effects are applied to both of the cameras with correct disparity. Therefore the SSAO shader and the antialiasing shader were attached to both of the cameras. Ignoring this guideline can lead to the appearance of flickering or shimmering and as a result headaches and eyestrain.

Field of View

It is important that the FOV of the virtual cameras matches the visual display area, defined as the display FOV, because deviations between them can be discomforting and can lead to cybersickness and to a maladaptation in the vestibular-ocular reflex during and even after the virtual experience. Therefore the default FOV was used.

Rendering Techniques

The DK2 has a resolution of 1920 x 1080. This means that images appear clearer and sharper compared to the DK1. However fine texture details or thin objects should be avoided, because they have the tendency to get lost between the pixels and text should be rendered large and clear enough to be readable. Therefore the game does hardly contain detailed textures and a large font was chosen. However when users played the game it became obvious that the used text was not large enough, which should be improved in the future. Also small object were not used as game content, except for the papyrus pieces the player has to collect.

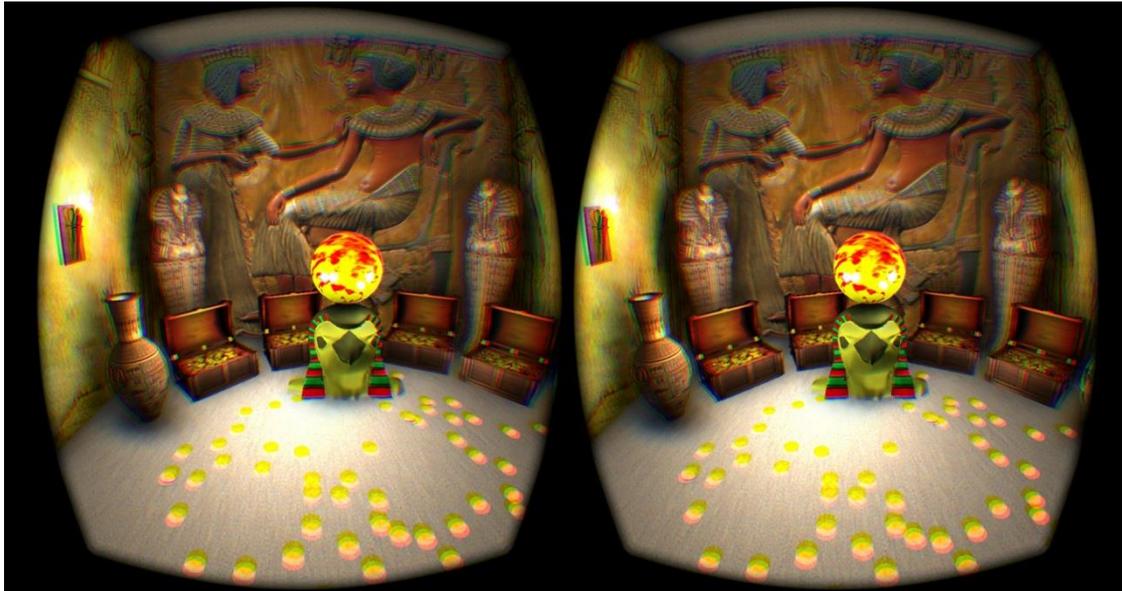


Figure 35: For the treasure room a brighter scenery was used

The DK2 gives more a honeycomb-shaped effect than a screen door effect and red colors tend to magnify this effect. Therefore almost no red colors were used, except of the red line on the floor. Bright screen images should also be avoided because they can produce display flicker. However this was not an issue in the game because the scenery was a dark temple system with torches on the walls. Only in the last room a brighter scenery was designed (see Figure 35). It is also important that the game runs at 75 fps, v-synced and unbuffered because the higher the refresh rate the less flicker is perceptible. This was also no problem, because the designed game fulfills this requirement.

Normal Mapping is a technique that provides realistic lighting cues to give the impression of depth and texture without having the vertex detail which would be needed to provide this impression. This technique is widely used in modern computer games, but looks flat when viewed with an HMD, because it does not account for binocular disparity (see Figure 36 Left). A technique known as Parallax Mapping should be used instead, but in the game normal mapping was used, because parallax mapping would have needed a height map in addition to the normal map and it would have been very time consuming and out of the scope of this work to create a height map for every surface where normal mapping was used, especially due to the fact that bought models came only with normal maps.

Motion

It is recommended to implement movement speeds that resemble real world human locomotion speeds. When the player is walking he should do this with a speed of approximately 1.4 m/s. The walking speed used in the game is 1.3 m/s, which I experienced as most comfortable during testing. This almost fits the natural human

locomotion speed. Normally the visual perception of acceleration can lead to discomfort because the human vestibular system responds to acceleration but not to constant speed, but with the use of the Virtualizer this can be neglected because the user gets vestibular and visual feedback instead of only visual feedback. Therefore self-acceleration is not a crucial factor as long as user and camera movements are never decoupled.

Additionally, movements should not be decoupled when the user is looking through walls or objects. Therefore the user can look through them when bending forward because it can lead to discomfort when the head would bump back. Also each body part can clip through objects at any time. To prevent the player from looking through walls or pillars, objects haven't been placed next to them and invisible colliders have been created a little bit in front of them, so that the user can bend a little bit forward before he reaches them. It is important that the distance from the invisible collider and the wall is small so that the user does not get the feeling that he is distant from it. Invisible colliders have only been included in front of objects that are equal or higher than the player's head, like walls or pillars, because they would intersect with it and the player could look through them.

It is important that the camera follows the head movement of the user at any time. Therefore it should be avoided to add a mild up-and-down movement to the camera to simulate the effects of walking like it is often done in normal first-person games. Although it was considered to implement it in the game, because of the leaning forward effect while walking in the Virtualizer, I haven't implemented it because of this guideline. The problem with the Virtualizer is that you bend forward while walking, which is against human locomotion nature, and thus it creates the feeling that the camera is jumping when you start or stop walking.

The unusual sensation of vertical acceleration, which occurs when walking up or downstairs can be discomforting for the user and thus should be avoided. Therefore the user walks on a flat surface and even when the stones are falling down in the first room, the colliders of the stones were disabled so that the user moves through the stones instead of over the stones and thus has no feeling of vertical acceleration. Also the need for backwards or sideways movements should be limited but should not be completely eliminated from the user's control scheme, because this can force the user to engage in relatively more motion. With the Virtualizer movement in any direction is possible and should not be a problem because the user gets both vestibular and visual movement. Unfortunately the Virtualizer stopped working correctly, described in section 6.1, and thus all movements instead of forward movement had to be eliminated.

User Interfaces

Traditional HUDs should not be used in Virtual Reality. An ideal solution would be to integrate the information of the HUD directly into the environment. The HUD occludes everything in the scene, which is not a problem in traditional games, but in VR when adding binocular disparity as depth cue, it can create a contradiction when a scene element comes closer to the player than the plane of the HUD. Although the HUD is perceived closer than the scene element according to the occlusion cue, it is perceived farther away according to the binocular disparity. This conflict can lead to discomfort when trying to fuse the images for the environment and the HUD. One possibility to solve this conflict is to move the HUD closer to the user, but this will most likely bring the HUD closer to the user than the recommended minimum distance of 75 cm. Therefore the information of the HUD should be included directly into the environment when you want to present the information in a clear and comfortable way that does not interfere with the image of the environment. The HUD of the developed game was integrated with the `OVRGUIObject` that is included in the Unity integration of the Oculus Rift. It is normally used for rendering reticles. A plane is rendered at a distance of 75 cm in front of the user. The plane is overlaid on the rendered environment so that it is always seen. Originally it was only rendered when it does not intersect with the environment but this function was deactivated. To prevent discomfort the user has the possibility to deactivate the HUD when he does not want to see it. The HUD consists only of hearts that represent the player's life and is rendered a little bit under the middle top of the screen, where it is still comfortable for the user to see it. Also the inventory and the calibration, as well as the start and win screen are rendered with this technique, but here the shader was changed for rendering the GUI plane so that the user can only see the rendered GUI plane and not the environment. The environment is paused when the GUI is opened.

User Input and Navigation

Traditional input devices are not ideal when playing a VR game. However, gamepads are a better solution than using a keyboard or a mouse, because the user cannot see his input device and therefore it should be intuitive. As described in section 4.3 Wiimote Nunchucks were used for navigating through the menu, re-calibrating and toggling the visibility of the HUD. The Nunchucks are supported by the PrioVR and they are intuitive to use.

It is important that changes to the user's location that are outside of the user's control like a jump in perspective or movement to another place, should be prevented because it can be disorienting. I didn't stick to that rule when it comes to calibration, because when calibrating the PrioVR the avatar gets rotated to a default rotation and then the camera gets rotated according to the forward direction of the avatar as described in section 4.

This leads to a short moment of disorientation, but the player doesn't see the camera moving because during calibration the calibration screen of the GUI is open.

Content Creation

The user can turn and look around anywhere at any time. Therefore it is important that this does not break immersion.

An avatar can give the user a stronger sense of immersion. It gives him a sense of scale and of his body's volume, but it is important that when the user is tracked that the avatar follows the input of the user with as less latency as possible. When there is no body tracking, and the avatar does something completely different than the user, like when the user is seated and the avatar's body is walking it can feel strange. Because of the fact that the PrioVR was not as accurate as promised the positions of the user's real limbs often differ to the positions of the avatar's limbs. Therefore the user had the option to recalibrate the system whenever the position of the avatar's body and limbs differ too much from the real positions.

In common first person games weapons and tools are rendered close to the camera. In VR the user would have to make large changes in eye convergence when changing the focus between weapons and the rest of the scene. Therefore the weapon should be part of the avatar. Because of the fact that a fully tracked avatar was used that holds a sword in one of his hands, this was no problem.

Due to the fact that the game is placed in an underground Egyptian temple system, there is no light from outside. Therefore multiple light sources were included. The fire is rendered as particles. Therefore billboards are used. Although it is recommended to not use billboards because they can look flat when viewed close or when they have sharp details like fire, no drawback was seen when using them. You have to go very close to the fire to see that quads are emerging from it and most of the light sources were placed at walls. The right image in Figure 36 shows the rendered particles for the fire.



Figure 36: Left: Example of Normal Mapping: As can be seen parts that are closer to the eyes appear flat; Right: Rendered particles

Another important factor when designing a VR game is designing audio, because sound is as important for an immersive VR game as vision. The player should hear sounds from his surroundings, because it delivers perceptual cues about the environment. Ideally a pair of headphones should be used and the audio output should follow the user's ears with any head movement. As described in section 4, headphones were used, but sound was sparsely integrated, because it is very hard to find realistic sound in the internet. However the sound that was used follows the user's ears at each moment. The player cannot hear his own footsteps, because when the Virtualizer is used as input device the player can see his own feet sliding over the floor and thus it would be strange if he would hear the sound of footsteps when he cannot actually see them.

Scale is an important factor in VR. The size of objects in relation to the own body should fit the real world scale, because the player is able to recognize when objects or his own body are set to a wrong scale. Ideally the avatar should be scaled to the real size of the user playing the game. However the real player height was neglected and the height of the avatar was set to 1.7 meters, but everything else had real world proportions compared to the avatar. However using the real player size would have been possible.

6.3 User Studies

As mentioned in 5.1, 40 users participated in the test, whereas 15 people were excluded from the user studies due to technical troubles with the Virtualizer. 18 out of the 25 remaining test participants were men and 7 were women. 15 of them were between 25 and 29 years old, 3 of them were between 18 and 24, 5 were between 30 and 34, 1 was

between 35 and 40 and 1 person was between 41 and 50. This section shows the results of the user studies in respect to gameplay, cybersickness and hardware.

6.3.1 Gameplay

In this section the results in respect to the gameplay are discussed. All questions regarding the gameplay were evaluated using the Likert scale with values between 1 and 7. As shown in Figure 37 the game experience was evaluated as rather realistic (4.86 ± 1.34). 11 out of 25 test participants evaluated this question with the value 5, which corresponds with the median of 5.

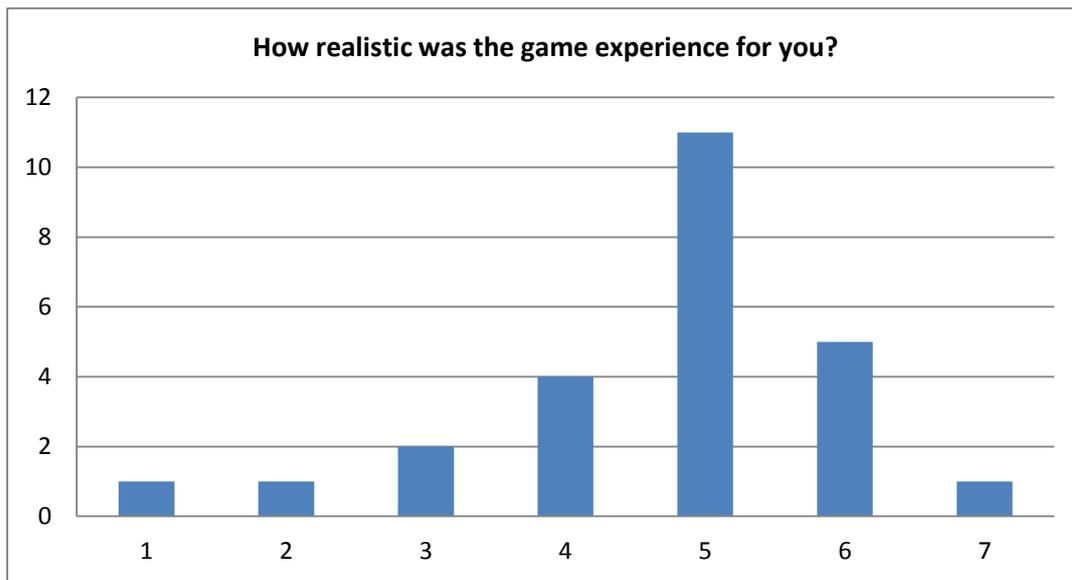


Figure 37: This figure shows how realistic the game experience has been for the users.

24 out of 25 test participants evaluated how uncomfortable it felt when enemies approached. One of the test participants got cybersick before meeting any enemies. The results of this question are not significant. Some participants felt rather comfortable and some felt rather uncomfortable (3.8333 ± 1.5511). As can be seen in Figure 38 the most given answer has been 5. The median value for this question is 4. No one has felt very uncomfortable.



Figure 38: This figure shows how uncomfortable the users have felt when enemies approached.

The difficulty of navigating in the virtual world has been evaluated from most of the test persons between 3 and 6 (4.36 ± 1.41). The value with the highest count is 5, which corresponds with the median of 5 (see Figure 39). Test persons claimed that they had difficulties to walk because sometimes walking was not detected and therefore was exhausting or that it was hard to choose the exact walking direction. They further claimed that walking in the Virtualizer was not precisely mapped to the VR environment. Sometimes walking was too slow and sometimes it was too fast. Further they gave the feedback that the body was often twisted which resulted in a wrong walking direction.

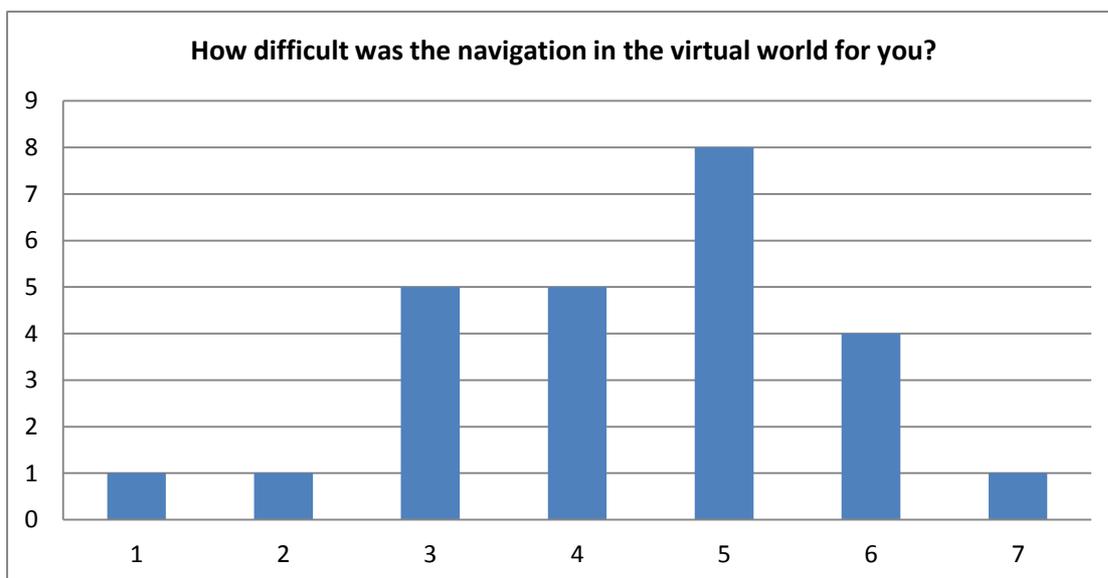


Figure 39: This figure shows how difficult the navigation in the virtual world was.

The question about how realistic the spatial proportions felt gave more significant results (3.72 ± 1.1). For 12 out of 25 people the spatial proportions have been right. For 9 users they were smaller than expected and for 4 people they were bigger than expected. However no one had the opinion that the proportions were far too small or far too big. The median value of 4 facilitates this result.

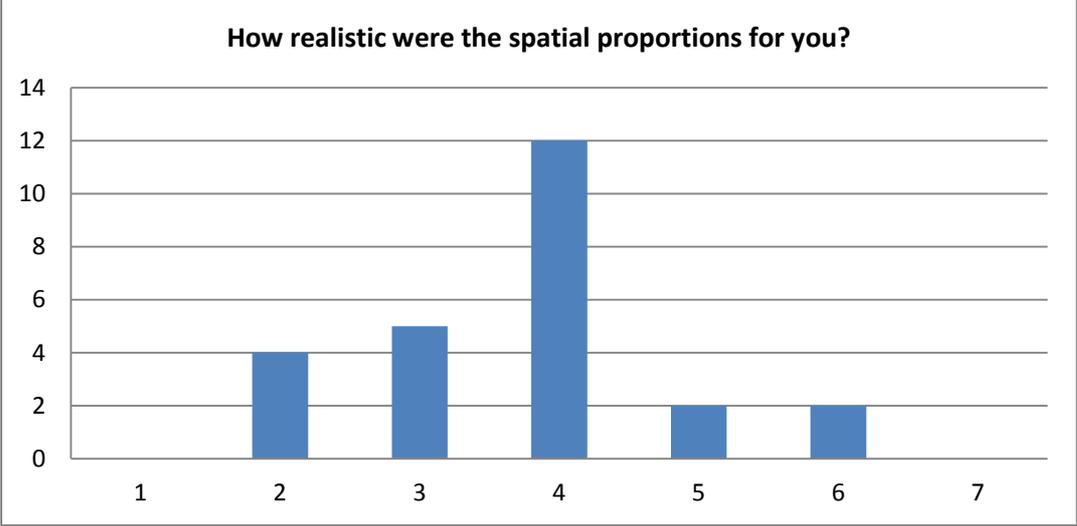


Figure 40: This figure shows how realistic the spatial proportions have been for the users.

Four questions have been asked to specific interaction tasks. Not all test participants could answer those questions, because some of them got cybersick during the game and had to quit. In total 17 out of 25 people reached the end of the game. The others had to quit earlier due to cybersickness symptoms. In the first room the users had to walk on a red line. The users were asked to evaluate how difficult it was for them to walk on this line. 24 out of 25 test participants performed this task. As can be seen in Figure 41 the results are not meaningful. For some of them it was rather easy to walk on the line and for some of them it was rather hard. The mean value is 2.958 with a standard deviation of 1.574. The median is 2.5. However no one claimed that it was very difficult to walk on the red line and everyone was able to manage this task in short time.

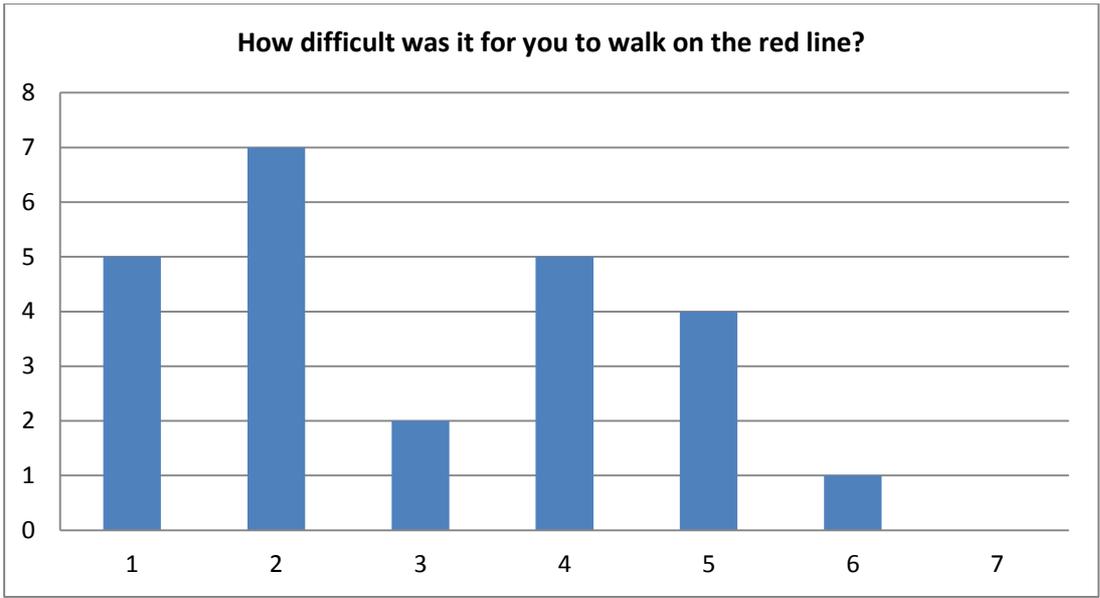


Figure 41: This figure shows how difficult it was for the users to walk on the red line in the first room.

24 test participants managed to continue to room 2. As described in section 3.3 they had to activate platforms on the floor. The users were asked to evaluate how difficult it was to activate the platforms. This question delivered no significant results (3.9167 ± 1.8863). Some people had troubles and some don't. 29.2% of the users answered this question with 2. The median value is 3.5. 12 test participants answered this question with a number under 4 and 11 users answered it with a number higher than 4. One participant evaluated the question with 4 (see Figure 42). The time the users needed to perform this task varies from a few seconds to a few minutes.

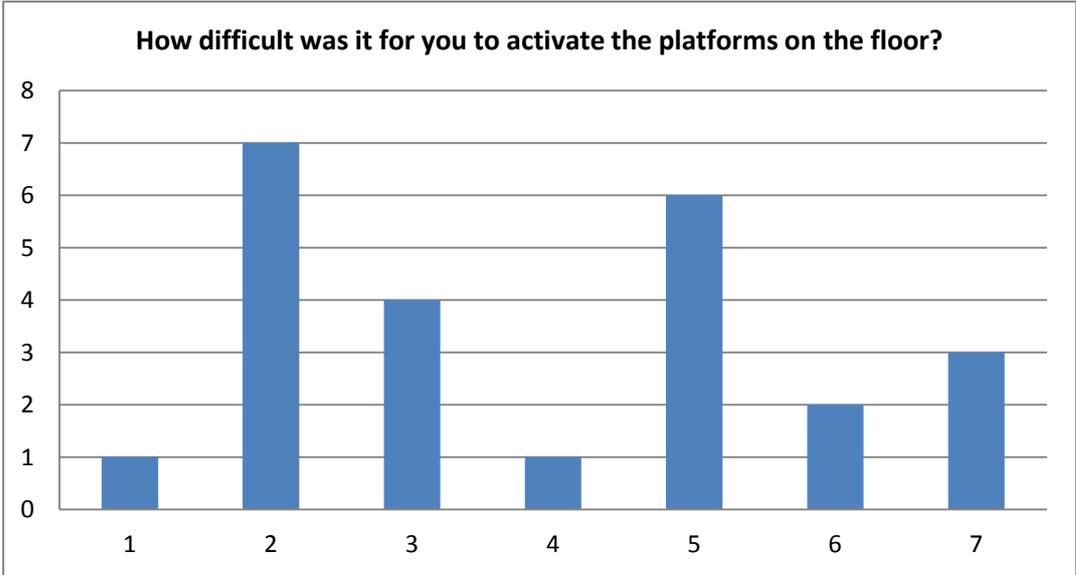


Figure 42: This figure shows how difficult it was for the users to activate the platforms on the floor in room 2.

23 users managed to get to room 5. Here they had to pick up a piece of papyrus from a treasure chest. As shown in Figure 43 no one had big difficulties to perform this task (2.5652 ± 1.1610). Most users had some minor difficulties. Only 4 users had no difficulties at all. Only 4 people answered this question with a number higher than 3.

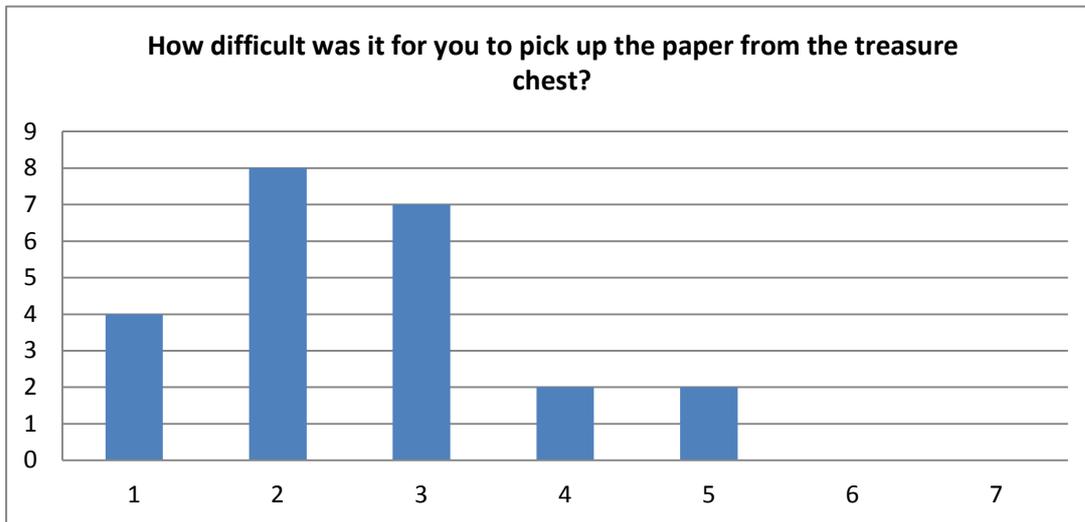


Figure 43: This figure shows how difficult it was for the users to pick up the paper in the treasure chest.

18 people managed to get to room 7. The other users had to quit due to cybersickness symptoms. In this room they had to push stones into the wall and evaluate how difficult it was for them to perform this task. The results of this evaluation are not meaningful (3.7778 ± 2.1572) as shown in Figure 44.

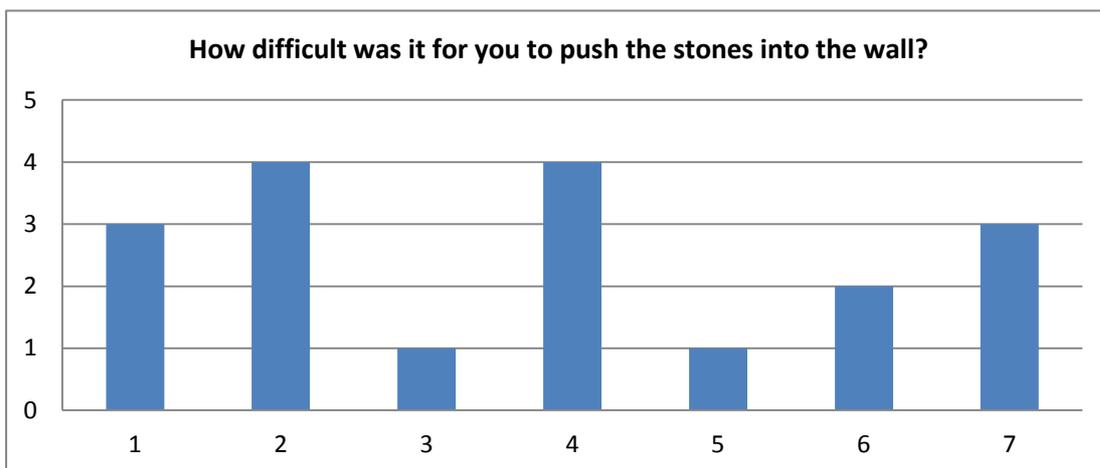


Figure 44: This figure shows how difficult it was for the users to push the stones into the wall.

The users had to evaluate questions about the virtual avatar. They were asked how realistic their virtual body felt like. Most of the participants answered this question between 3 and 5 (4.32 ± 1.4059). Only 2 people answered the question with a value smaller than 3 and 4 people answered it with a value higher than 5. The median value is 4. The results can be seen in Figure 45. People claimed that the arms of the virtual avatar have been too short and too thin. Some people claimed that all the limbs have been too short. For one participant it was unfamiliar to see another body than his own body. Some people claimed that the mapping between the real and virtual body didn't completely match and that the arm pose of the hand holding the sword was unnatural and that the arms were sometimes in strange angles. Tall participants also claimed that the avatar seemed to be too small. This can be attributed to the fixed avatar size of 170 cm.

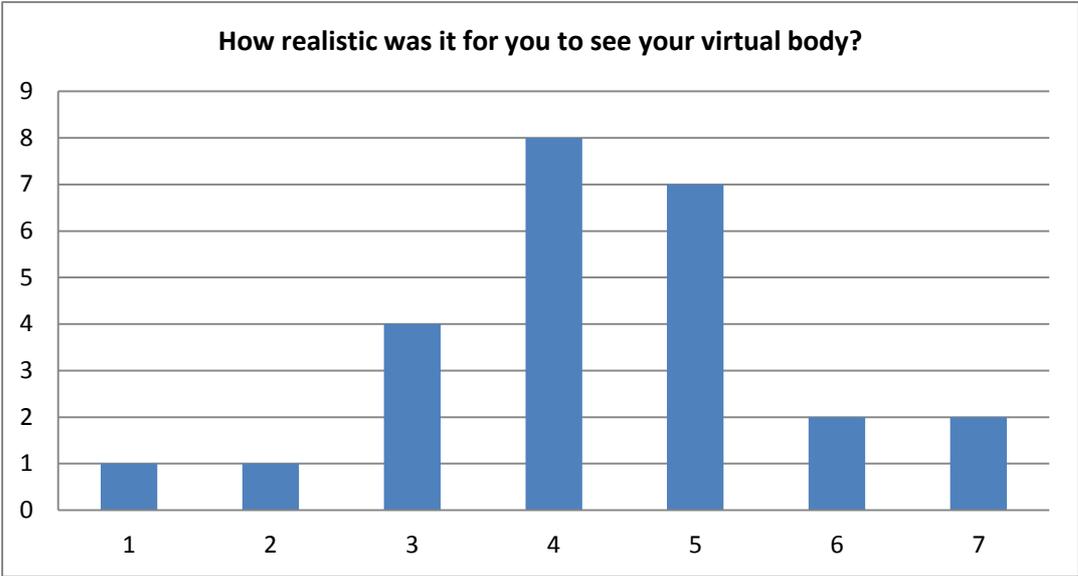


Figure 45: This figure shows how realistic it was for the users to see their own virtual body.

Further the users were asked to evaluate how comfortable they have felt in their virtual body. The majority of the users felt rather comfortable (4.92 ± 1.5253). 40% of the test persons answered this question with 6 (see Figure 46). The median value is 5.

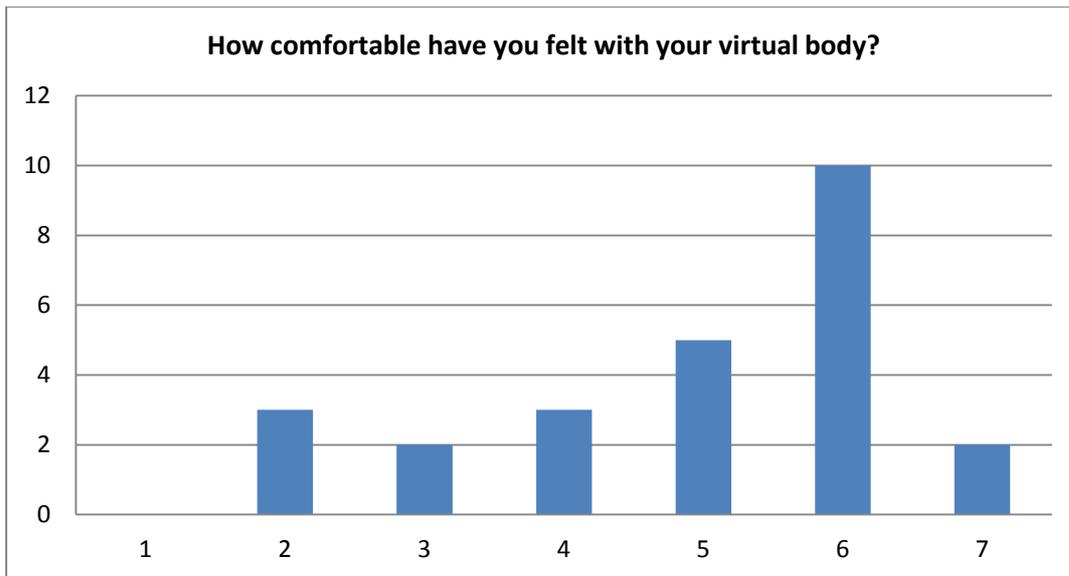


Figure 46: This diagram shows how comfortable the users have felt with their virtual body.

The users also evaluated how realistic the body proportions seemed to be. As can be seen in Figure 47 the results are not clear (3.56 ± 1.7814). However 60% of the users answered the question with a value less than 4 and thus evaluated the body proportions as rather unrealistic. Only 30 % answered the question with a value higher than 4. The median value is 3.

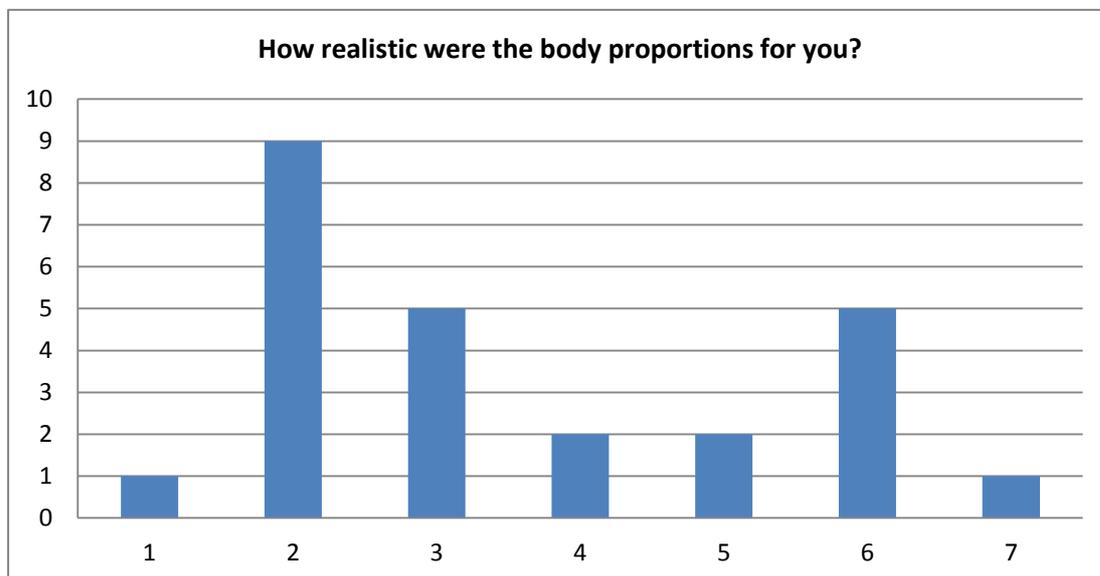


Figure 47: This figure shows how realistic the body proportions have been for the users.

In summary it turned out that the virtual avatar should have larger limbs than in reality. The proportions of the virtual body were taken from a real human, but it seems that due to the large FOV of the Oculus the limbs seem to be too small and too thin. Also the size of the avatar should be adapted to the player's size. Further, both the PrioVR and the

Virtualizer have to be enhanced to enable a better interaction, because most people claim that the body was twisted and therefore the walking direction was wrong. It is assumed that the reason for this is the interference between the metal ring of the Virtualizer and the magnetometers in the PrioVR as described in section 2.2.2. However as seen in Figure 37 the game experience was evaluated as rather realistic. All results in detail can be found in Appendix II.

6.3.2 Cybersickness

In this section the results of the cybersickness symptoms are shown. All questions regarding the cybersickness symptoms were evaluated using the Likert scale with values between 1 and 7. As shown in Figure 48 the results regarding tiredness and exhaustion of the test participants are not significant (2.88 ± 1.7397). 28% of the test persons have not felt tired or exhausted. Further 24% claimed that they felt a little bit tired/exhausted (24%). Only one person claimed that he is very tired/exhausted. The median value is 2.

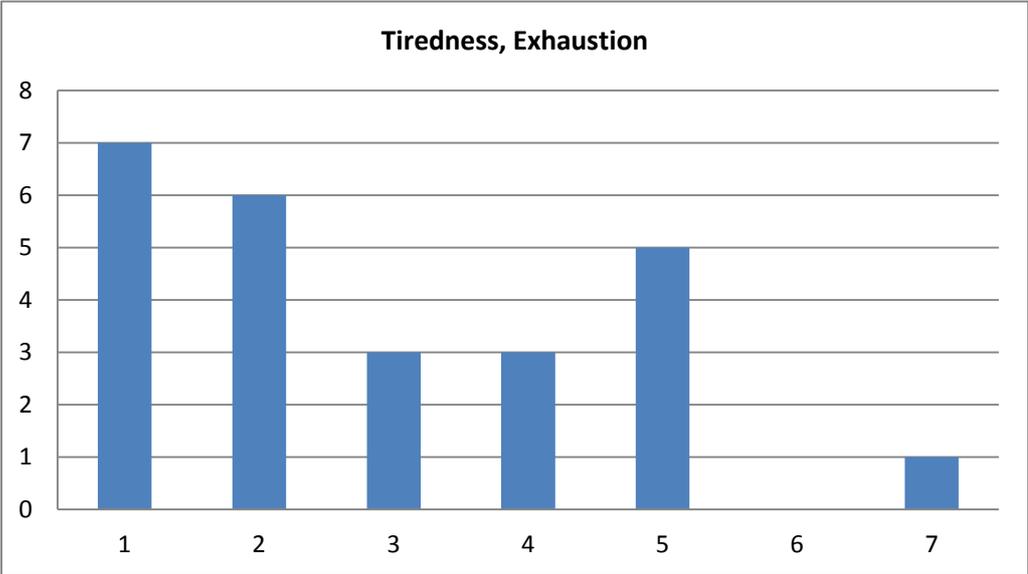


Figure 48: This figure shows the occurrence of tiredness/exhaustion during the user tests.

I evaluated the results regarding tiredness/exhaustion against different factors that can influence cybersickness. The only significant factor found in respect to this cybersickness symptom is the difficulty to walk in the Virtualizer. The following figure shows the results from test participants that had difficulties to walk in the Virtualizer compared to the results from users that had no difficulties to walk.

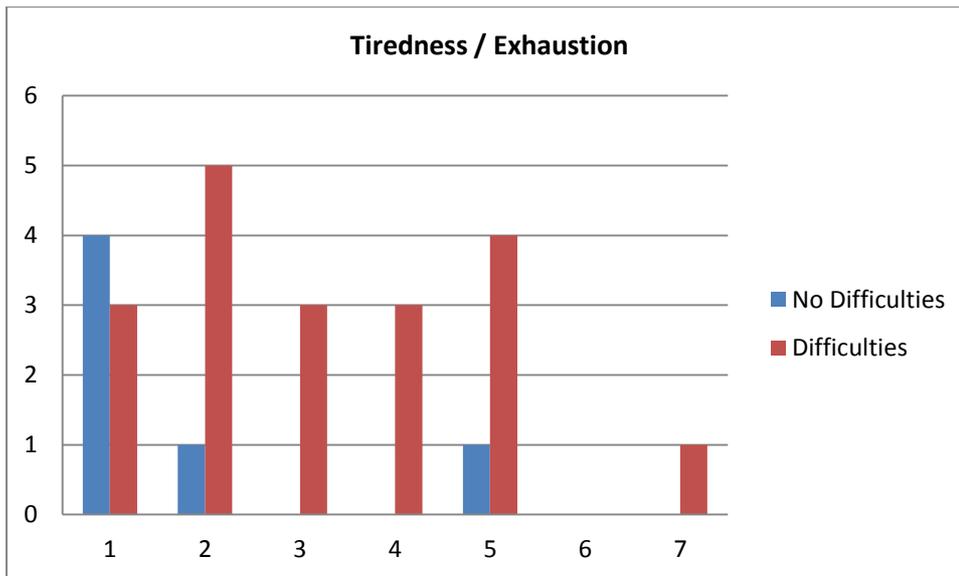


Figure 49: This figure shows how tired/exhausted test persons felt when having difficulties/no difficulties to walk in the Virtualizer.

It can be seen that from the 6 test participants, which had no difficulties to walk in the Virtualizer, only one answered this question with a value higher than 2. 4 of them have not been tired at all. However the results for the users that had difficulties to walk were not significant. Because of the small number of people that had no difficulties to walk the significance of the results is questionable.

Figure 50 shows the results regarding dizziness. As can be seen, 6 users claimed to be not dizzy at all. 2 players got very dizzy. 28% of the test persons answered this question with a value of 5. The results are not significant (3.28 ± 1.9261). However it can be seen that there is a peak at the value of 5. The median value is 3.

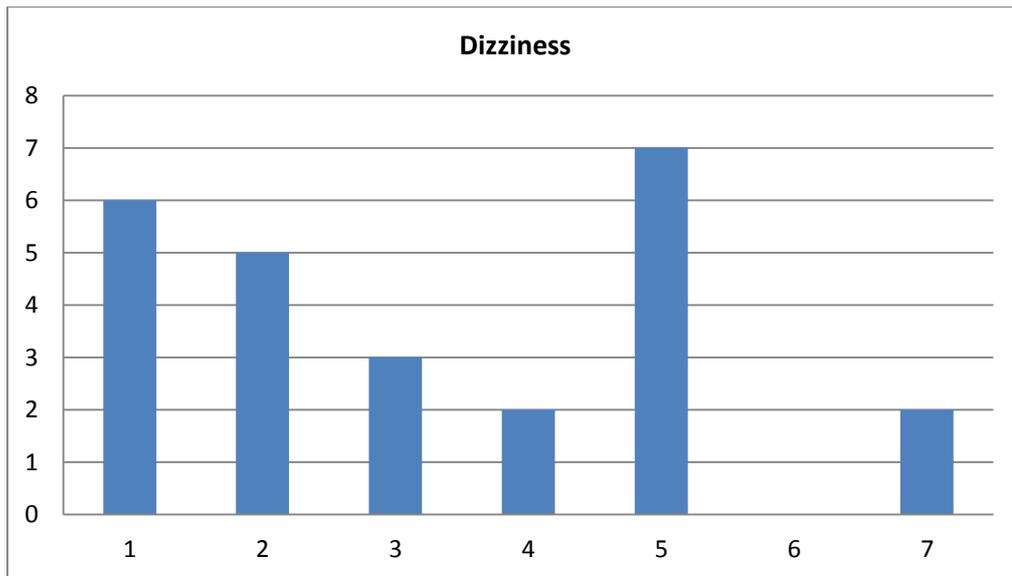


Figure 50: This figure shows the occurrence of dizziness during the user tests.

Key factors that influence the possibility to get dizzy were searched. One of the factors that influenced the results is the use of an optical aid in daily life. As shown in Figure 51, only 10% of the persons that use an optical aid in daily life claimed that they didn't get dizzy, whereas 33.33% of the persons that are not wearing any optical aid in daily life claimed that they didn't get dizzy.

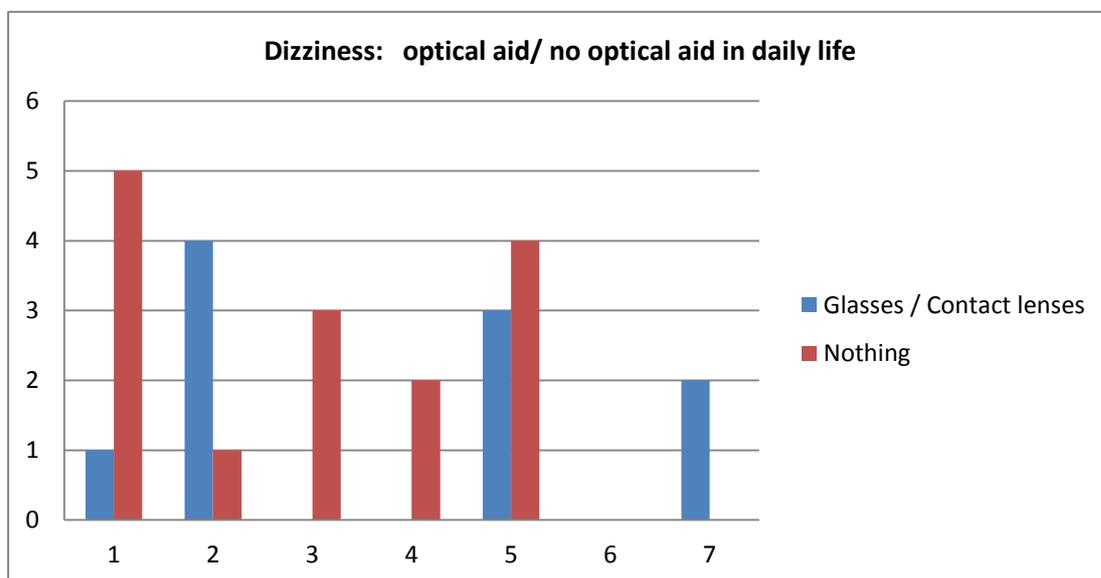


Figure 51: This figure compares the possibility to get dizzy when wearing an optical aid and when not wearing an optical aid.

The two persons that claimed to feel very dizzy did not use their optical aid during the user test. Further they were male, had difficulties to walk and are never watching 3D movies.

Figure 52 shows the results of the user tests regarding nausea. 40% of the test persons did not feel nauseous at all. The rest of the answers are almost equally distributed (2.96 ± 2.1695). The median value is 2, which can be explained by the high number of test persons that answered the questions with the number 1.

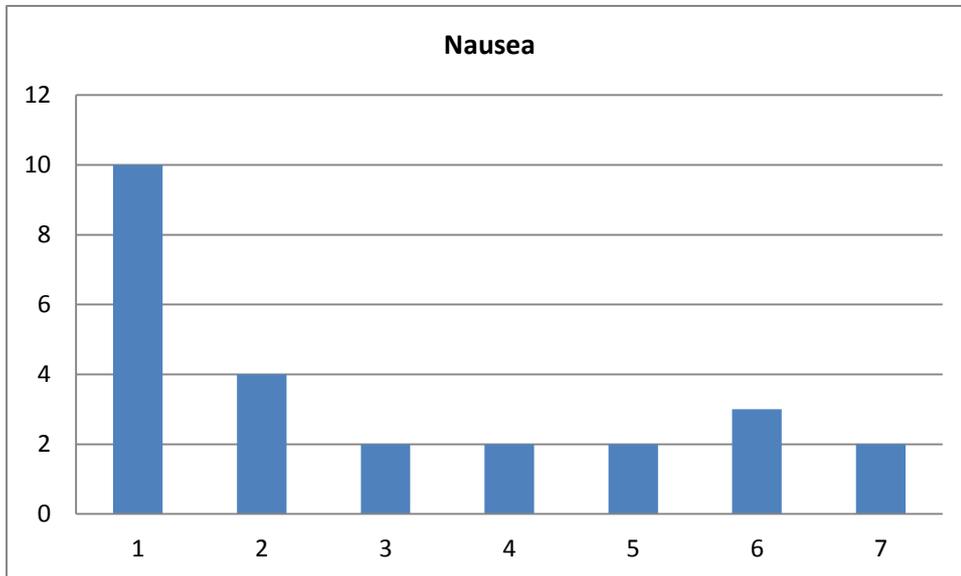


Figure 52: This figure shows the occurrence of nausea during the user tests.

The major key factor that influences the possibility to get nauseous is the gender of the test person. As shown in Figure 53 only 14.92% of the female users did not get nauseous whereas 50% of the male test persons did not get nauseous.

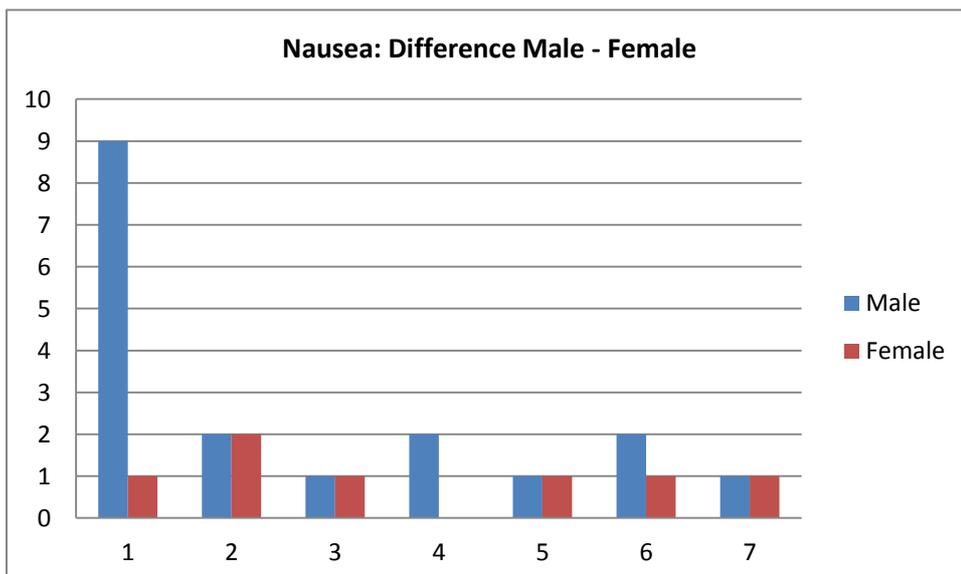


Figure 53: This figure shows how the gender influences the possibility to get nauseous.

Also using an optical aid in daily life seems to influence the results regarding nausea. 46.6% of the persons that are not using an optical aid in daily life did not get nauseous, whereas only 30% of the persons that use an optical aid did not get nauseous.

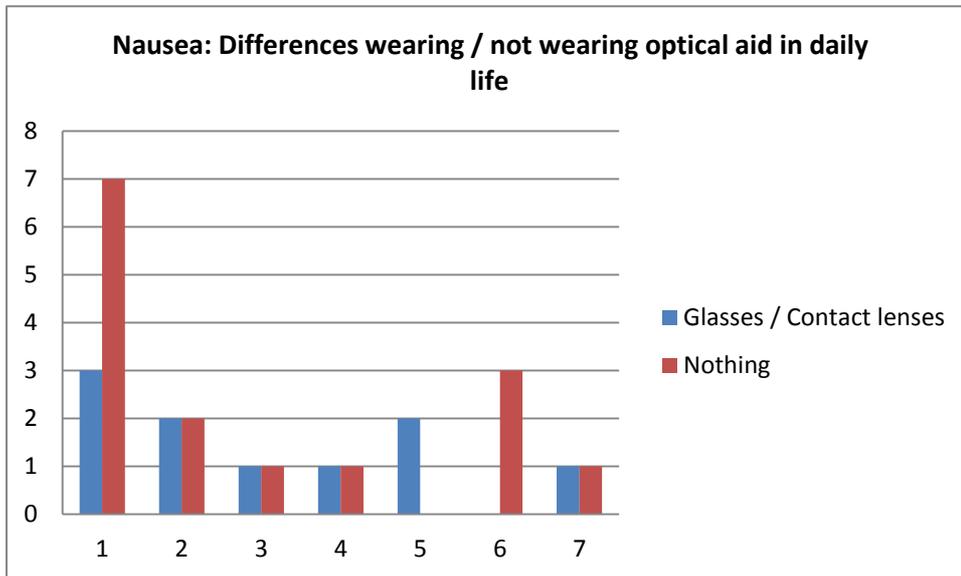


Figure 54: This figure shows how the use of an optical aid in daily life influences the possibility to get nauseous.

Figure 55 shows the results in respect to the occurrence of headache. 72% of the test persons did not feel any headache. Further 20% answered the question with a value of 2. One person answered the question with a value of 5 and one person with a value of 6. The results show that headache was not a common symptom (1.56 ± 1.261). The median value of 1 supports this statement.

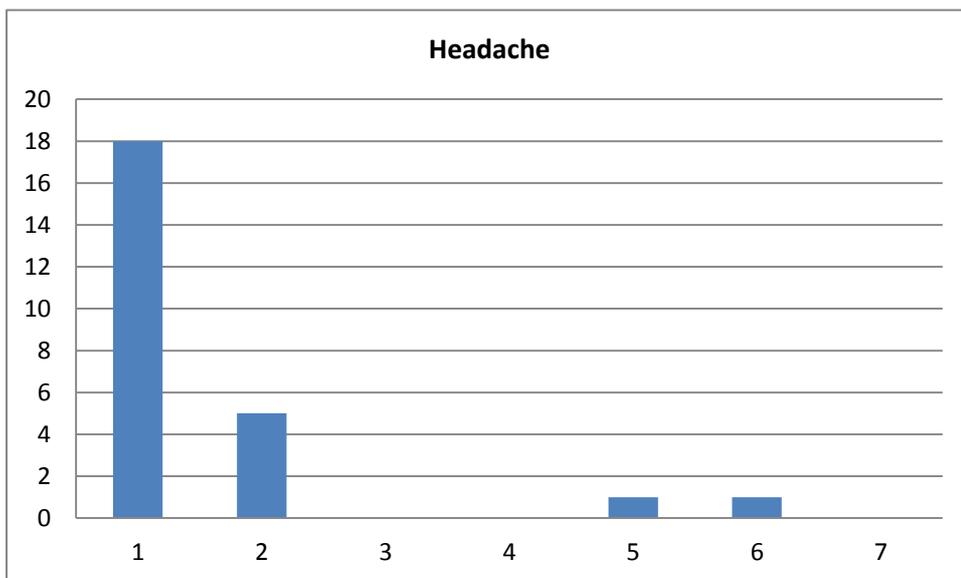


Figure 55: This figure shows the occurrence of headache during the user tests.

The two persons that answered the question with a number higher than 2 are wearing optical aids in daily life and did not wear one during the test.

Figure 56 shows that 40% of the test persons didn't get eye strain. The distribution decreases towards higher values and only one of the users answered the question with a value higher than 4 (2.08 ± 1.2557). The median value is 2.

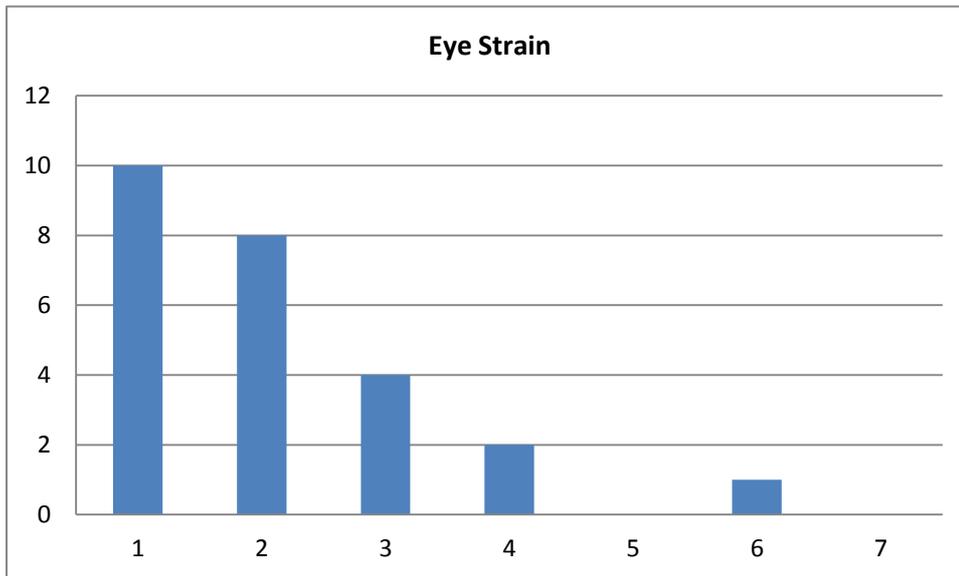


Figure 56: This figure shows the occurrence of eye strain during the user tests.

The person that answered the question with the value 6 was male, wears an optical aid in daily life that he did not use during the test, had difficulties to walk and never watches 3D movies. Figure 57 shows the occurrence of eye strain of people that had difficulties to walk in the Virtualizer compared to people that had no difficulties to walk. As can be seen from the 6 persons that did not have difficulties to walk in the Virtualizer, 5 of them did not feel eye strain and the other one answered the question with a value of 2. Therefore difficulties to walk in the Virtualizer seem to be a key factor that increases the possibility of getting eye strain.

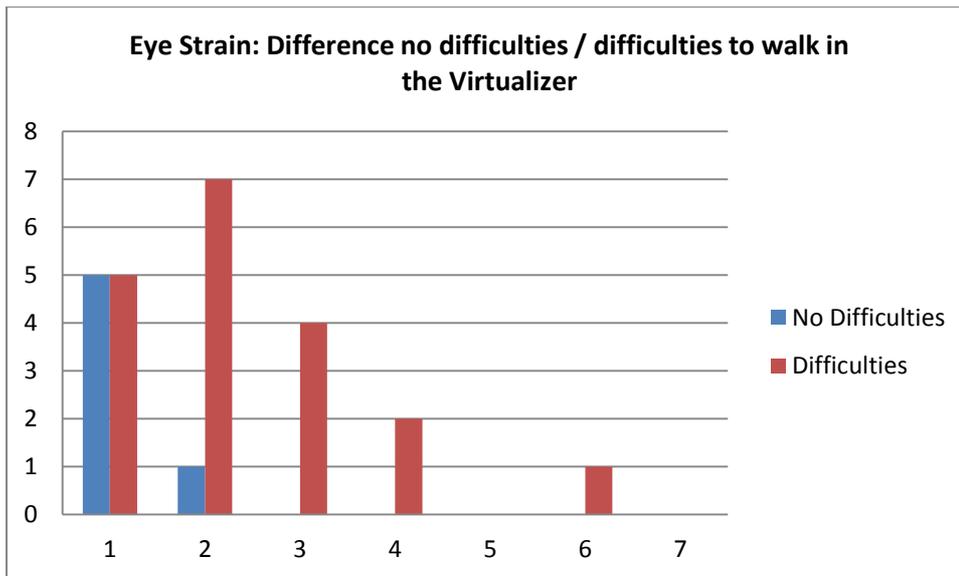


Figure 57: This figure shows how difficulties to walk in the Virtualizer influence the occurrence of eye strain.

The results regarding blurred sight are similar to the results regarding eye strain. Figure 58 shows that 48% of the test participants did not have a blurred sight and that the distribution decreases at higher values with a small peak at the value 5 (2.32 ± 1.6258). The median value is 2.

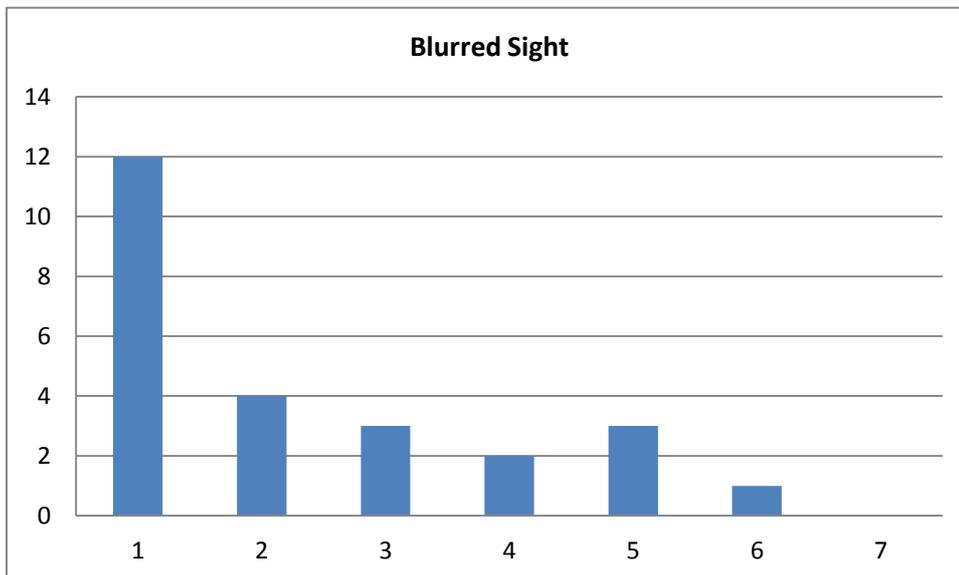


Figure 58: This figure shows the occurrence of blurred sight during the user tests.

The person that answered the question with the number 6 was male, wears an optical aid in daily life that he didn't wear during the user test, had difficulties to walk and never watches 3D movies.

Figure 59 shows the results in respect to difficulties to focus. As can be seen the distribution is similar to the distribution regarding blurred sight and eye strain. 44% of the test persons did not have a blurred sight and the distribution decreases to higher values (1.96 ± 1.1358). No one answered this question with a value higher than 5. The median value is 2.

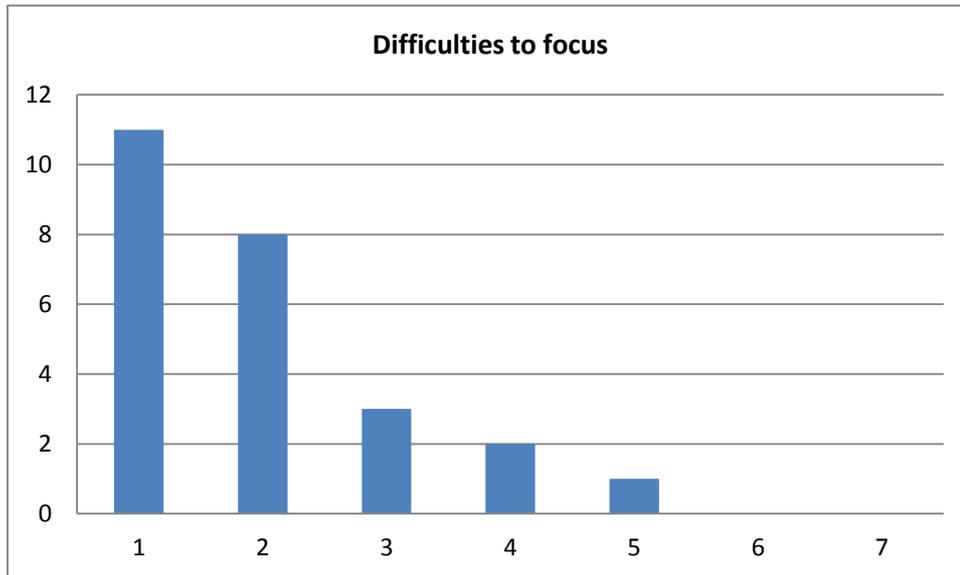


Figure 59: This figure shows the occurrence of difficulties to focus during the user tests.

The person that answered the question with a value of 5 is male, wears an optical aid that he wore during the test, had difficulties to walk and never watches 3d movies. Difficulties to walk in the Virtualizer are a major key factor influencing the occurrence of difficulties to focus. As shown in Figure 60, 4 out of the 6 persons that had no difficulties to walk in the Virtualizer had no difficulties to focus and the 2 other users answered the question with a value of 2. Values higher than 2 occurred only with persons that had difficulties to walk.

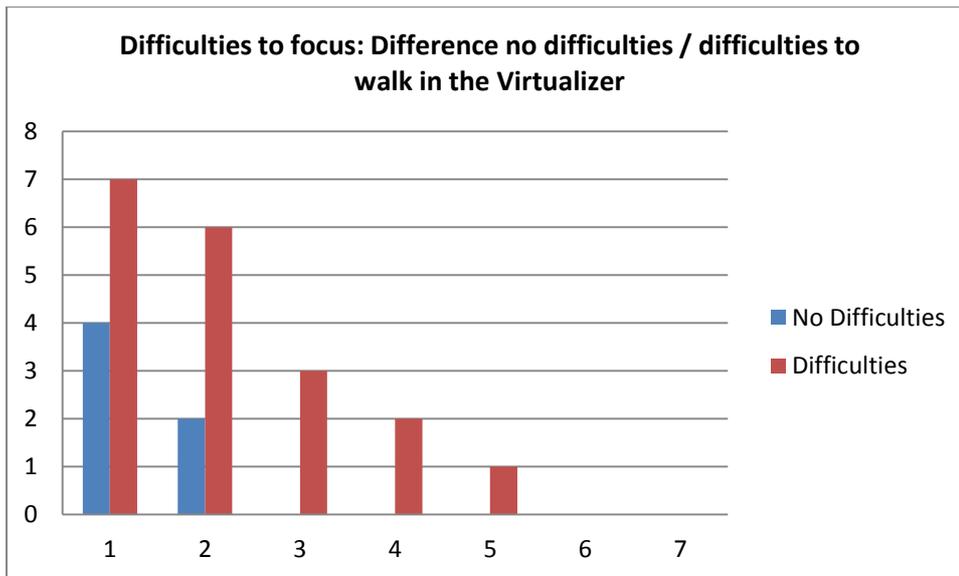


Figure 60: This figure shows how difficulties to walk in the Virtualizer influence the occurrence of difficulties to focus.

The results regarding difficulty in concentration have a similar distribution than the previous ones. 48% of the test persons did not have difficulties in concentration and the distribution decreases with higher values (1.76 ± 0.9256). No one answered this question with a value higher than 4. The median value is 2.

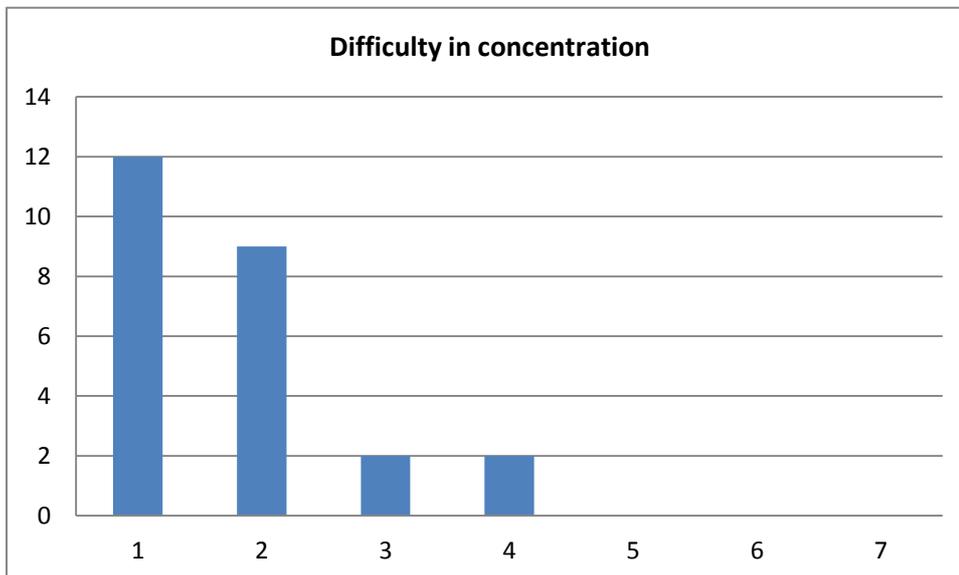


Figure 61: This figure shows how difficulties to walk in the Virtualizer influence the occurrence of difficulties in concentration.

No key factors that influence the occurrence of difficulties in concentration could be identified.

As shown in this section cybersickness symptoms occur when playing the developed game, which is a problem. Some people got cybersickness symptoms to a high degree. Only 2 of the test participants got no symptoms at all. Both are male, are not wearing glasses in daily life and had no difficulties to walk in the Virtualizer. The Virtualizer seems to be the major key factor for occurrence of tiredness/exhaustion, eyestrain and difficulties to focus. Headache seems not to be a big problem, but 76% of the test persons got dizzy and 60% of the test persons even got nauseous.

6.3.3 Hardware

In this section the results in respect to the hardware are presented. The test participants were asked how realistic the virtual game experience was in comparison to a normal game. Figure 62 shows the results of this question (4.6957 ± 1.6358). 23 out of the 25 users answered this question. 60.8% of the users answered this question with a value higher than 4. Only one person was of the opinion that the game was very unrealistic compared to a normal video game. 17.4% answered the question with the value 4, which means that they are of the opinion that the virtual game was as realistic as a normal video game. The median value is 5.

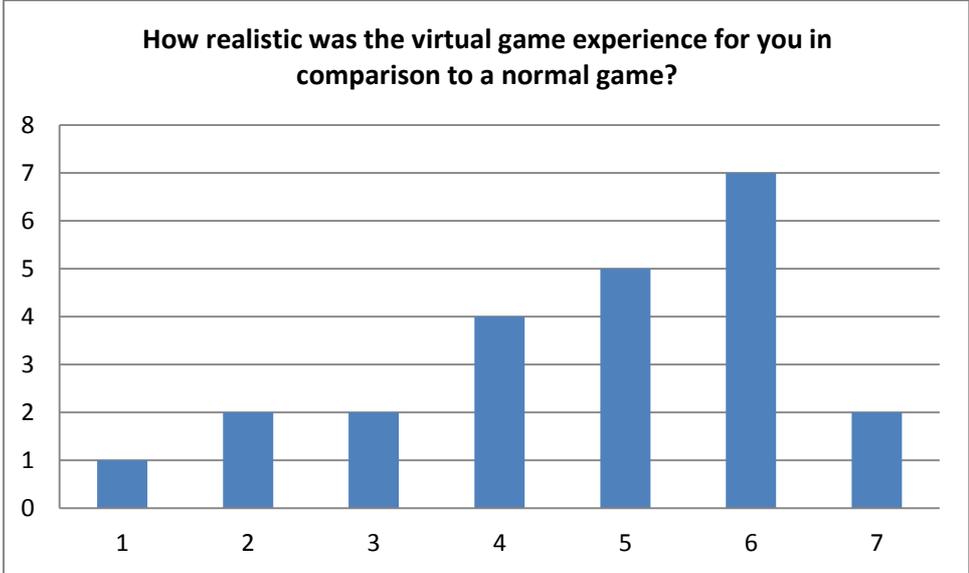


Figure 62: This figure shows how realistic the virtual game experience was in comparison to a normal video game.

Figure 63 shows how realistic the virtual game experience was rated in comparison to a video game in 3D mode (4.9286 ± 0.9169). 14 users answered this question. All of the users answered this question with a value higher than 3, which means that no one was of the opinion that the virtual game was less realistic than a game played in 3D mode. 35.7% of the test participants rated the game as realistic as a game played in 3D mode. The rest of the users found it more realistic. The median value is 5.

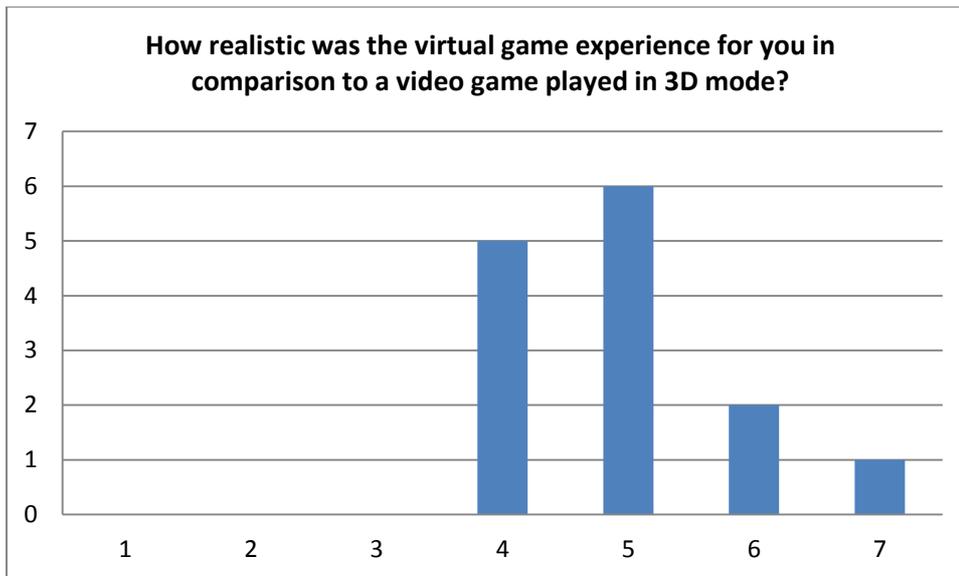


Figure 63: This figure shows how realistic the virtual game experience was in comparison to a video game played in 3D mode.

Regarding the Oculus Rift, the test participants were asked how they liked the graphics. As shown in Figure 64, 68% of the users answered this question with a value higher than 4 (4.88 ± 1.5631). No one answered the questions with the value 1. However 20% of the users answered this question with a value smaller than 4. The median value is 6.

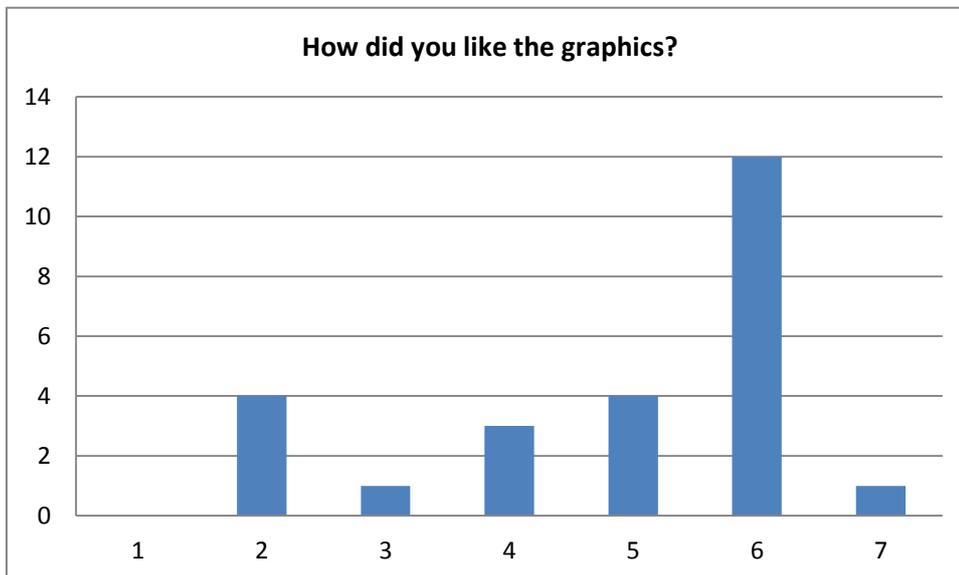


Figure 64: This figure shows how the test persons liked the graphics.

Figure 65 shows how the perception was for the users (5.36 ± 1.1504). 84% answered this question with a value higher than 4, thus the majority found the perception rather good. The median value is 6.

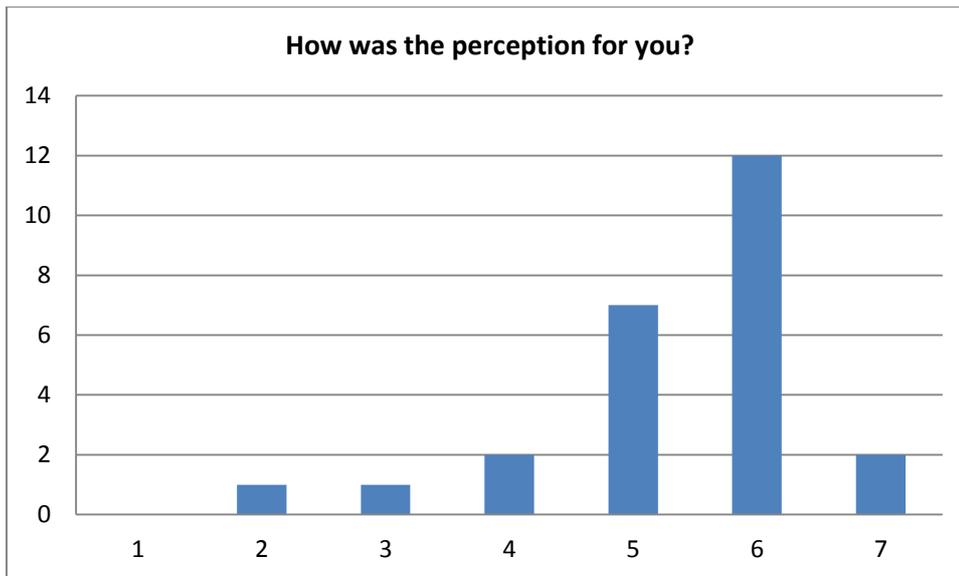


Figure 65: This figure shows how the perception was for the test persons.

In respect to the Virtualizer the users were asked how difficult walking in the Virtualizer was. Figure 66 shows that walking was rather difficult (4.72 ± 1.4295). 60% of the users answered this question with a value higher than 4. Only 16% of the test participants answered the question with a value smaller than 4 and 24% answered the question with the value 4. The median value of 5 correlates with the fact that walking was rather difficult.

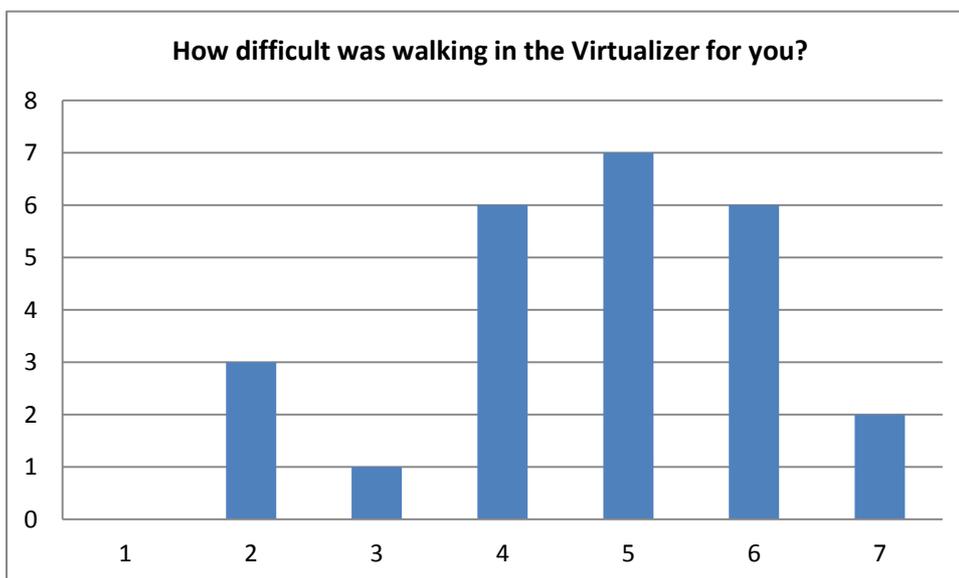


Figure 66: This figure shows how difficult walking in the Virtualizer was.

The users were asked if they had difficulties to walk in the Virtualizer. 76% of the users answered this question with “Yes”. The test participants claimed different problems: e.g. that a precision between slow and fast walking was missing, that the surface was not as

slippery as it should be, that walking movements were hardly detected, that the belt system was disturbing, that it was hard to choose the right walking direction, that they walked too slow, that the walking direction and body rotations didn't match or that it was exhausting to slide in the middle of the platform.

As can be seen in Figure 67, 3 out of the 6 test persons that claimed that they did not have difficulties to walk in the Virtualizer answered the question about how difficult walking in the Virtualizer was with a value higher than 3.

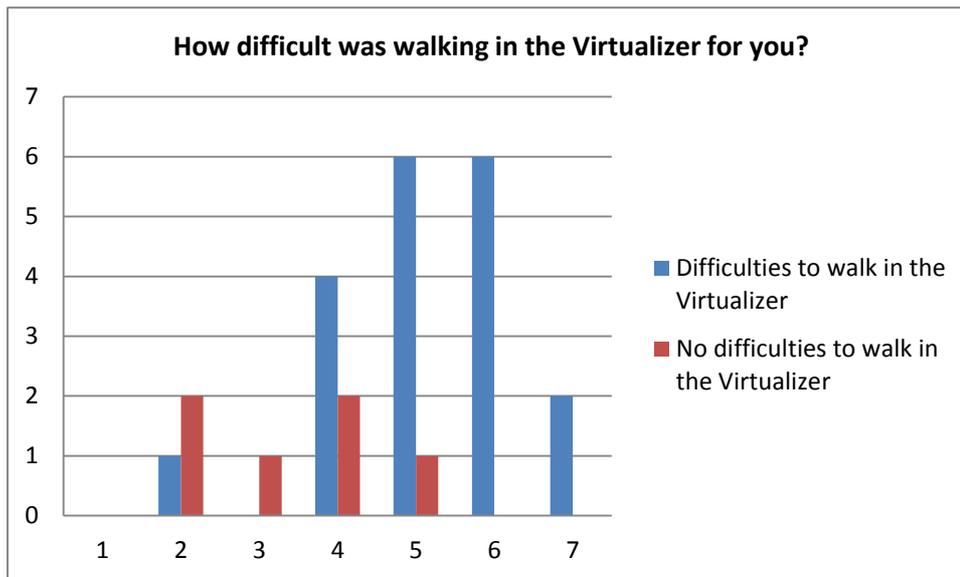


Figure 67: This figure shows how difficulties to walk in the Virtualizer influence the feeling of how difficult it was to walk in the Virtualizer.

This section showed that the majority of the persons had problems walking in the Virtualizer. Further the majority of the persons liked the graphics of the Oculus Rift. Only a fifth of the persons were rather disappointed from the graphics. Therefore the hardware has to be improved to reach better results. The detailed results can be found in Appendix II.

7 Conclusion

This thesis described the implementation and design of a virtual reality game for the Oculus Rift, the PrioVR and the Virtualizer. It showed which design guidelines have to be followed and which problems can occur when developing such a game. Further the execution of the user tests as well as the results of the user tests were presented.

40 people participated in the user tests, whereas 15 were excluded due to technical troubles with the Virtualizer. The results showed that the game experience was rather realistic for the majority of the test participants. The spatial proportions seemed wrong for 52% of the users. The spatial proportions as well as the body proportions were designed according to real world measurements. The body proportions seemed to be too small for the majority of the test participants. It is assumed that the spatial as well as the body proportions can seem wrong due the large FOV of the Oculus and due to the fact that the player was not scaled to his real size. However these are just assumptions. Factors that give the player the wrong feeling about proportions have to be identified in the future.

Cybersickness symptoms occurred at 23 of 25 persons and thus factors have to be identified that lead to these symptoms. It was shown that difficulties to walk in the Virtualizer have an influence on the following cybersickness symptoms: tiredness/exhaustion, eye strain and difficulties to focus. Therefore an improvement of the Virtualizer can reduce these symptoms. However no factors in respect to the other symptoms could be identified, but it seems that people that are wearing an optical aid in daily life have a higher possibility of getting dizzy and that the gender influences the occurrence of nausea.

Most people had difficulties in terms of navigation. This can be affiliated to the imperfect hardware. It was shown that the magnetometers of the sensors of the PrioVR drifted due to the metal ring of the Virtualizer. Further cables disconnected and sensors died during the tests, which made re-calibration necessary. Also the Virtualizer worked improperly. The sensor did not detect all walking movements made by the test persons. Due to the drift of the PrioVR the walking direction was often hard to choose. The majority of the participants had difficulties to walk in the Virtualizer. None of the test persons claimed that it was very easy to walk in the Virtualizer. Therefore improvements of the PrioVR as well as of the Virtualizer have to be made to reach better navigation in the virtual world. It is hoped that the consumer versions of these two technologies get rid of the problems and make navigation easy and realistic.

The results regarding the Oculus Rift are better. The majority of the test persons rather liked the graphics. However 20% of the users were disappointed by the graphics, but the

consumer version will have a higher resolution and therefore it is assumed that the results would get better when testing with the consumer version.

In the future this study should be repeated with the consumer versions of the hardware to show how the improved hardware can lead to better results in terms of cybersickness and navigation. Further adaptations in the game design should be made to improve the feeling of correct body and spatial proportions and to make the game experience more realistic. In terms of body proportions the player should be scaled according to his real body size and limbs should be made bigger than real world measurements. To reach a more realistic game experience the models have to be made more realistic. They should contain more details and thus consist of more polygons. Also additional shader effects should be integrated to reach a higher feeling of presence. However the higher polygon count and additional shader effects would lead to decreased performance. Therefore a compromise has to be found to balance realism and performance. With the increasing performance of high end graphics cards it is likely to reach a more realistic game experience in the future.

Bibliography

- [1] P. R. Desai, P. N. Desai, K. D. Ajmera und K. Mehta, „A Review Paper on Oculus Rift - A Virtual Reality Headset,“ *International Journal of Engineering Trends and Technology Volume 13 Nr. 4*, pp. 175-179, July 2014.
- [2] J. J. L. V. Jr., „A Discussion of Cybersickness in Virtual Environments,“ *ACM SIGCHI Bulletin Volume 32 Issue 1*, pp. 47-56, 1 January 2000.
- [3] O. VR, „Oculus - Best Practice Guide,“ Oculus VR, [Online]. Available: http://static.oculus.com/sdk-downloads/documents/Oculus_Best_Practices_Guide.pdf. [Zugriff am 27 April 2015].
- [4] C. VR, „Kickstarter - Control VR,“ [Online]. Available: <https://www.kickstarter.com/projects/controlvr/control-vr-motion-capture-for-vr-animation-and-mor>. [Zugriff am 22 March 2015].
- [5] PrioVR, „PrioVR,“ [Online]. Available: <http://priovr.com/>. [Zugriff am 22 March 2015].
- [6] „Perception Neuron,“ Perception Neuron, [Online]. Available: https://neuronmocap.com/products/perception_neuron. [Zugriff am 22 March 2015].
- [7] C. VR, „Control VR,“ [Online]. Available: <http://controlvr.com/>. [Zugriff am 22 March 2015].
- [8] S. Razzaque, Z. Kohn und M. C. Whitton, „Redirected Walking,“ *Proceedings of the eurographics workshop on virtual reality*, pp. 298-294, 2001.
- [9] J. Souman, P. Giordano, M. Schwaiger, I. Frissen, T. Thümmel, H. Ulbrich, A. D. Luca, H. H. Bühlhoff und M. O. Ernst, „CyberWalk: Enabling Unconstrained Omnidirectional Walking through Virtual Environments,“ in *ACM Transactions Applied Perception, Vol. 8, No. 4, Article 25*, 2011.
- [10] Cyberith, „Kickstarter: Cyberith Virtualizer,“ [Online]. Available:

<https://www.kickstarter.com/projects/1259519125/cyberith-virtualizer-immersive-virtual-reality-gam/>. [Zugriff am 8 February 2015].

- [11] V. Omni, „Virtuix Omni,“ Virtuix Omni, [Online]. Available: <http://www.virtuix.com>. [Zugriff am 8 February 2015].
- [12] H. Iwata und T. Fujii, „VIRTUAL PERAMBULATOR: A Novel Interface Device for Locomotion in Virtual Environment,“ in *Proceedings of the 1996 Virtual Reality Annual International Symposium (VRAIS '96)*, 1996.
- [13] I. Goradia, J. Doshi und L. Kurup, „A Review Paper on Oculus Rift & Project Morpheus,“ *International Journal of Current Engineering and Technology*, Vol.4, No.5, pp. 3196-3200, October 2014.
- [14] K. Vasylevska, I. Podkosova und H. Kaufmann, „Walking in Virtual Reality: Flexible Spaces and Other Techniques,“ in *The Visual Language of Technique: Volume 2 - Heritage and Expectations in Research*, Wien, Springer Verlag, 2015, pp. 81-97.
- [15] H. Iwata, „Locomotion Interfaces,“ in *Human Walking in Virtual Environments*, New York, Springer Science + Business Media, 2013, pp. 199-218.
- [16] H. Iwata, „Artificial reality for walking about large scale virtual space,“ *Hum Interface News Rep 5(1) (in Japanese)*, pp. 49-52, 1990.
- [17] H. Iwata, H. Yano und H. Tomioka, „Powered Shoes,“ in *ACM SIGGRAPH 2006 Emerging Technologies*, Boston, Massachusetts, 2006.
- [18] H. Iwata, H. Yano und M. Tomiyoshi, „String Walker,“ in *ACM SIGGRAPH 2007 Emerging Technologies*, San Diego, California, 2007.
- [19] Cyberith, „Cyberith,“ [Online]. Available: <http://www.cyberith.com>. [Zugriff am 8 February 2015].
- [20] R. P. Darken, W. R. Cockayne und D. Carmein, „The Omni-Directional Treadmill: A Locomotion Device for Virtual Worlds,“ *Proceedings of the 10th Annual ACM Symposium on User Interface Software and Technology*, pp. 213-221, 1997.

- [21] A. Nagamori, K. Wakabayashi und M. Ito, „The ball array treadmill: a locomotion interface for virtual world,“ in *Proceedings of the IEEE VR2005*, 2005.
- [22] H. Iwata, „Walking About Virtual Environments on an Infinite Floor,“ *Virtual Reality, 1999. Proceedings., IEEE*, pp. 286 - 293, 13.-17. März 1999.
- [23] H. Iwata, H. Yano und F. Nakaizumi, „GaitMaster: A Versatile Locomotion Interface for Uneven Virtual Terrain,“ in *Virtual Reality, 2001. Proceedings. IEEE*, p. 131-137, 2001.
- [24] H. Iwata, H. Yano, H. Fukushima und H. Noma, „CirculaFloor,“ *Computer Graphics and Applications, IEEE, volume 25, number 1*, pp. 64-67, January 2005.
- [25] M. C. Whitton und T. C. Peck, „Stepping-Driven Locomotion Interfaces,“ in *Human Walking in Virtual Environments*, New York, Springer, 2013, pp. 241 - 262.
- [26] M. Slater, A. Steed und M. Usoh, „The virtual treadmill: A naturalistic metaphor for navigation in immersive virtual environments,“ *The 1st Eurographics Workshop on Virtual Reality*, pp. 71-86, 1993.
- [27] J. Templeman, P. Denbrook und L. Sibert, „Virtual Locomotion: Walking in Place through Virtual Environments,“ *Presence volume 8 number 6*, pp. 598-617, December 1999.
- [28] L. L. Arns, A New Taxonomy for Locomotion in Virtual Environments. Ph.D. Dissertation, Iowa State University: Iowa State University, 2002.
- [29] M. Whitton, J. Cohn, J. Feasel, P. Zimmons, S. Razzaque, S. Poulton, B. McLeoad und F.P.Brooks, „Comparing VE locomotion interfaces,“ *Virtual Reality 2005, Proceedings VR 2005, IEEE*, pp. 123-130, March 2005.
- [30] Y. L., A. RS und R. SK, „New simple virtual walking method-walking on the spot,“ in *Proceedings of 9th annual immersive projection technology (IPT) symposium*, 2004.
- [31] G. Bruder, F. Steinicke und P. Wieland, „Self-motion illusions in immersive virtual reality environments,“ in *Proceedings of IEEE Virtual Reality*, Singapore, 2011.

- [32] E. A. Suma, D. M. Krum und M. Bolas, „Redirected Walking in Mixed Reality Training Applications,“ in *Human Walking in Virtual Environments*, New York, Springer, 2013, pp. 319-331.
- [33] N. Nitzsche, U. D. Hanebeck und G. Schmidh, „Motion compression for telepresent walking in large target environments,“ *Presence Teleoper. Virtual Environ.* 13(1), pp. 44-60, February 2004.
- [34] J. Su, „Motion compression for telepresence locomotion,“ *Presence Teleoper. Virtual Environ.* 16(4), pp. 385-398, August 2007.
- [35] S. Razzaque, D. Swapp, M. Slater, M. C. Whitton und A. Steed, „Redirected Walking in Place,“ *Proceedings of the workshop on virtual environments*, pp. 123-130, 2002.
- [36] S. Razzaque, „Redirected Walking,“ *Dissertation and computer science technical report TR05-018; University of North Carolina at Chapel Hill*, 2005.
- [37] E. Hodgson, E. Bachmann und D. Waller, „Redirected walking to explore virtual environments: assessing the potential for spatial interference,“ *ACM Transactions on Applied Perception, Volume 8, Issue 4, Article No. 22*, November 2011.
- [38] T. Field und P. Vamplew, „Generalised Algorithms for Redirected Walking in Virtual Environments,“ *AISAT 2004 - Int. Conf. Artif. Intell. Sci. Technol.*, pp. 1357-1366, 2004.
- [39] E. A. Suma, S. Clark, D. Krum, S. Finkelstein, M. Bolas und Z. Wartell, „Leveraging Change Blindness for Redirection in Virtual Environments,“ *IEEE Virtual Reality Conference*, pp. 159-166, 2011.
- [40] E. A. Suma, Z. Lipps, S. Finkelstein, D. M. Krum und M. Bolas, „Impossible Spaces: maximizing natural walking in virtual environments with self-overlapping architecture,“ *IEEE Transactions on Visualization and Computer Graphics* 18(4), pp. 555-564, April 2012.
- [41] K. Vasylevska, H. Kaufmann, M. Bolas und E. A. Suma, „Flexible Spaces: Dynamic Layout Generation for Infinite Walking in Virtual Environments,“ in *IEEE Symposium on 3D User Interfaces (3DUI)*, Orlando, Florida, 2013.

- [42] B. Williamson, C. Wingrave und J. J. L. V. Jr., „Full Body Locomotion with Video Game Motion Controllers,“ in *Human Walking in Virtual Environments: Perception, Technology and Application*, New York Heidelberg Dordrecht London, Springer, 2013, pp. 351-376.
- [43] D. A. Bowman, E. Kruijff, J. J. L. JR. und I. Poupyrev, „3D User Interface Input Hardware,“ in *3D user Interfaces: Theory and Practice*, Boston, Pearson Education, Inc., 2005, pp. 96-105.
- [44] G. Welch, G. Bishop, L. Vicci, S. Brumback, K. Keller und D. Colucci, „High-Performance Wide-Area Optical Tracking: The HiBall Tracking System,“ *Teleoperators and Virtual Environments Vol. 10 Nr. 1*, pp. 1-21, 1 February 2001.
- [45] D. Wormell und E. Foxlin, „Advancements in 3D Interactive Devices for Virtual Environments,“ *Proceedings of the Workshop on Virtual Environments*, pp. 47-56, 2003.
- [46] C. Schönauer, T. Pintaric und H. Kaufmann, „Full Body Motion Capture: A Flexible Marker-Based Solution,“ in *Proceedings of Workshop on Accessibility Engineering with user models, simulation and VR*, Nottingham, UK, 2012.
- [47] C. Schönauer, T. Pintaric, H. Kaufmann, S. Jansen-Kosternik und M. Vollenbroek-Hutten, „Chronic Pain Rehabilitation with a Serious Game using Multimodal Input,“ *Virtual Rehabilitation (ICVR), 2011 International Conference on Virtual Rehabilitation*, pp. 1-8, 27-29 June 2011.
- [48] T. Pintaric und H. Kaufmann, „Affordable Infrared-Optical Pose-Tracking for Virtual and Augmented Reality,“ *Proceedings of IEEE VR Workshop on Trends and Issues in Tracking for Virtual Environments*, pp. 44-51, 14 March 2007.
- [49] PrioVR, „Kickstarter - PrioVR,“ [Online]. Available: <https://www.kickstarter.com/projects/yeitechnology/priovr-suit-up-game-on/>. [Zugriff am 22 March 2015].
- [50] D. A. Bowman, E. Kruijff, J. J. L. JR. und I. Poupyrev, „3D User Interface Output Hardware,“ in *3D User Interfaces: Theory and Practice*, Boston; USA, Pearson Education, Inc., 2005, pp. 29-86.

- [51] K. Omura, S. Shiwa und F. Kishino, „3D Display with Accommodative Compensation: Employing Real-Time Gaze Detection,“ *Journal of the Society for Information Display*, pp. 889-892, 1996.
- [52] C. L. o. t. U. o. Quebec, „Cyberpsychology Lab of the University of Quebec: Cybersickness,“ [Online]. Available: 3.uqo.ca/cyberpsy/en/cyberma_en.htm. [Zugriff am 12 April 2015].
- [53] redOrbit, „The History of Virtual Reality,“ redOrbit, [Online]. Available: http://www.redorbit.com/education/reference_library/general-2/history-of/1113182398/the-history-of-virtual-reality/. [Zugriff am 7 June 2015].
- [54] P. Games, „A Brief History of Video Game Virtual Reality, and why this time will be different,“ Prima Games, [Online]. Available: <http://www.primagames.com/games/killzone-shadow-fall/feature/brief-history-video-game-virtual-reality-and-why-time-will-be-different>. [Zugriff am 7 June 2015].
- [55] G. Nexus, „The History of Virtual Reality & The Future: Rift, Omni, STEM, castAR,“ Gamers Nexus, [Online]. Available: <http://www.gamersnexus.net/guides/1208-history-of-virtual-reality-and-future>. [Zugriff am 7 June 2015].
- [56] I. VR, „Iris VR - Technolust,“ Iris VR, [Online]. Available: <http://irisvirtualreality.com/un-portfolio/technolust-2/>. [Zugriff am 7 June 2015].
- [57] R. Kennedy, N. Lane, K. Berbaum und M. Lilienthal, „Simulator Sickness Questionnaire: An enhanced method for quantifying simulator sickness,“ *International Journal of Aviation Psychology* 3(3), pp. 203-220, 1993.
- [58] „Iris VR - Technolust,“ Iris VR, [Online]. Available: <http://irisvirtualreality.com/un-portfolio/technolust-2/>. [Zugriff am 6 June 2015].

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Questionnaire

Dear study participant!

At the end of this study I'd like you to fill out this questionnaire and thank you for your participation.

Please read the questions carefully before answering them.

***Mandatory**

General Questions

1. Age *

- < 18
- 18 - 24
- 25 - 29
- 30 - 34
- 35 - 40
- 41 - 50
- > 50

2. Sex *

- male
- female

3. Do you wear glasses / contact lenses in daily life? *

- Yes
- No

4. If yes, which optical aid did you wear while playing? *

- Glasses
- Contact lenses
- Nothing

Questions about the Gameplay

5. How realistic was the game experience for you? *

1 2 3 4 5 6 7
very unrealistic very realistic

6. Have you felt uncomfortable when enemies approached? *

1 2 3 4 5 6 7
very comfortable very uncomfortable

7. How difficult was the navigation in the virtual world for you? *

1 2 3 4 5 6 7
very easy very difficult

8. Which difficulties did you have while navigating?

9. How realistic were the spatial proportions for you? *

1 2 3 4 5 6 7
far too small far too big

10. How difficult was it for you to walk on the red line? *

1 2 3 4 5 6 7
very easy very difficult

11. How difficult was it for you to pick up the paper from the treasure chest? *

1 2 3 4 5 6 7
very easy very difficult

12. How difficult was it for you to activate the platforms on the floor? *

1 2 3 4 5 6 7
very easy very difficult

13. How difficult was it for you to push the stones into the wall? *

1 2 3 4 5 6 7
very easy very difficult

14. How realistic was it for you to see your virtual body? *

1 2 3 4 5 6 7
very unrealistic very realistic

15. What was unfamiliar about it?

16. How comfortable have you felt with your virtual body? *

1 2 3 4 5 6 7
very uncomfortable very comfortable

17. How realistic were the body proportions for you? *

1 2 3 4 5 6 7
very unrealistic very realistic

Side effects

To which extent have you felt the afflictions mentioned below during the gameplay?

18. Tiredness, Exhaustion *

1 2 3 4 5 6 7
not at all very much

19. Dizziness *

1 2 3 4 5 6 7
not at all very much

20. Nausea *

	1	2	3	4	5	6	7	
not at all	<input type="radio"/>	very much						

21. Headache *

	1	2	3	4	5	6	7	
not at all	<input type="radio"/>	very much						

22. Eye Strain *

	1	2	3	4	5	6	7	
not at all	<input type="radio"/>	very much						

23. Blurred Sight *

	1	2	3	4	5	6	7	
not at all	<input type="radio"/>	very much						

24. Difficulties to focus *

	1	2	3	4	5	6	7	
not at all	<input type="radio"/>	very much						

25. Difficulty in concentration *

	1	2	3	4	5	6	7	
not at all	<input type="radio"/>	very much						

User Behavior

26. How often do you play video games? (in hours per week) *

- Never
- 0 - 5
- 6 - 10
- 11 - 15
- > 15

27. How realistic was the virtual game experience for you in comparison to a normal video game?

1 2 3 4 5 6 7
very unrealistic very realistic

28. To which game did you compare it?

29. How often do you watch 3D movies? (in hours per week) *

- Never
- 0 - 5
- 6 - 10
- 11 - 15
- > 15

30. How often do you play video games in 3D? (in hours per week) *

- Never
- 0 - 5
- 6 - 10
- 11 - 15
- > 15

31. How realistic was the virtual game experience for you in comparison to a video game you played in 3D mode?

1 2 3 4 5 6 7
very unrealistic very realistic

32. To which game did you compare it?

Questions about the Oculus Rift

33. Have you used the Oculus Rift before? *

Yes

No

34. Have you ever used another HMD (= Head Mounted Display)? *

A HMD is a display device, worn on the head or as part of a helmet that has a small display optic in front of one or each eye.

Yes

No

35. How did you like the graphics? *

	1	2	3	4	5	6	7	
not at all	<input type="radio"/>	very much						

36. How was the perception for you? *

	1	2	3	4	5	6	7	
very bad	<input type="radio"/>	very good						

Questions about the Virtualizer

37. Have you used the Virtualizer before? *

Yes

No

38. How difficult was walking in the Virtualizer for you? *

	1	2	3	4	5	6	7	
very easy	<input type="radio"/>	very difficult						

39. Did you have difficulties to walk in the Virtualizer? *

Yes

No

40. If yes, which?

Questions about the PrioVR

41. Have you ever used a Motion Capture suit before? *

Yes

No

42. Have you ever used the PrioVR before? *

Yes

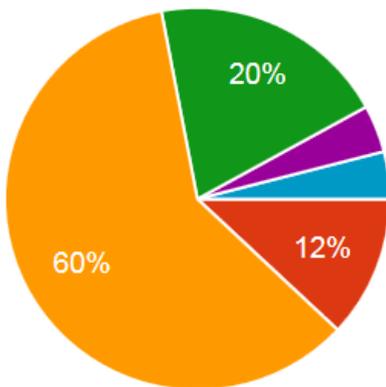
No

Improvements / Comments

43. Place for comments, points of criticisms, improvement suggestions, etc.

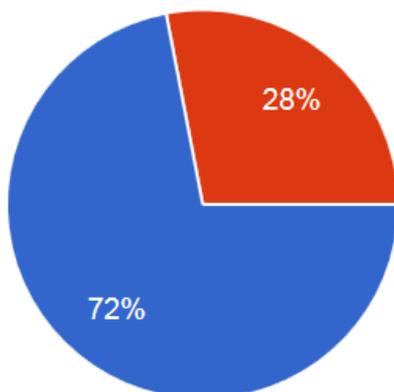
General Questions

Age



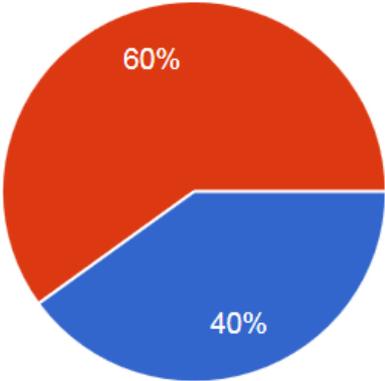
< 18	0	0%
18 – 24	3	12%
25 – 29	15	60%
30 – 34	5	20%
35 – 40	1	4%
41 – 50	1	4%
> 50	0	0%

Sex



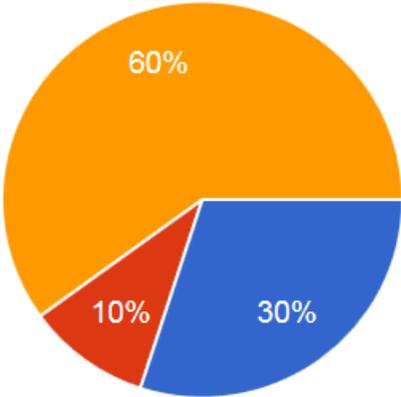
male	18	72%
female	7	28%

Do you wear glasses / contact lenses in daily life?



Yes	10	40%
No	15	60%

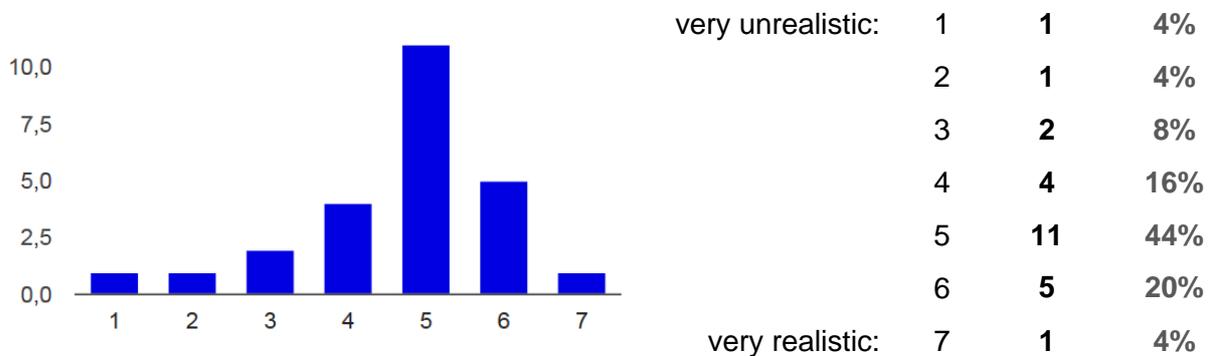
If yes, which optical aid did you wear while playing?



Glasses	3	30%
Contact lenses	1	10%
Nothing	6	60%

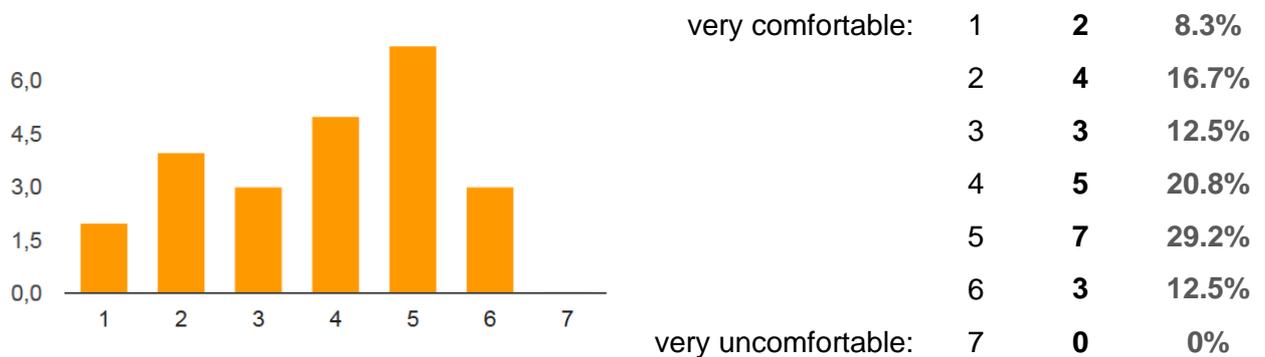
Questions about the Gameplay

How realistic was the game experience for you?



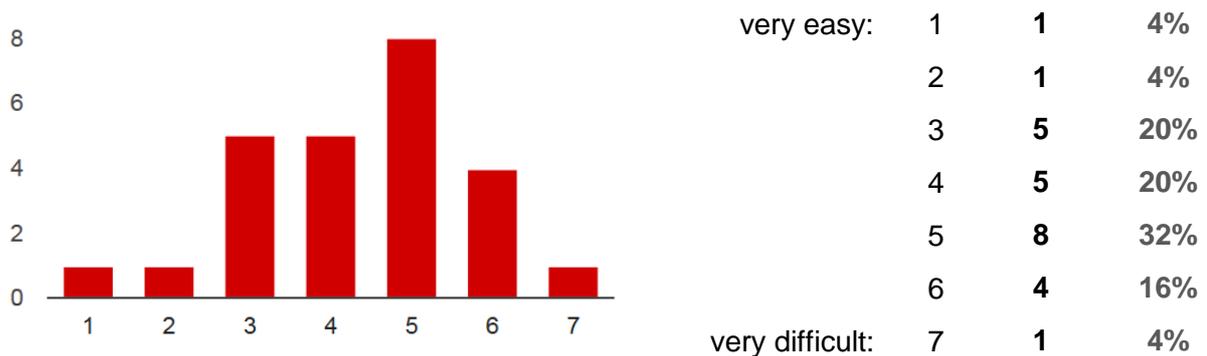
Mean value	4.68
Standard deviation	1.3454
Variance	1.81
Median value	5

Have you felt uncomfortable when enemies approached?



Mean value	3.8333
Standard deviation	1.5511
Variance	2.4058
Median value	4

How difficult was the navigation in the virtual world for you?



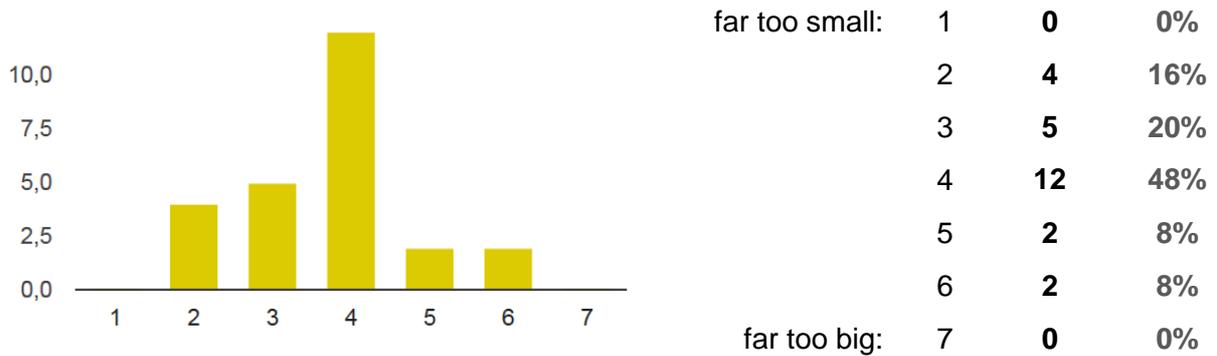
Mean value	4.36
Standard deviation	1.4107
Variance	1.99
Median value	5

Which difficulties did you have while navigating?

- Sometimes walking was not detected and thus it was exhausting to walk through the corridors.
- It was hard to choose the exact walking direction. Walking in the Virtualizer was also not precisely mapped to the VR environment (sometimes the avatar walked too fast and sometimes too slow).
- Walking was too exhausting and thus I got dizzy / sick from it.
- Instructions were correct but I had too much self-motivation and thus had to repeat some of the rooms.
- Walking was difficult in the beginning. It got better during the test.
- Walking direction and body rotations have been often different; frequent re-calibration was necessary
- Got stuck in the pile of stones
- In the room with many corridors
- Fast walking was not possible
- Walking was pretty slow. I would expect to move faster. Sometimes the character went in another direction than I went.
- It was hard to apply the correct pressure in the Virtualizer and I had to pay attention at the chest direction all the time.
- Body was often twisted. When the body was straight it was easy to walk especially at higher speeds.
- Slow movement. Changing direction was difficult at small movements e.g. when activating the platforms on the floor.
- Moving forward was not so easy.

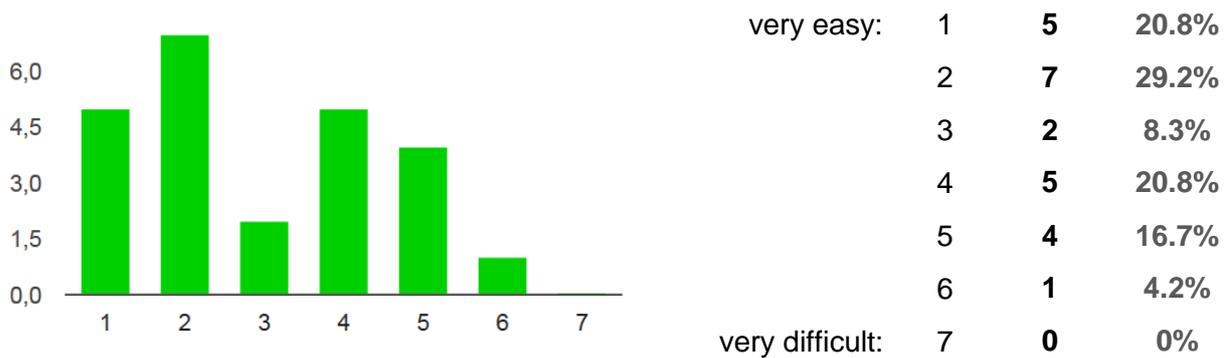
- Sometimes the direction was wrong (slight sideways walking). It was sometimes difficult to change between slow and fast walking.
- Walking was difficult.
- Coordination and locomotion

How realistic were the spatial proportions for you?



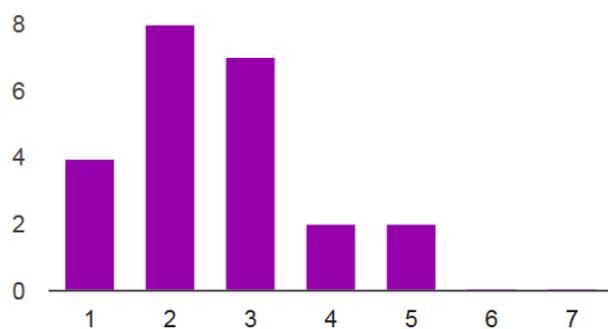
Mean value	3.72
Standard deviation	1.1
Variance	1.21
Median value	4

How difficult was it for you to walk on the red line?



Mean value	2.9583
Standard deviation	1.5737
Variance	2.4764
Median value	2.5

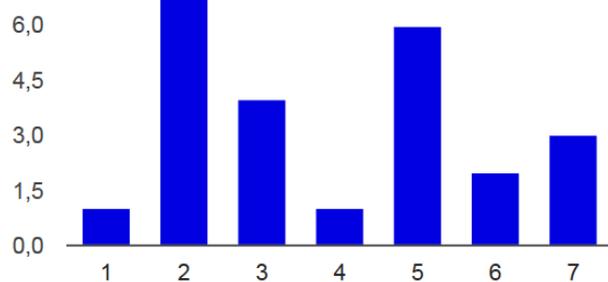
How difficult was it for you to pick up the paper from the treasure chest?



very easy:	1	4	17.4%
	2	8	34.8%
	3	7	30.4%
	4	2	8.7%
	5	2	8.7%
	6	0	0%
very difficult:	7	0	0%

Mean value	2.5652
Standard deviation	1.1610
Variance	1.3478
Median value	2

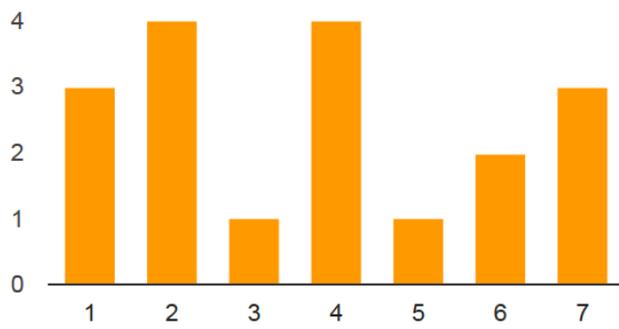
How difficult was it for you to activate the platforms on the floor?



very easy:	1	1	4.2%
	2	7	29.2%
	3	4	16.7%
	4	1	4.2%
	5	6	25%
	6	2	8.3%
very difficult:	7	3	12.5%

Mean value	3.9167
Standard deviation	1.8863
Variance	3.5580
Median value	3.5

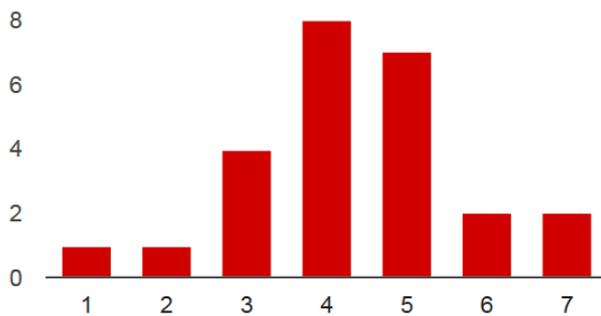
How difficult was it for you to push the stones into the wall?



Label	Difficulty Level	Frequency	Percentage
very easy:	1	3	16.7%
	2	4	22.2%
	3	1	5.6%
	4	4	22.2%
	5	1	5.6%
	6	2	11.1%
	7	3	16.7%
very difficult:			

Mean value	3.7778
Standard deviation	2.1572
Variance	4.6536
Median value	4

How realistic was it for you to see your virtual body?



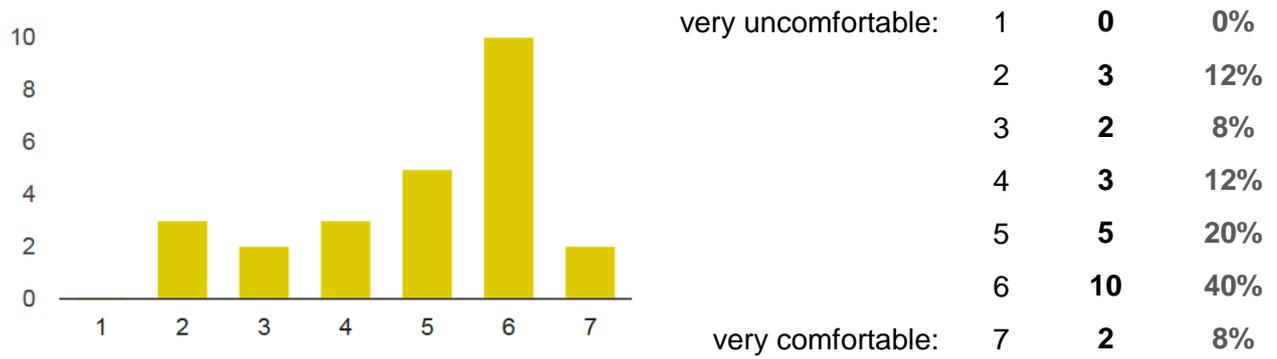
Label	Realism Level	Frequency	Percentage
very unrealistic:	1	1	4%
	2	1	4%
	3	4	16%
	4	8	32%
	5	7	28%
	6	2	8%
	7	2	8%
very realistic:			

Mean value	4.32
Standard deviation	1.4059
Variance	1.9767
Median value	4

What was unfamiliar about it?

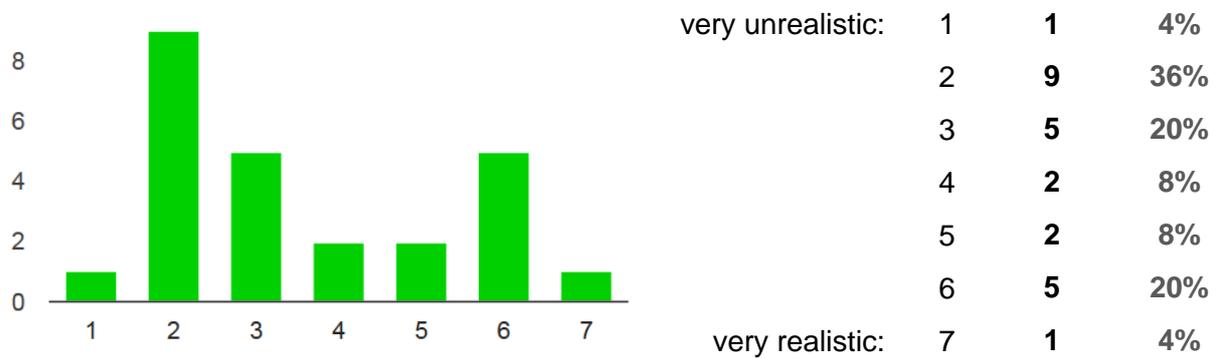
- Short arms
- Dizziness; quitted in the room with the snakes
- Size / proportions of the limbs unrealistic
- The sword was in my face
- Short limbs
- Too thin arms, wrong proportions
- The limbs have been too small and too thin.
- Everything
- Proportions are too small
- Arm pose of the hand holding the sword was unnatural
- To see another body than my own
- The arms were too short and the hands were too small.
- Proportions, and the movement with the head, because I am used to control with thumb sticks and to see myself
- I had the feeling that I am very small in the game
- The arms were too short and too thin and they were too low positioned at the body
- Arms / legs too short
- The arms were sometimes in strange angles
- Mapping didn't completely match.
- It was too small, and the hands were too short.
- The body was twisted to the viewing direction, or the camera was inside the body.
- The body seemed to be too small (I am 185cm).

How comfortable have you felt with your virtual body?



Mean value	4.92
Standard deviation	1.5253
Variance	2.3267
Median value	5

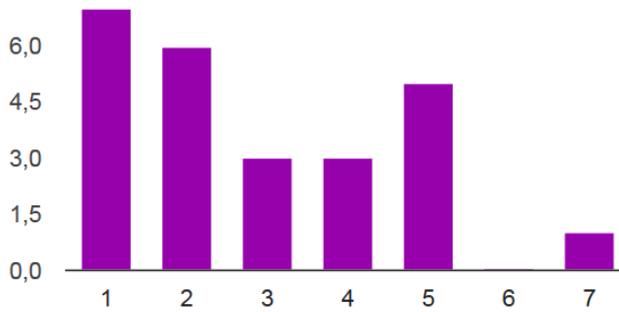
How realistic were the body proportions for you?



Mean value	3.56
Standard deviation	1.7814
Variance	3.1733
Median value	3

Side effects

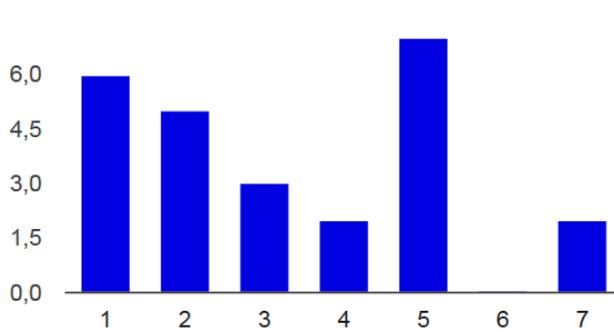
Tiredness, Exhaustion



not at all:	1	7	28%
	2	6	24%
	3	3	12%
	4	3	12%
	5	5	20%
	6	0	0%
very much:	7	1	4%

Mean value	2.88
Standard deviation	1.7397
Variance	3.0267
Median value	2

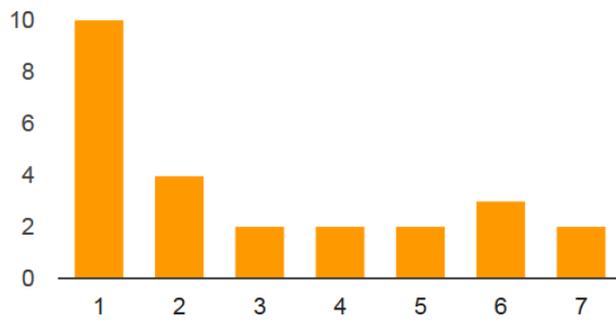
Dizziness



not at all:	1	6	24%
	2	5	20%
	3	3	12%
	4	2	8%
	5	7	28%
	6	0	0%
very much:	7	2	8%

Mean value	3.28
Standard deviation	1.9261
Variance	3.71
Median value	3

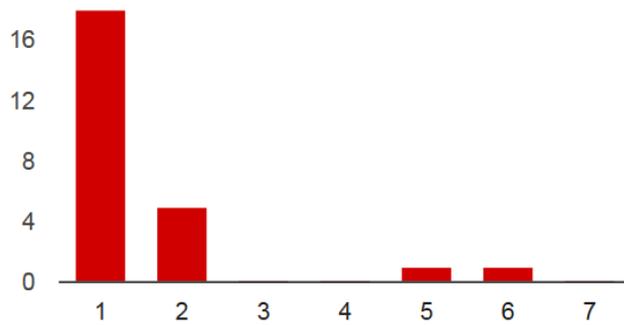
Nausea



not at all:	1	10	40%
	2	4	16%
	3	2	8%
	4	2	8%
	5	2	8%
	6	3	12%
very much:	7	2	8%

Mean value	2.96
Standard deviation	2.1695
Variance	4.7067
Median value	2

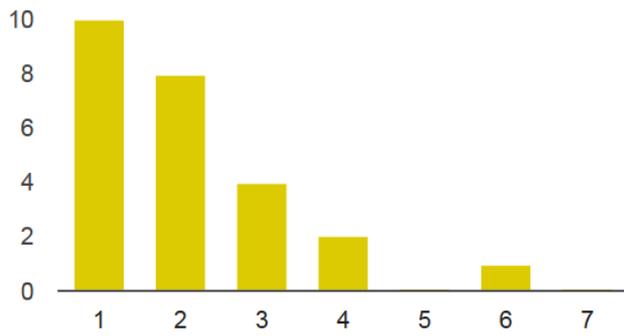
Headache



not at all:	1	18	72%
	2	5	20%
	3	0	0%
	4	0	0%
	5	1	4%
	6	1	4%
very much:	7	0	0%

Mean value	1.56
Standard deviation	1.2610
Variance	1.59
Median value	1

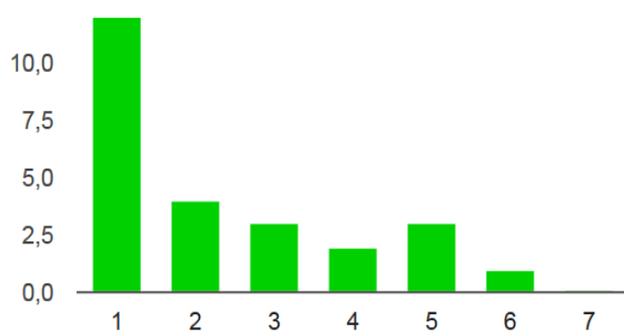
Eye Strain



not at all:	1	10	40%
	2	8	32%
	3	4	16%
	4	2	8%
	5	0	0%
	6	1	4%
very much:	7	0	0%

Mean value	2.08
Standard deviation	1.2557
Variance	1.5767
Median value	2

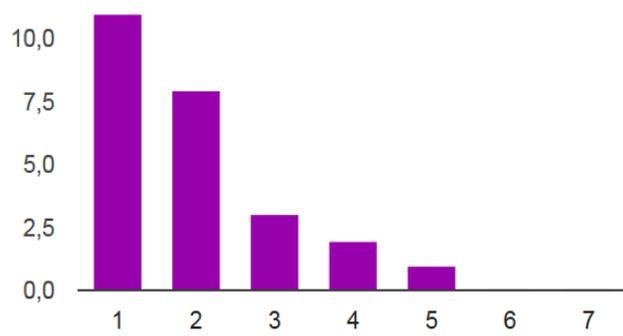
Blurred Sight



not at all:	1	12	48%
	2	4	16%
	3	3	12%
	4	2	8%
	5	3	12%
	6	1	4%
very much:	7	0	0%

Mean value	2.32
Standard deviation	1.6258
Variance	2.6433
Median value	2

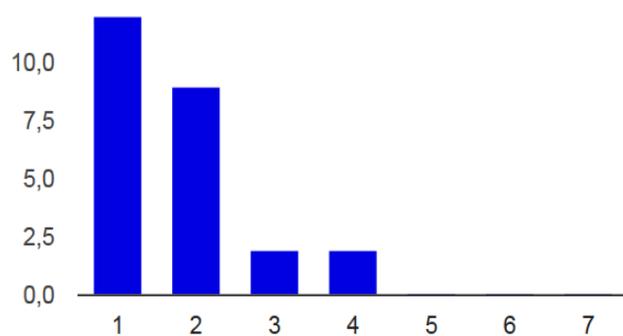
Difficulties to focus



not at all:	1	11	44%
	2	8	32%
	3	3	12%
	4	2	8%
	5	1	4%
	6	0	0%
very much:	7	0	0%

Mean value	1.96
Standard deviation	1.1358
Variance	1.29
Median value	2

Difficulty in concentration

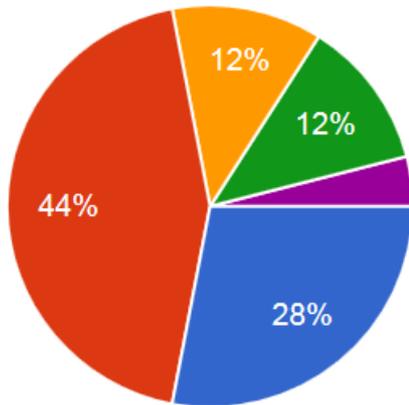


not at all:	1	12	48%
	2	9	36%
	3	2	8%
	4	2	8%
	5	0	0%
	6	0	0%
very much:	7	0	0%

Mean value	1.76
Standard deviation	0.9256
Variance	0.8567
Median value	2

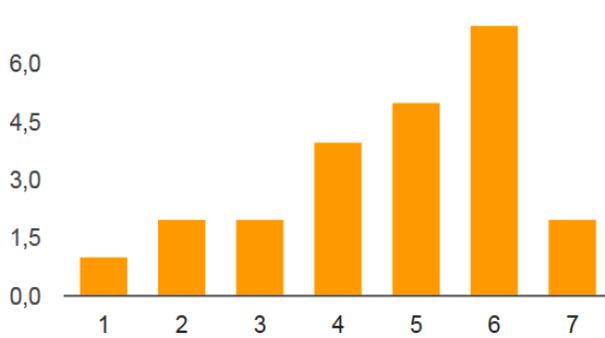
User Behavior

How often do you play video games? (in hours per week)



Never	7	28%
0 – 5	11	44%
6 – 10	3	12%
11 – 15	3	12%
> 15	1	4%

How realistic was the virtual game experience for you in comparison to a normal video game?



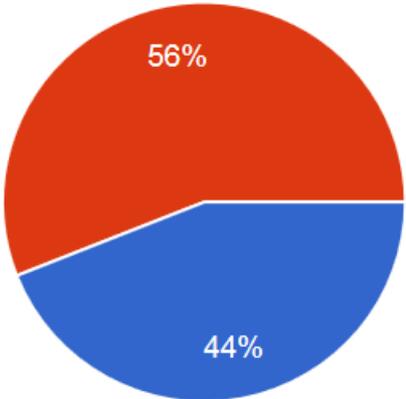
very unrealistic:	1	1	4.3%
	2	2	8.7%
	3	2	8.7%
	4	4	17.4%
	5	5	21.7%
	6	7	30.4%
very realistic:	7	2	8.7%

Mean value	4.6957
Standard deviation	1.6358
Variance	2.6759
Median value	5

To which game did you compare it to?

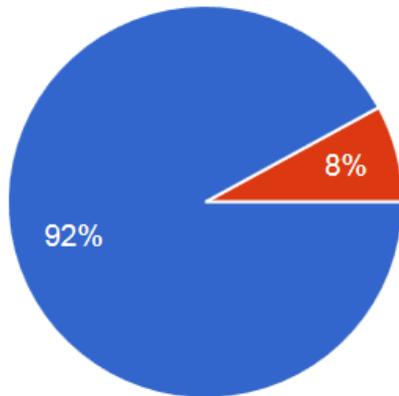
- Halo 1-4, CoD
- Doom
- I don't know such a game
- Chivalry
- Elder Scrolls
- Minecraft
- TESO
- Dark Souls
- Doom 2
- Team Fortress 2
- Doom
- Call of Duty
- Tomb Raider
- Prince of Persia

How often do you watch 3D movies? (in hours per week)



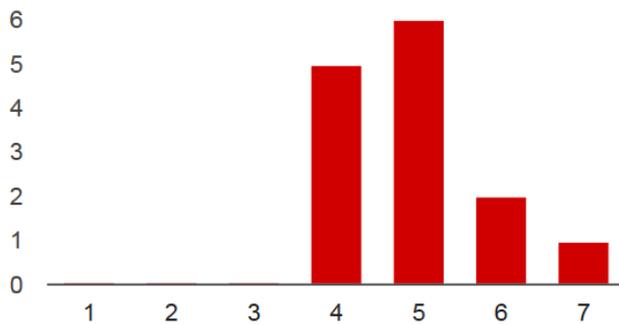
Never	11	44%
0 – 5	14	56%
6 – 10	0	0%
11 – 15	0	0%
> 15	0	0%

How often do you play video games in 3D? (in hours per week)



Never	23	92%
0 – 5	2	8%
6 – 10	0	0%
11 – 15	0	0%
> 15	0	0%

How realistic was the virtual game experience for you in comparison to a video game you played in 3D mode?



very unrealistic:	1	0	0%
	2	0	0%
	3	0	0%
	4	5	35.7%
	5	6	42.9%
	6	2	14.3%
very realistic:	7	1	7.1%

Mean value	4.9286
Standard deviation	0.9169
Variance	0.8407
Median value	5

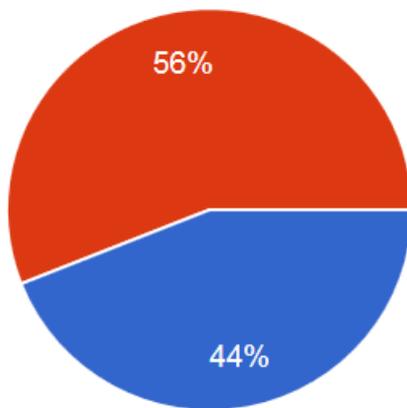
To which game did you compare it?

- Doom
- Medal of Honor
- Colin McRae Rally

- Team Fortress
- Call of Duty Black ops 2
- Team Fortress 2
- Sonic
- I don't play games in 3D mode

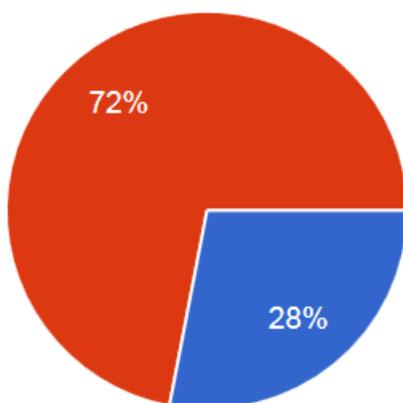
Questions about the Oculus Rift

Have you used the Oculus Rift before?



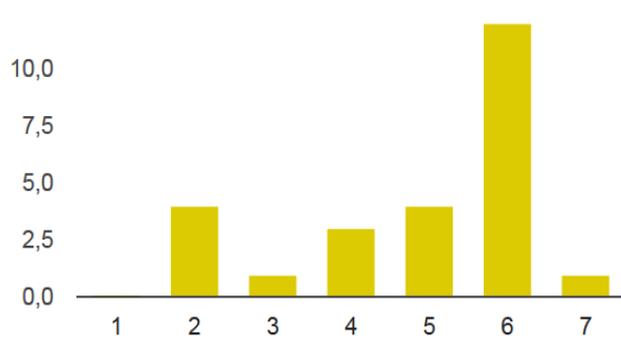
Yes	11	44%
No	14	56%

Have you ever used another HMD (= Head Mounted Display)?



Yes	7	28%
No	18	72%

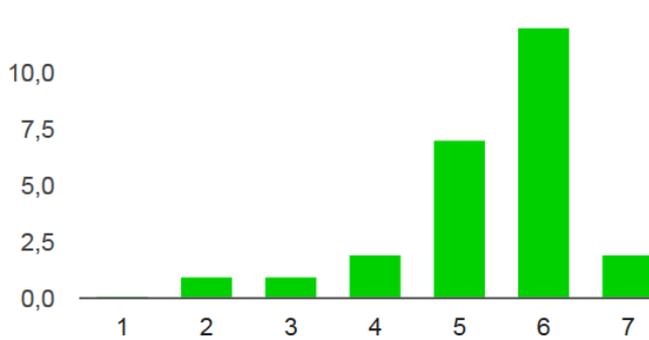
How did you like the graphics?



not at all:	1	0	0%
	2	4	16%
	3	1	4%
	4	3	12%
	5	4	16%
	6	12	48%
very much:	7	1	4%

Mean value	4.88
Standard deviation	1.5631
Variance	2.4433
Median value	6

How was the perception for you?

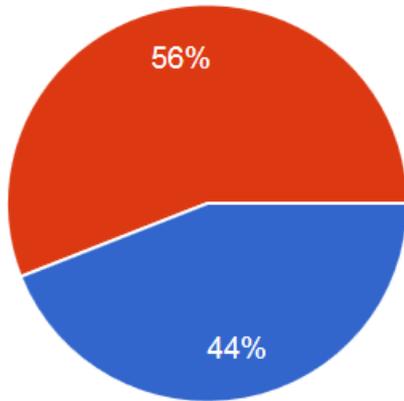


not at all:	1	0	0%
	2	1	4%
	3	1	4%
	4	2	8%
	5	7	28%
	6	12	48%
very much:	7	2	8%

Mean value	5.36
Standard deviation	1.1504
Variance	1.3233
Median value	6

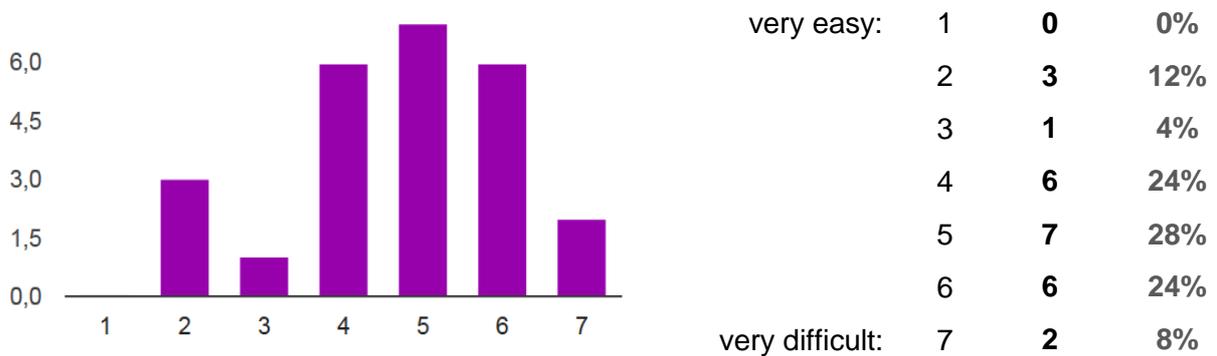
Questions about the Virtualizer

Have you used the Virtualizer before?



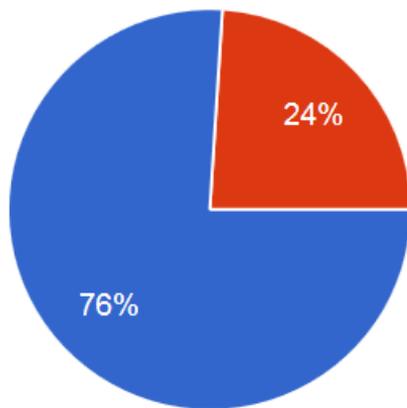
Yes	11	44%
No	14	56%

How difficult was walking in the Virtualizer for you?



Mean value	4.72
Standard deviation	1.4295
Variance	2.0433
Median value	5

Did you have difficulties to walk in the Virtualizer?



Yes	19	76%
No	6	24%

If yes, which?

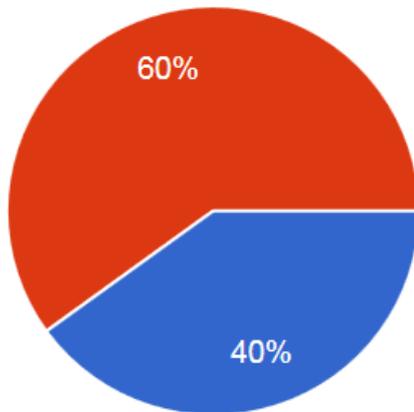
- Missing precision between slow and fast walking
- Not as slippery as it should be + 1 direction movement available is not very good.
- Balance shift was not ideal
- Walking movements were hardly detected and thus I had to struggle when walking.
- Belt system is disturbing. It would be better to have a complete belt that is mounted to the ceiling with a hook.
- Difficulties when moving forward.
- It was hard to choose the walking direction precisely and to achieve precision position changes.
- Too large steps for the sensor
- The virtual character was moving much slower. Sometimes the character went in another direction than I went.
- Detection of walking. Got better with time.
- It was hard to understand how to apply force to it.
- Sometimes slow locomotion speed
- I walked a little bit too slow. The avatar should move more unity forward per real step.
- Walking direction and body rotations didn't match.
- It is exhausting to slide in the middle of the platform
- It was difficult to move forward.
- Walking velocity in comparison to the already walked steps
- Dizziness and nausea because of the jerky up and down movement during walking. Leaning forward to reach the sensors with the feet was exhausting,

because when leaning forward I made a bigger step backwards and didn't touch the sensors.

- No perfect calibration -> drifted to the right

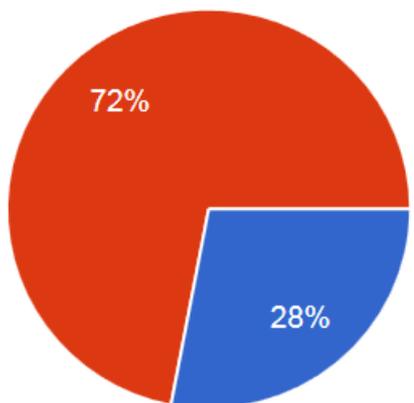
Questions about the PrioVR

Have you ever used a Motion Capture suit before?



Yes	10	40%
No	15	60%

Have you ever used the PrioVR before?



Yes	7	28%
No	18	72%

Improvements / Comments

Place for comments, points of criticism, improvement suggestions, etc.

- I am looking forward to a second part and would be participating again.
- Nice
- It is fun, good graphics / nice world
- Putting on the equipment was tedious; quitted the game in the room before last because of dizziness
- Body suit with a hook on the back for mounting it on the ceiling
- Nausea in the last third of the game and thus had to quit in the last room.
- Implementing real Virtualizer components (3 metal pillars) in the virtual game (context dependent game objects), which the player avoids to touch or hit. I was carefully when kicking and this reduces the virtual experience.
- The game looks very good in terms of graphics, content, and playing. The only disadvantages are the limitations in the technology, particularly Virtualizer and PrioVR, because these are not perfect.
- Dizziness and nausea due to the jerking of the view during walking. I quitted the game in the room before last. More sensors on the platform to make walking easier.
- Sounds should be of the same volume – if they are abrupt or too loud – that's a bit disturbing. The reaching (hand length) probably needs to be bigger due to limited field of view. Or bigger colliders on joints / targets to make the game not so exhausting. I liked the tasks! That was really nice. Thanks!
- It would be a better experience if the avatar would be scaled to the real body size. (I am 1.9m)
- The mapping of the real body movements to the avatar could be more precise to feel more secure during the whole game and to be able to move more confident. I had to quit the game in the room before last. I could not solve the images because of decreasing concentration.
- I quitted in the beginning of the first room because of dizziness.
- Very nice designed game!