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In-place 3D Locomotion for Public VR Exhibits

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Contents

Abstract xiii

Überblick xv

Acknowledgements xvii

Conventions xix

1 Introduction 1

1.1 Research Questions 2

1.2 Outline 3

2 Related Work 5

2.1 Horizontal Locomotion 5

2.1.1 Velocity Control 6

Arm-Swinging 7

Arm-Cycling 8

VRStep 10

2.1.2 Steering Control 11

Walking-in-Place with Lean-directed steering 12

2.2 Vertical Movement 13

Ladders 14

3 Discussing Locomotion Methods 15

Walking-in-Place With Hand-directed Steering 16

Walking-in-Place With Gaze-directed Steering 17

Walking-in-Place with the use of Ladders 18

Walking-in-Place with the use of Platforms 19

Arm-Cycling With Gaze-directed Steering 20

Arm-Cycling With Swim-directed Steering 21

4 Preliminary study 23

4.1 Study Design 23

4.2 Results 26

4.3 Evaluation of the preliminary study 27

5 User Study 31

5.1 Hypotheses 31

5.2 Apparatus 32
5.3 Implementation 35
5.3.1 Implementation of Walking-in-Place . 35
5.3.2 Implementation of Arm-Cycling . . . 38
5.3.3 Implementation of Gaze-directed steering 38
5.3.4 Implemetation of Platform-travel . . . 40
5.3.5 Implementation of Ladder-traveling . 40
5.3.6 Implementation of Hand-directed steering 41
5.4 Study Design 42
5.5 Results 42

6 Evaluation 49

6.1 Velocity control 49
6.2 Steering Control 50
6.3 Qualitative Feedback 51
6.4 Implications 51

7 Summary and Future Work 53

7.1 Summary and Contributions 53
7.2 Future work 54

Bibliography 55

Index **61**

List of Figures

2.1 Arm-Swinging 8

2.2 Arm-Cycling 9

2.3 Walking-in-Place 11

2.4 Ladder-traveling 14

3.1 Walking-in-place with hand-directed steering 16

3.2 Walking-in-place with gaze-directed steering 17

3.3 Ladder-traveling 18

3.4 Platform-travel 19

3.5 Arm-cycling with gaze-directed steering . . . 20

3.6 Arm-cycling with swim-directed steering . . 21

4.1 Screenshot of Splitscreen video 24

4.2 Maze of the preliminary study 25

4.3 Landmark1 25

4.4 Landmark2 26

4.5 Ranking 1 27

4.6 Ranking 2 28
4.7 Ranking 3 29
4.8 Ranking 4 30

5.1 Top view of the museum 32
5.2 In-game screenshot of how chests were hidden 33
5.3 In-game screenshot of the lowest floor 33
5.4 Closed treasure chest 34
5.5 Opened treasure chest 35
5.6 Deriving acceleration out of positional data . 36
5.7 Step-detection algorithm 37
5.8 Creating direction-vector with side-tilt 39
5.9 Calculation angle for side-tilt 40
5.10 Caculating angle for front-tilt 41
5.11 User study 43
5.12 Mean of body translation 44
5.13 Mean of head rotation 46

6.1 Ranking after user study 52

List of Tables

2.1 Methods and vestibular feedback 6

4.1 Acceptance Results 27

4.2 Premo Results 27

5.1 Usability Questionnaire Results 45

5.2 Simulator Sickness Questionnaire Results . . 45

5.3 Body translation 46

5.4 Time 46

5.5 Distance 46

5.6 Rotation 47

5.7 Means of sum of errors 47

Abstract

Virtual reality offers different opportunities to exhibitions and museums. For example it enables users to enter closed areas or to view exhibits on their own while in a crowded area. With more powerful smartphones virtual reality becomes available in mobile applications. However, the context of an exhibition creates very unique requirements to the interactions. First, the user is located in a public environment, which makes social acceptance of the method mandatory. Also, users should be able to locomote freely around objects, so vertical movement must be possible.

In this thesis we develop six possible locomotion methods that build on techniques found in previous work. We examine walking-in-place and arm-cycling combined with the two steering selections gaze-directed steering and hand-directed steering as well as with ladder-traveling and platform-traveling. In a preliminary study on the social acceptance of locomotion methods we see that arm-cycling was experienced as unpleasant. However, we show in our user study that users felt more in control with arm-cycling compared to walking-in-place. Further we show, that most users like arm-cycling after they tried it. Users tend to need less space with arm-cycling. Hand-directed steering is less intuitive than the other steering controls and ladder-traveling is more complex and more unrealistic than platform-traveling. Overall we present gaze-directed steering to be the better choice in time critical tasks, while platform-travel is better when realism is needed.

Überblick

Durch Virtual Reality entstehen neue Möglichkeiten für Ausstellungen und Museen. So können zum Beispiel gesperrte Bereiche virtuell betreten oder Ausstellungsstücke alleine betrachtet werden, obwohl der Nutzer sich an einem belebten Ort befindet. Durch leistungsstärkere Smartphones wird Virtual Reality auch in mobilen Applikationen möglich. Jedoch ergeben sich durch die Verwendung in Ausstellungen auch besondere Anforderungen. Da der Nutzer sich an einem öffentlichen Ort befindet, ist soziale Akzeptanz dieser Methode obligatorisch.

In dieser Arbeit entwickeln wir auf der Basis von Literatur sechs verschiedene Fortbewegungsmethoden. Wir beleuchten Walking-in-Place und Arm-Cycling verbunden mit den zwei Richtungssteuerungen Gaze-directed steering und Hand-directed steering, sowie Ladder-traveling und Platform-traveling. In einer Vorstudie zur sozialen Akzeptanz hat sich gezeigt, dass Arm-Cycling als unangenehm wahrgenommen wird. In unserer Userstudie konnten wir jedoch zeigen, dass Nutzer mit Arm-Cycling, verglichen zu Walking-in-Place, ein höheres Kontrollgefühl haben. Weiterhin konnte Arm-Cycling die meisten Nutzer nach dem Ausprobieren überzeugen. Außerdem zeigte sich, dass Nutzer mit Arm-Cycling weniger Platz benötigen. Hand-directed steering war unintuitiver als die anderen Richtungssteuerungen und Ladder-traveling ist komplexer und unrealistischer als Platform-traveling. Insgesamt ist Gaze-directed steering die bessere Wahl bei zeitkritischen Aufgaben, während Platform-travel die bessere Methode ist, wenn es auf Realismus ankommt.

Acknowledgements

At first, I want to thank my supervisors Sebastian Hueber and Adrian Wagner for answering me thousand questions over the last months.

Secondly, I want to thank each participant in the preliminary and in the user study for their time and effort.

Conventions

Throughout this thesis we use the following conventions.

Text conventions

Definitions of technical terms or short excursus are set off in coloured boxes.

Excursus:
Excursus are detailed discussions of a particular point in a book, usually in an appendix, or digressions in a written text.

Definition: *Excursus*

The whole thesis is written in English.

Chapter 1

Introduction

In this thesis we are evaluating locomotion techniques which can be used in public exhibition, allow for vertical movement and are applicable on smartphones

VR has become popular in the last few years. With the wide availability of consumer products, researchers came up with the idea of using VR in exhibitions. For example Lepouras et al. [2001] came up with the idea of using virtual environments in real museums. With VR we could give users the opportunity to inspect exhibits in more detail, reach closed areas and explore the exhibition alone while in a crowded environment. In big open spaces like a cathedral we could even give users the ability to fly. The main disadvantage of VR is the need for powerful PCs and special hardware and in most cases tracking devices needs to be mounted on walls and the ceiling. However smartphones become more powerful over time and therefore VR is entering the mobile market with e.g. Google Cardboard or Samsung Gear VR. Consequently one could use the visitors smartphone to offer a virtual experience. However with the use of mobile VR in exhibitions other problems arise which are no problem for common applications. Exhibitions are crowded spaces and therefore we have to take care of bystanders and the social acceptance. Also the space users have on hand is limited. According to Tregillus and Folmer [2016], common locomotion methods like Look-Down-To-Move are not suitable for our case, because they are lowering immersion. Further we need a locomotion method to travel also vertical, since our exhibition room might be a big hall.

Since VR came up in the early 90s of the last century researchers began to investigate different ways to locomote virtually. Therefore Boletsis and Cedergren [2019] found in a literature study that virtual locomotion represents a scientific field which is good explored. Nevertheless, accordingly to Lai et al. [2015], there are only a few ways to locomote vertically. In this thesis we investigate different locomotion methods which allow for 3-dimensional travel. We will examine the applicability of these locomotion methods and further we will have a look at the usability in a user study. In the process we will have a look at the ability of users to orientate and collect data on the user experience.

1.1 Research Questions

We decided on the following Research Questions.

- Which locomotion method should we use for 3-dimensional locomotion?
- Which locomotion method has the highest social acceptance?
- How can we prevent locomotion methods from appearing awkward to bystanders?
- Which 3-dimensional locomotion method is space effective?
- How can we ensure that users stay orientated?
- Which 3-dimensional locomotion method is best for the sense of presence?
- How strong are users affected by simulator sickness in vertical travel and are there differences between methods?

1.2 Outline

In the following chapter we present selected work on locomotion in VR either allowing for horizontal or 3-dimensional travel. Chapter 3 then decides on 6 different locomotion methods, in respect of the literature from Chapter 2. Then we examine the social acceptance of this six locomotion methods in Chapter 4. Further we describe the implementation and the design of our user study in Chapter 5. We evaluate the findings of the user study then in Chapter 6 and give some implications for developers. Lastly, we summarize in Chapter 7.

Chapter 2

Related Work

As human beings are incapable of flying, horizontal locomotion in VR realistically matches the human abilities and is, accordingly to Boletsis and Cedergren [2019], well explored. However, in our context vertical locomotion is also required. In this chapter we first have a look on current techniques for horizontal travel in a mobile context. After that we will picture locomotion techniques which also allow for vertical travel.

2.1 Horizontal Locomotion

Real walking is a good way, but not applicable for us

According to Bowman [2005], locomotion and pathfinding is a main task in common video games and also in virtual reality. A good way to locomote in virtual reality is to walk naturally (Bowman [2005]). But real walking is not effective when it comes to space restrictions (Bowman [2005]) , since we can't span longer distances. To walk further than a few meters we have to use some sort of technique to travel without (or less) physical movement. For free movement through the vertical environment one can split between velocity and direction control. Velocity control is needed to define a movements pace, steering control to define the moving direction.

We are splitting into velocity and steering control

2.1.1 Velocity Control

Joystick control causes simulator sickness

When we think about controlling velocity in virtual reality one could think about using the thumb-sticks or a joystick. With this the user wouldn't experience physical travel and its main downside is the capability of simulator sickness, which is, accordingly to Treisman [1977], among other factors caused by the lack of vestibular feedback.

Definition: *Simulator Sickness*

SIMULATOR SICKNESS:
Simulator Sickness is a byeffect which is caused by deviation of proprioceptive and visual feedback (Treisman [1977]). Most commonly it is experienced with nausea, vertigo and transpiration.

Since vestibular feedback is a relevant factor it is useful to split further into methods which preserve vestibular feedback and those which don't. A few different methods classified whether they preserve vestibular cues are listed in the Table 2.1.

Definition: *vestibular feedback*

VESTIBULAR FEEDBACK:
Vestibular feedback is generated by the vestibular system located in the inner ear. This sensory organ contributes to the sense of balance and acceleration. (Lawson and Riecke [2014])

Table 2.1: Methods and vestibular feedback

Vestibular feedback	No vestibular feedback
Real Walking	Joystick
Redirected Walking	Fixed velocity (LDTM)
Walking in Place	Arm-Cycling
Treadmills	

Real walking is the best way to gain spatial understanding.

Another important property of a locomotion method is whether it gives the user the ability to gain spacial understanding of his virtual surroundings. Spatial understanding is important for the user to be able to orientate and not get lost. It has been shown, that full physical movement plays a role to gain spatial understanding (Ruddle and Lessels [2006]). After Darken and Peterson [2014] real walking is the best way to gain spacial understanding, but walking-in-place can also give spacial understanding (Slater et al. [1995]). Also real walking and walking-in-place perform good when it comes to sense of presence (Riecke et al. [2010]). With the sense of presence we give the user the feeling of being really there (Bowman [2005]). As claimed by Bowman [2005], it is also important that the locomotion method is intuitive and does not create high cognitive load, since this would prevent that the user can focus on other tasks.

But Walking-in-Place is also good.

WALKING-IN-PLACE:
With walking-in-place users only lift their feed without making steps forward.(see Figure 2.3)

Definition: *Walking-in-Place*

SPATIAL UNDERSTANDING:
Spatial understanding or spatial orientation is the ability to determine the owns position and rotation in the room.

Definition: *Spatial Understanding*

SENSE OF PRESENCE:
With the sense of presence the user forgets his real surroundings and perceives the virtual environment as real.

Definition: *Sense of Presence*

Arm-Swinging

Arm-swinging (see Figure 2.1) was invented by McCullough et al. [2015] as a way to locomote in VR with a walking-like arm movement. They used accelerometers on the arm of the user. As indicator for spacial understanding they measured the ability of the participants to face a remembered point in VR. They compared arm-swinging to real walking and joystick-control. In their user study with 12 participants the spacial understanding of the users was not affected with arm-swinging, compared to real walking.

Arm-swinging is an walking-like arm movement

Spacial understanding is not affected with arm-swinging.

In a further study by Wilson et al. [2016] arm-swinging was compared to walking-in-place and real walking. Their implementation of walking-in-place used two accelerometers placed at the participants feet. They were using a similar approach to measure the spacial understanding. In a

No significant differences between arm-swinging and walking-in-place in spatial understanding

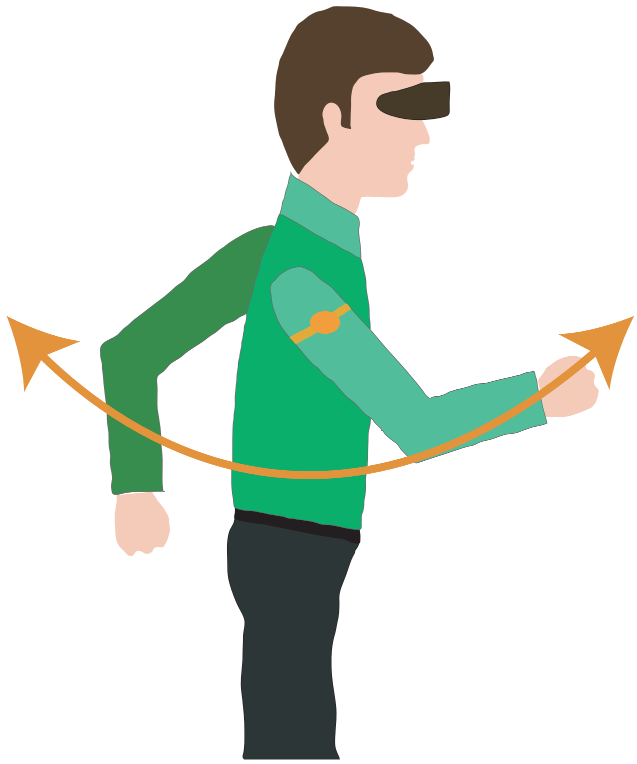

Figure 2.1: With arm-swinging the user performs a walking-like arm-movement without taking steps.

user study of 18 participants they could establish a significant difference between real walking and arm-swinging in terms of spatial understanding. This is directly contradicting to the founding of McCullough et al. [2015]. Wilson et al. assumed this could be due to outliers of participants who might need more training. Further they were able to show that there was no significant difference between arm-swinging and walking-in-place (Wilson et al. [2016]).

Arm-Cycling

The movement of arm-cycling is like a breast-stroke

Arm-cycling was invented by Coomer et al. [2018] based on the work of McCullough et al. and Wilson et al. Arm-cycling has a slightly different motion which the user is performing and uses tracked controllers instead of accelerom-

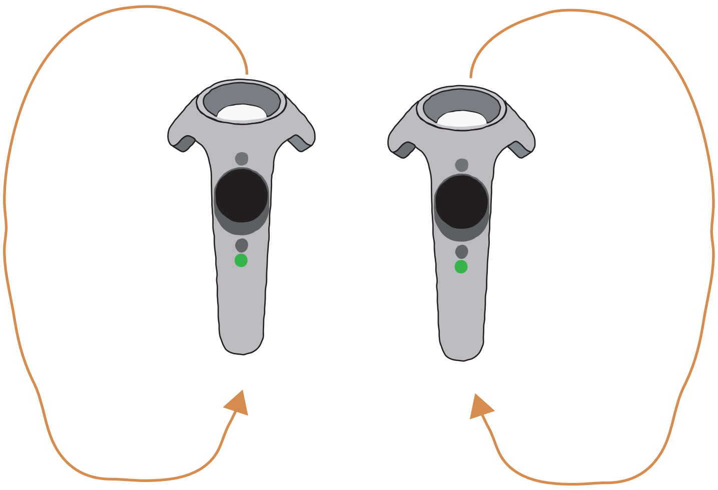

Figure 2.2: Arm-cycling is a breast-stroke like arm-movement. The displacement of the controller is used to control velocity

eters. This means that positional tracking is available. The user has a controller in each hand and has to press both triggers. Then he performs a circular motion like a breast-stroke with the controllers (see Figure 2.2). The absolute displacement of the controller is then used to control velocity. Since it is using the displacement, the user can also perform a motion like arm-swinging to move forwards (Coomer et al. [2018]). With arm-cycling Coomer et al. introduced a second new locomotion method called "Point-tugging". With point-tugging the user grabs a point in 3D-Space and can pull himself either towards or away from the point.

They used a search task for evaluation

To evaluate their two new methods they led participants perform a search task in a virtual town. Teleporting and joystick-control were also evaluated in their study. Fifteen treasure chests were spread randomly and eleven of them contained a treasure. Participants had to find every full treasure chest to complete the task. The time, amount of revisits of chests, the traveled distance and the amount of rotation were recorded. After the task was completed participants had to fill a survey with 15 questions on a Likert-Scale from 1 to 5 and a Simulator Sickness Questionnaire by Kennedy et al. [1993]. This procedure was repeated four times for every condition. Before the trial, participants had to fill a Simulator Sickness Questionnaire for the baseline.

Participants felt more in control with arm-cycling compared to three other methods

Arm-cycling had no impact on simulator sickness

They found that participants felt with arm-cycling and joystick more in control than with teleporting and point-tugging. Point-tugging and arm-cycling was more tiring. Participants described teleporting and point-tugging as more frustrating and experienced with joystick and especially with point-tugging simulator sickness. As Christou and Aristidou [2017] suggested teleport had no impact on simulator sickness and also arm-cycling had no impact.Arm-cycling had the lowest distance traveled and the lowest amount of revisits.

VRStep

VRStep is mobile implementation of Walking-in-Place

For mobile locomotion it is a common approach to simply toggle with a button whether the user is walking or not (Tregillus and Folmer [2016]). This is known as Look-Down-To-Move (LDTM). Accordingly to Tregillus and Folmer [2016] LDTM can lower immersion and brings the user out of focus. Tregillus and Folmer [2016] were proposing a walking-in-place (see Figure 2.3) approach for mobile applications called VRStep. Tregillus et al. were using the build-in accelerometer of a smartphone. As stated by Foster et al. [2005] accelerometer are more accurate, when they are worn closer to the feet. Accuracy is a mature concern, because low starting and stopping latency is important for walking-in-place (Templeman et al. [1999]).

VRStep uses the accelerometer of a smartphone

VRStep was more preferred by users compared to LDTM

Eighteen participants were in their trial. They found, that there was no significant difference between locomotion methods in terms of time and distance when participants

Figure 2.3: With walking-in-place users perform a walking like movement without taking steps forward.

had to walk in straight line between two points. For an obstacles avoidance task they could see a lower time for LDTM. Users preferred walking-in-place significantly more often in terms of learnability and immersion.

2.1.2 Steering Control

There are some methods for steering control like joystick control, gaze-directed steering, hand-directed steering and lean-directed steering. Controlling the direction with a joystick would be an easy approach because this input is commonly used in video games, but there are findings, that this method does not offer high presence. Another approach is to bundle gaze direction and travel direction as gaze-directed steering. This is more intuitive for the user, but

Interesting methods are Gaze-directed, Hand-directed and Lean-directed steering has the disadvantage that the user can't look in another direction while walking (Bowman [2005]).Hand-directed steering allows that, because it derives the direction from a tracker in the hand of the user. But this can be unintuitive and therefore it causes high cognitive load (Bowman [2005]). However, it is excellent to gain spatial understanding (Bowman [2005]). Decoupling of travel- and gaze-direction can be done more natural, when placing the tracker on the torso of the user (LaViola [2017]). But this is not practical for horizontal travel (LaViola [2017]). Lean-directed steering uses the leaning direction of the user. This can cause simulator sickness (LaViola [2017]), but expands presence (Kruijff et al. [2016]).

Walking-in-Place with Lean-directed steering

Tregillus et. al. added Lean-directed steering to VRStep

In a further publication of Tregillus et al. [2017] they were investigating a lean-directed steering control for mobile context. They added a lean-interface to VRStep for enabling omnidirectional movements. However, they used the leaning of the head based on the assumption, that head-tilt is similar to whole body leaning (Tregillus and Folmer [2016]). Thus, walking-in-place controls the velocity, while tilting controls the direction.

They used an avoidance task

In a user study with 25 participants, they were comparing walking-in-place with head-tilt to a method called TILT which used only head tilt. Joystick-control was also evaluated. In the trial participants had to walk down a corridor with obstacles to avoid. Simulator Sickness was measured with a Simulator Sickness Questionnaire (SSQ) by Kennedy et al. [1993] and qualitative feedback was collected.

They found, that TILT had a significant lower completion time compared to WIP-TILT and Joystick control.Since this was unexpected, they concluded the difference was due to more effort by the user in WIP-TILT (Tregillus and Folmer [2016]). Participants experienced low to mild simulator sickness with no significant differences between methods. (Tregillus and Folmer [2016]). The most participants preferred TILT and found it to be the most efficient while they found WIP-TILT to have the highest presence. Tregillus et al. concluded that WIP-TILT got the lowest rankings by participants because TILT used less energy and most of the participants were already familiar with joystick input.

They found, that WIP-TILT had the highest sense of presence. WIP-TILT wasn't liked by participants

2.2 Vertical Movement

Vertical movement allows the user to travel up or downwards. The most common method is hand-directed steering (Bowman [2005]), where the user travels in the direction he is pointing. Another approach is PenguFly, a technique which derives velocity and steering from the position of handtrackers and a headtracker (von Kapri et al. [2011]) PenguFly has shown't to cause Simulator Sickness (von Kapri et al. [2011]). NuNav3D was using a depthcamera to obtain hand motions. With that, they could derive different poses to control the virtual camera (Papadopoulos et al. [2012]). A complete other approach is March-and-Reach from Lai et al. [2015]. This method uses ladders where users have to pull themselves up trough grabbing ladder rungs and making big steps. The idea to use ladders to climb them virtually came up already in 1994 with Slater et al. [1994]. After our definition ladder-traveling is a form of passive steering.

Vertical movement allows for travel up and downwards

Common locomotion methods are Hand-directed steering, PenguFly, NuNav3D and ladder-traveling

PASSIVE AND ACTIVE STEERING:
In this thesis we call locomotion methods in which users don't steer while traveling vertically **passive**. We call the opposite **active**.

Definition:
Passive and active steering

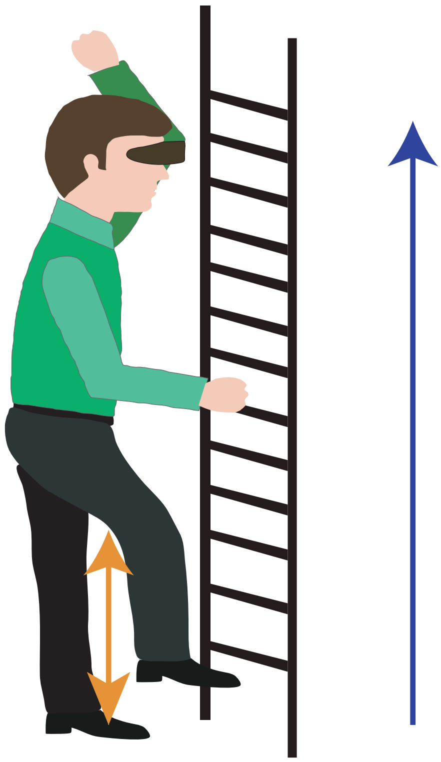

Figure 2.4: With ladder-traveling the user is moving vertical with ladders. He is indicating with his arm whether he is moving up or downwards.

Ladders

Ladder climbing was invented by Slater et al. in 1994

In 1994 Slater et al. [1994] introduced in their paper "STEPS AND LADDERS IN VIRTUAL REALITY" a way to climb ladders while using walking-in-place. The user was walking and colliding with ladders. Once the user has collided with the ladder he goes into climbing mode. In this mode he is moving up or down, when he continues walking (see Figure 3.3). To indicate whether the user is moving up or down, he is holding is hand over or under his head.

Chapter 3

Discussing Locomotion Methods

Our locomotion method needs to be applicable in a public environment, should be cost effective and make use of mobile hardware. Also it is mandatory that users are not disorientated. A high sense of presence is also interesting and since users are exploring a virtual counterpart of their real surroundings we want to sustain their spatial understanding. From the vertical travel locomotion methods described in Chapter 2 only hand-directed steering is suitable for us. However, hand-directed steering could be confusing to the user, as stated by Bowman et al. [1997]. PenguFly is known for causing nausea (von Kapri et al. [2011]) and NuNav3D needs a depthcamera (Papadopoulos et al. [2012]). Also teleporting would not be suitable for us, since it is, accordingly to Bolte et al. [2011], disorientating. Walking-in-place has better characteristics, since it offers presence (Riecke et al. [2010]), spatial orientation (Lathrop and Kaiser [2002]), performs well in terms of simulator sickness (Jaeger and Mourant [2001]) and is also appropriable in mobile contexts (Tregillus et al. [2017]). Arm-swinging has shown to be as good as walking-in-place in terms of spatial orientation (Wilson et al. [2016]) and arm-cycling has also a low potential to cause simulator sickness (Coomer et al. [2018]). We decided to use walking-in-place and arm-cycling for vertical travel.

We will use hand-directed steering

PenguFly and NuNav3D are not feasible for us

We will use walking-in-place and arm-swinging

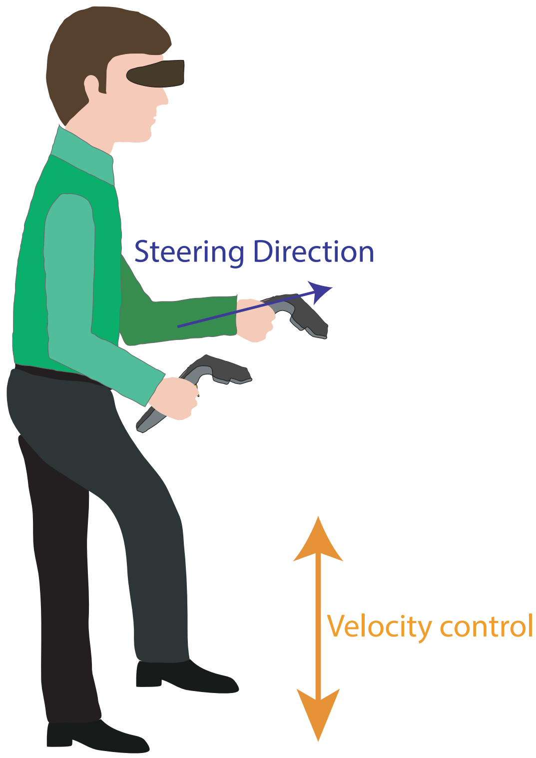

Figure 3.1: Walking-in-place is used to control the velocity and hand-directed steering is used to choose the direction.

Walking-in-Place With Hand-directed Steering

As claimed by Bowman [2005] Hand-directed steering is a common approach.We were using a controller to obtain the direction of the hand. The controller could be changed easily to a more mobile device like a smartwatch. We were using walking-in-place to control velocity, since we need one free hand. However hand-directed steering could be confusing to the user (Bowman et al. [1997]). In Figure 3.1 walking-in-place with hand-directed steering is shown.

Figure 3.2: Walking-in-place with gaze-directed steering. The user controlles the velocity with walking-in-place and is moving in the direction that he looks.

Walking-in-Place With Gaze-directed Steering

We assume that a vertical locomotion method with Gaze-directed steering is more intuitive. Based on the idea of Tregillus et al. [2017] we were adding a leaning interface to walking-in-place, since leaning offers higher presence (Wang and Lindeman [2012]). Since only a few percents with head-tilt are backwards movement (Tregillus et al. [2017]), we were using forward and backward tilt to travel vertically. To walk forward users simply use gaze-control. Users are still able to avoid obstacles with side-tilt.In Figure 3.2 walking-in-place with gaze-directed steering is shown.

We assume that Gaze-directed steering is more intuitive than Hand-directed steering in vertical travel

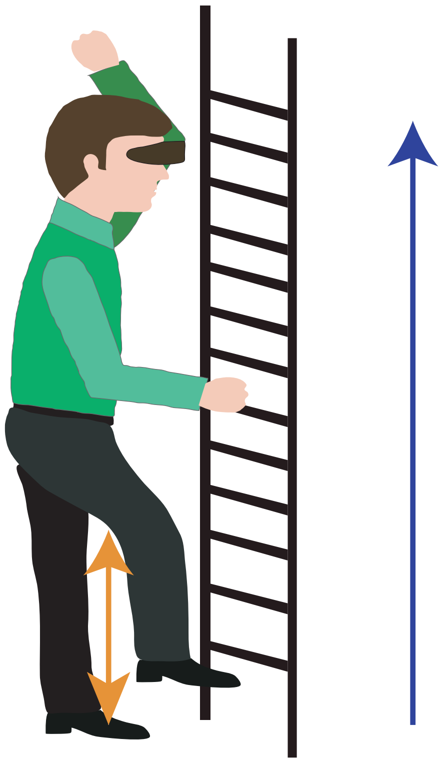

Figure 3.3: This picture shows ladder-traveling in climbing mode. The user indicates with his left arm, that he wants to travel upwards.

Walking-in-Place with the use of Ladders

We are using the approach of Slater for our implementation of Ladder-traveling

The march-and-reach attempt by Lai et al. [2015] is not suitable for us, since we would need to have two tracked controllers with a grab input. However, they were comparing march-and-reach to a locomotion technique where users climb ladders with walking-in-place. They couldn't discover any difference in presence and saw a low potential for simulator sickness (Lai et al. [2015]). We were using a method where we used walking-in-place and gaze-directed steering, but ladders to climb up or down. Similar to Slater et al. [1994] we led users walk against ladders. Near the ladder, walking will lead to climbing up, if the hand is above the users head. A hand lower the head will result in climbing down. To give the user the ability to reach every height,

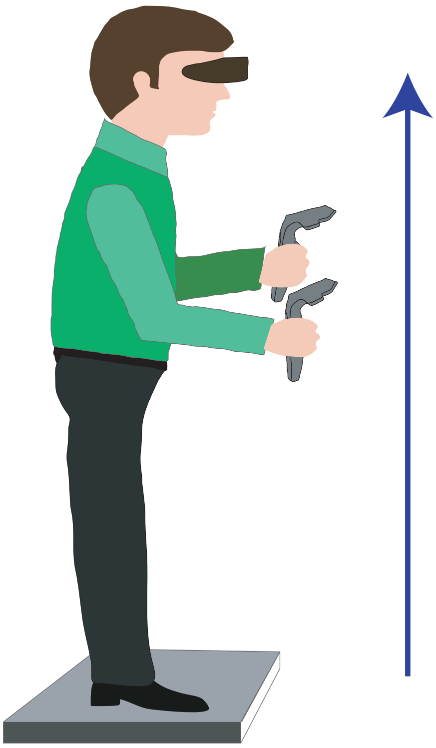

Figure 3.4: This picture shows platform-travel.

we made the ladder infinite and users could not fall down. To escape the ladder and travel on a reached height, users had to indicate that with a stretched out arm. We also gave users the ability to avoid obstacles in horizontal travel with side-tilt.In Figure 3.3 ladder-traveling is shown.

Walking-in-Place with the use of Platforms

Since we didn't give users the ability to fall of ladders, one could argue that this technique feels unnatural. To implement that in ladder-climbing we would need to track the users feet. This would have led to too much hardware for our mobile context. We decided to use paired platforms which travel against to each other up and down. Users can then walk onto a platform and are lifted up with it. This approach has the ability to fall, but user can't reach ev-

With ladder-traveling, users can't fall

We are using platforms to travel more realistic

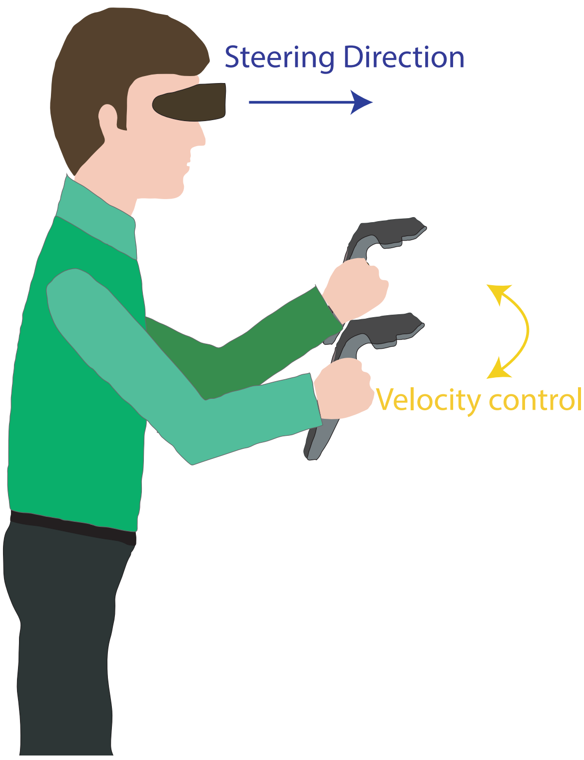

Figure 3.5: The user controls the velocity with a breast-stroke like arm-movement. He moves in the direction he is looking.

ery height. To locomote horizontally we used walking-in-place with gaze-directed steering and gave users the ability to avoid obstacles with side-tilt. In Figure 3.4 platform-traveling is shown. In our definition of active and passive steering, platform-traveling also belongs to passive steering.

Arm-Cycling With Gaze-directed Steering

Arm-cycling with gaze-directed steering is good at spatial awareness and orientation

Coomer et al. [2018] could show that arm-cycling gives spatial awareness and the ability to orientate. Since it is derived from arm-swinging which is shown to be as good as walking-in-place in terms of spatial orientation (Wilson et al. [2016]). It is likely, that Arm-Cycling also performs as

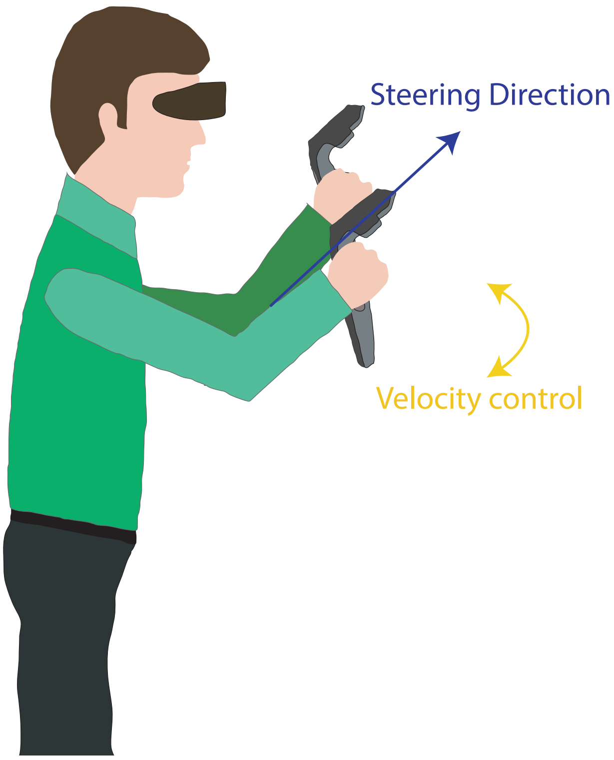

Figure 3.6: The user controls the velocity with a breast-stroke like arm-movement. He moves in the direction he is swimming.

good as walking-in-place in terms of spatial orientation. We were using arm-cycling with head-tilt with gaze-directed steering, so users can ascend and descend with head-tilt and also avoid obstacles with side-tilt. Arm-cycling needs positional tracking, but we assumed, that one could also use accelerometers to determine the position. Then we could use a smartwatch. In Figure 3.5 arm-cycling with gaze-directed steering is shown.

Arm-Cycling With Swim-directed Steering

Arm-Cycling with gaze-directed steering doesn't give users the ability to look around while they are traveling. We invented swim-directed steering. With that, the user is trav-

Swim-directed steering might be an intuitive way to decouple gaze and direction eling in the direction of his breast-stroke. The disadvantage of this approach is the need for a smartwatch on each wrist and one would need to implement a synchronizing process to obtain the relative position between the smartwatches and the head tracker. In Figure 3.5 arm-cycling with swim-directed steering is shown.

Chapter 4

Preliminary study

Since we are interested in a locomotion method which can be used in a public environment we had to examine the acceptability in a crowded place (Malhotra and Galletta [1999]). Using Virtual Reality in public could come to the user as socially incompatible caused by either too much spatial use or movements considered as inappropriate (Rico and Brewster [2010]). Rico and Brewster [2010] has shown, that surveys with the use of videos are an appropriate way to gain evidence about the future acceptance of a motion. So we were designing a preliminary study in which we were examining the user acceptance of the methods we proposed in Chapter 3.

In our preliminary we were examining the technology acceptance of our locomotion methods

4.1 Study Design

We were using videos of a performing person which is traveling inside a maze (see Figure 4.1). This maze contains three floors and the performing person will locomote from the first floor to the third floor. Also the first person view of the performing person was captured to give participants simultaneously inside and outside view, since it has been shown that the usefulness of a technology can also increase technology acceptance (Davis et al. [1989]). We showed six different videos to the participants, while each video was

We were designing a maze and showed the participants videos of a performing person locomoting through this maze

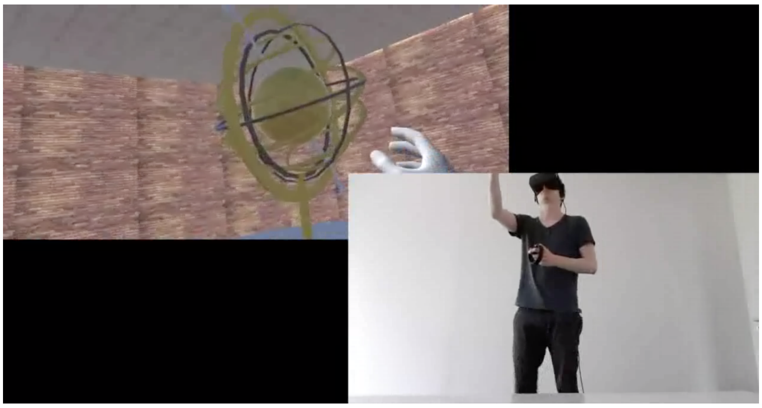

Figure 4.1: Splitscreen video of inside and outside view of a locomotion method.

showing one specific locomotion method. The video contained the video of the performing person and the first person view in split screen (see Figure 4.1). We were using 3D models placed on every floor to give participants landmarks (see Figure 4.4 and 4.3). Before the trail we made participants familiar with the layout of the maze by showing them a 3D-map and a camera flight (see Figure 4.2). Each method was shortly explained in a text. Then the participants saw the video. After they finished they had to fill a questionnaire. We were asking for the user acceptance in a crowded space and also in an empty space, since acceptance and social norms differ between public and private places (Rico and Brewster [2010]). To measure the participants emotions on a locomotion method we were using the 16 point scale by PrEmo. We were asking for either emotions on using method in private and also in a crowded environment. Before the trail a baseline was captured and after the trail participants gave demographic information and rated the methods.

We used a questionnaire to ask for the user acceptance

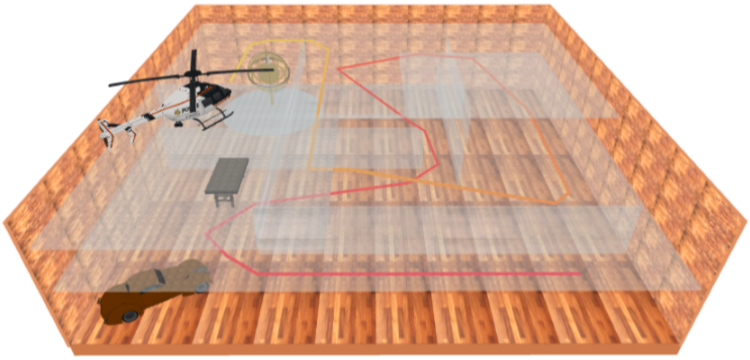

Figure 4.2: The picture that was used to explain the maze. The path represents the path the performing person will take.

Figure 4.3: Helicopter Object used as landmark.

We were using an online survey tool since we had to show videos to the participant, nevertheless one investigator was sitting next to the participant since we needed to ensure that videos are watched to the end (Mendelson et al. [2017]). The investigator acted also as reference person to give answers and to eliminate obscurities. At some points the investigator was not physical present but was cut in via video chat. We were using a latin square of six to permutate the videos.

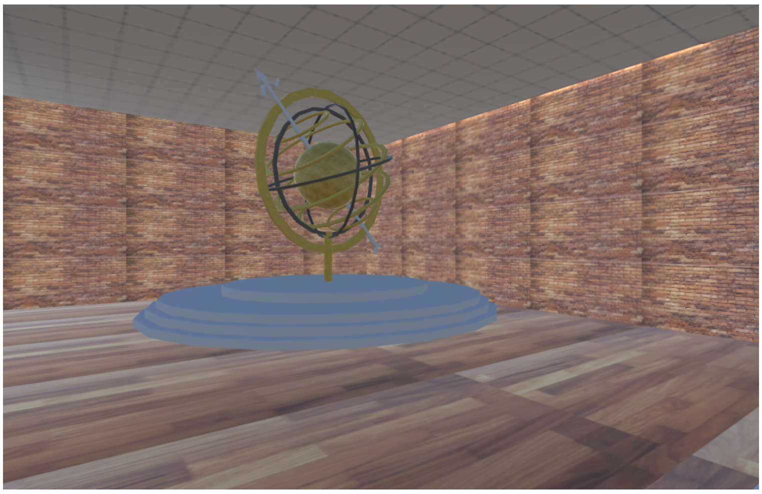

Figure 4.4: Astronomical Object used as landmark.

4.2 Results

We saw a lower acceptance for arm-cycling

In our study participated 8 subjects(3 female) with an average age of 24.3 years. Five of our participants where complete or moderate open to technology, while six of them had no or just little experience with Virtual Reality. We ran a ANOVA for repeated measures and could reveal, that the acceptance for the methods in private rooms differ significantly between methods. With bonferroni correcting we could see, that walking-in-place with gaze-directed steering is significantly more accepted than arm-cycling with gaze-directed steering. Without bonferoni correction there is also a significant lower acceptance in private places of arm-cycling with swim-control than platform-traveling. Also with arm-cycling and gaze-directed steering we saw the same outcome, compared to platform- and ladder-traveling. When we had a look on the ratings, participants rated arm-cycling the worst in terms of practicability, appearance and it got the lowest rankings on the question if participants wanted to try the method on their own in public as well as in private.

Table 4.1: Acceptance Results

Mean of Acceptance Results						
How likely would you use this Method?	WiP Hand-directed	WiP Gaze-directed	Ladder-travelling	Platform-traveling	Arm-Cycling Gaze-directed	Arm-Cycling Swim-directed
At home	3.00	3.88	3.50	3.63	2.38	2.50
On an exhibition	3.13	3.63	3.62*	3.75*	2.75*	2.38*
1 = totally disagree 5 = totally agree Significant values are marked with *						

Table 4.2: Premo Results

Premo Results						
How likely would you use this Method?	WiP Hand-directed	WiP Gaze-directed	Ladder-traveling	Platform-traveling	Arm-Cycling Gaze-directed	Arm-Cycling Swim-directed
Which emotion do you experience while watching?	2.71	1.86	5.29	3.43	2.43	1.43
What do you think are the emotions of the person?	2.29	3.00	3.57	3.57	1.17	2.00
Mean of positive minus negative emotions Higher values are better						

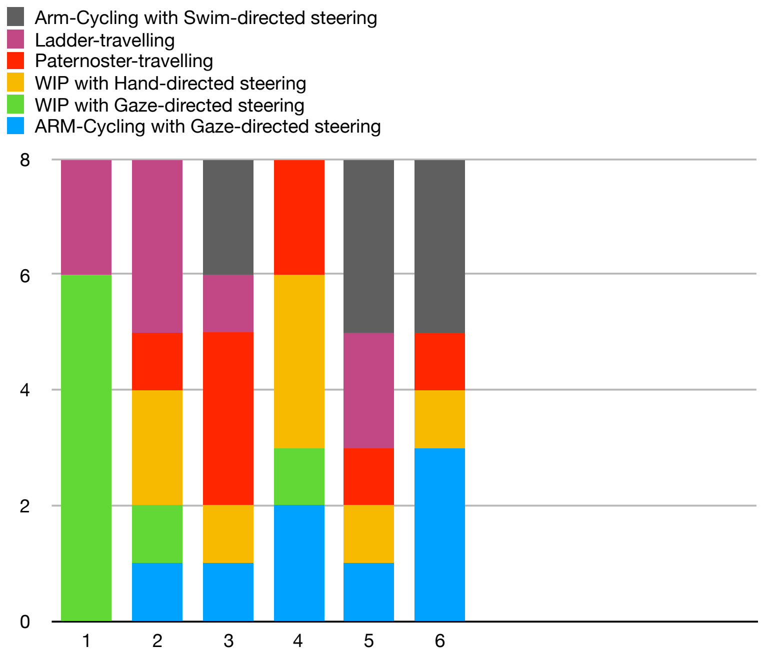

Figure 4.5: Ranking of the Question "Which method would you like to try on your own?"

4.3 Evaluation of the preliminary study

Arm-cycling has a lower acceptance than walking-in-place. Some participants gave the feedback, that arm-cycling

We decided to exclude Arm-Cycling with Swim-Control

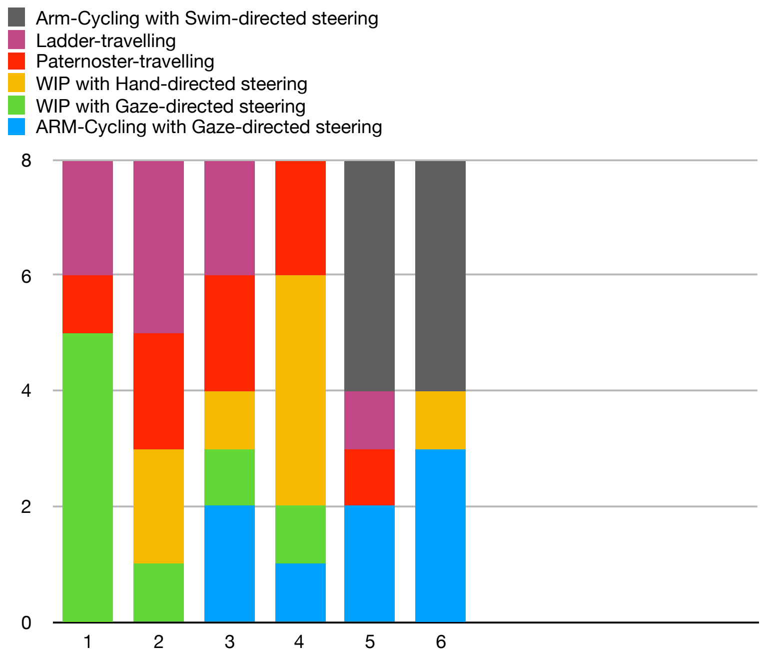

Figure 4.6: Ranking of the Question "Which method would you like to try on your own in public?"

looks exhausting, even when walking-in-place is a full-body-movement while arm-cycling is not. So, we can't be sure that this attitude didn't affect the rating, but even when a movement needs more energy, it can still be more accepted (Rico and Brewster [2010]). That people found it exhausting, can't fully explain the low rankings. Another explanation is that a swimming-like movement doesn't look natural enough in a crowded place. Motions, that don't mimic everyday movements tend to be less accepted (Rico and Brewster [2010]). But participants can still change their mind between a survey and after they used a motion (Rico and Brewster [2010]) and since we are still interested in how arm-cycling performs compared to walking-in-place we decided to include arm-cycling with gaze-control to our main study. However we decided to exclude arm-cycling with swim-control since arm-cycling with gaze-Control is more comparable to walking-in-place with gaze-control.

However, we were still interested in how arm-cycling with gaze-control performs

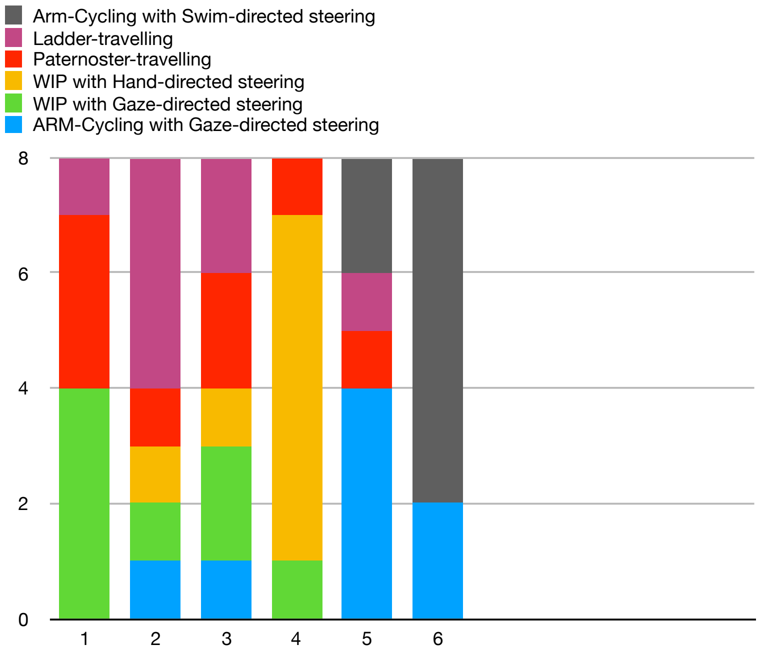

Figure 4.7: Ranking of the Question "Which method looks the best?"

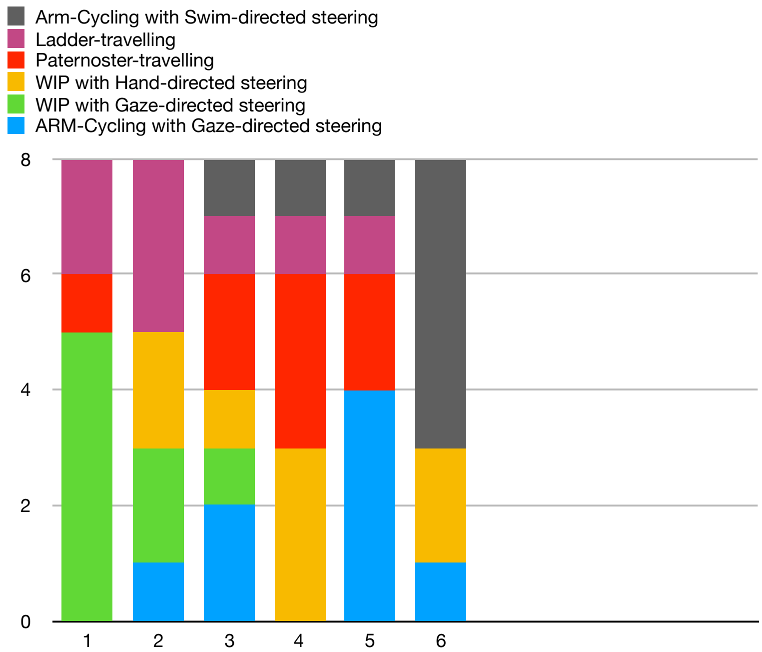

Figure 4.8: Ranking of the Question "Which method would looks practicable?"

Chapter 5

User Study

Based on our observations in Chapter 4 we were designing a study to evaluate the actual performance of the five locomotion methods which we established. We were using a search task, since this technique was already used in several publications (Coomer et al. [2018]). In our task participants were wearing a HMD and exploring a virtual museum. In this museum, treasure chests were placed and a fixed amount of them were containing a treasure. While users are executing the search task, we were measuring different parameters like the time to complete, the number of treasures found, the number of revisited chests and the distance traveled.

In our mainstudy participants performed a search task

5.1 Hypotheses

- Hypothesis H1: There is a difference in orientation between gaze-directed and hand-directed steering.
- Hypothesis H2: There is also a difference in orientation between passive and active steering controls.
- Hypothesis H3: Users like walking-in-place more than arm-cycling.
- Hypothesis H4: Arm-Cycling is more tiering than walking-in-place.

Figure 5.1: In-game screenshot from the ceiling of our museum. On both sides we placed galleries.

- Hypothesis H5: Walking-in-place is better in terms of simulator sickness.
- Hypothesis H6: There is a difference between active and passive locomotion methods in terms of simulator sickness.
- Hypothesis H7: Users find platform-travel more realistic than ladder-traveling.
- Hypothesis H8: Users need less space with arm-cycling than with walking-in-place.

5.2 Apparatus

We used HTC VIVE and UNITY 3D

We were using a HTC Vive with two controllers and Unity 3D Version 2018.2.14 to implement our study. Although HTC Vive is not a mobile device we used it, as it was more easy to implement hand input with it. Nevertheless all of our results are transferable to a mobile setup with a smartphone and two smartwatches or hand-trackers. We were building a virtual museum which was three stories hight. An in-game screenshot is shown in Figure 5.1. Our museum was build as a big hall with a floor area of 40 by 70 meters and a height of 20 meters. On the two longer sides

We builded a three stories high museum with galleries

Figure 5.2: In-game screenshot of the gallery on the first floor. We used exhibits to hide treasure chests.

Figure 5.3: In-game screenshot of the lowest floor.

we placed galleries on the middle and on the upper floor. There was no connection between the two opposing sides of galleries. In the galleries, curtains and exhibits were used to form corridors to block the direct way of the user and to hide the treasure chests (See Figure 5.2). On the lowest floor we only used exhibits to hide treasure chests (see Figure 5.3). We placed also a big skeleton of a horse in the middle of the museum, which reached from the lowest floor to the ceiling. Our intention was to have an obstacle to prevent participants from direct travel. The treasure chests were chests which could be opened by the participant through walking up to them (See Figures 5.4 and 5.5). To prevent

We used treasure chests which had to be found by the participant

Figure 5.4: A treasure chest. These chests were hidden 15 times in the museum

opening them by mistake, participants had to gaze at the treasure chest. After walking away, the treasure chests were closing themselves. There was no specific indicator, that a treasure chests either contained a treasure or if the participant had already opened it. Therefore participants had to remember which treasure chest they already had visited. The placement and whether a chest is full or not changed between the different trials. The containing of a treasure was decided at random, however we simply build two different placement configurations and used them alternately. Permanently the amount of treasures the participant hadn't found and the amount of errors the participant had made were visible in the sight of the participant.

We used 15 chest. 11 of them contained a treasure

Definition: *UNITY 3D*

UNITY 3D:
Unity 3D is a multi-platform Game Engine.

Definition: *HTC VIVE*

HTC VIVE:
HTC VIVE is a VR-kit by HTC. The headset comes with a resolution of 1080 by 1200 pixels per eye and uses a refresh rate of 90 Hz. The kit comes with two controllers.

Figure 5.5: A full treasure chest. Exactly 11 chests were containing a treasure.

5.3 Implementation

We bought a bundle of game assets called Museum Level Interior Pack[1] in the Unity Assets Store which contained several museum related 3D models. With these models we were building the virtual museum.

5.3.1 Implementation of Walking-in-Place

The walking-in-place implementation *VRSTEP* by Tregillus et al. [2017] is available for download in the Unity Asset Store, but unfortunately not compatible with HTC VIVE. Therefore we had to implement walking-in-place on our own, but we used the same approach like Tregillus et al. described in VRStep. For our implementation of walking-in-place we were using the accelerometer of the HTC Vive Headset. However, we were not able to obtain data directly from the sensor. Instead we used the position of the headset and derived the velocity and further the acceleration (see Figure 5.6). We were gaining the positional data directly via OpenVR and were polling data with the use of a separated thread to read detached from the update

We used the accelerometer of the HTC VIVE Headset for our implementation

[1]https://assetstore.unity.com/packages/3d/environments/museum-level-interior-pack-105256

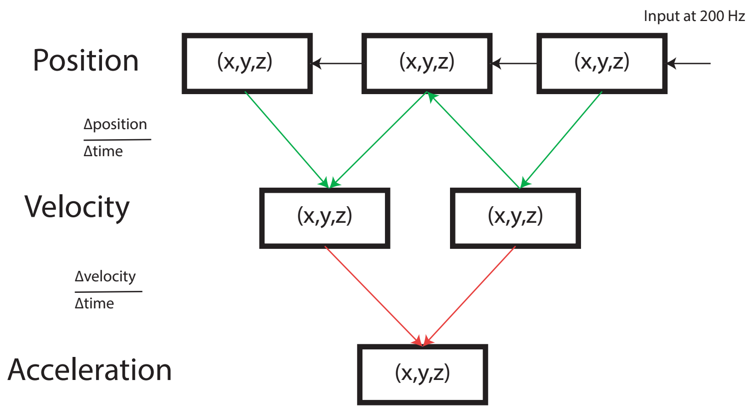

Figure 5.6: The deriving of acceleration out of positional data. The data is sampled into a ring buffer. On every new sample the positions are derived into velocity and then into acceleration.

process of Unity. With that, we were able to sample data at 200 Hz. We were then using the same algorithm Tregillus and Folmer [2016] used for VRStep. This algorithm was developed by Zhao [2010] and uses a peak-detection to search for steps. First, the input is smoothed by a ring buffer of 8 samples. Every 50 samples a new dynamic threshold is calculated as the center of the maximal and minimal amplitude. In the event of a peak that falls below that dynamic threshold a step event is fired, but only in the case that the slopes is higher than another predefined threshold (see Figure 5.7). As described in the algorithm we were using a sampling rate for the acceleration of 50 Hz.

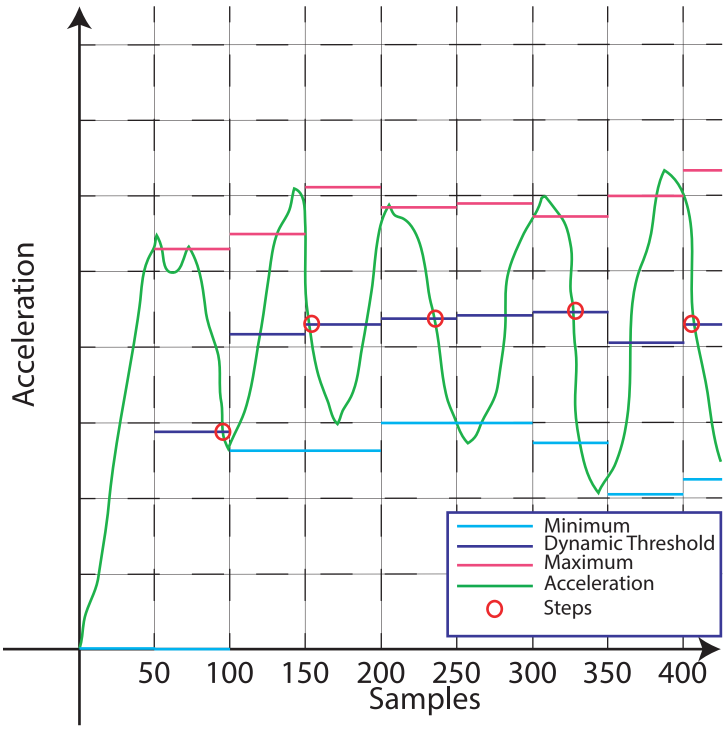

Figure 5.7: The step-detection algorithm. A step event is triggered, when the acceleration falls below a dynamic threshold. This threshold is adjusted every 50 samples.

OpenVR:
OpenVR is an API published by Valve which serves between applications and the HTC VIVE hardware.

Definition: *OpenVR*

On each step we were then adding a specific amount of $0.75\frac{m}{s}$ of velocity to the participant, until he reached a maximum velocity of $2.7\frac{m}{s}$. The velocity, was lowered by $1.215\frac{m}{s}$ per second, which lead to 2.2 seconds for the participant to stop. The maximum speed is reached after two steps. We decided on these values to be similar to real walking.

The maximum velocity is $1.215\frac{m}{s}$ which is reached after 2 steps. The stopping time is 2.2 seconds

Some papers introduced a count of four steps within a specific time period to start walking, due to false steps (Slater et al. [1994]). To comply with false steps we added a re-

We were using the trigger of the HTC VIVE to disable unwanted walking fractory phase after a step had been detected. In this time of 0.6 seconds no other step was counted. Also only when the participant pressed one of the triggers of the HTC VIVE steps were counted. This prevented users from walking unintentionally and could be easily removed for mobile usage.

5.3.2 Implementation of Arm-Cycling

Our implementation of arm-cycling used the absolute change in distance between the controllers to create forward movement

Like Coomer et al. [2018] we were using the absolute change of distance between the two controllers and transferred this into movement. This results in a movement by either moving the controller towards or away from each other. In our case users had also to press one of the triggers on the HTC VIVE controller. There is no need for that, but we introduced it to eliminate bias for comparing with our walking-in-place implementation. When the participant moved the two controllers one meter away from each other, this corresponded to one meter forward movement. If the participant was doing one stroke a second, while he moves the controller to roughly 0.7 meters away from each other, then this was leading to $1.4\frac{m}{s}$ of velocity.

One stroke a second leads roughly to $1.4\frac{m}{s}$

5.3.3 Implementation of Gaze-directed steering

Definition: *Gameobject*

GAMEOBJECT:
Gameobjects are entities of objects in Unity 3D. Every gameobject has a transform which consists of a position, a rotation and a scale. This Transform-class offers also vectors which represent different directions relative to the gameobjects rotation, e.g. the forward vector which points to the front.

We declared to thresholds for side-tilt and forward-tilt. If the threshold is exceeded we either move sideways or up

Unity uses a (x,y,z) vector system with the y-axis determining the height. For the Gaze-directed steering we were obtaining the forward vector of the camera gameobject in Unity. The vector represents the orientation of the gameobject and in this case the direction of view. We are using

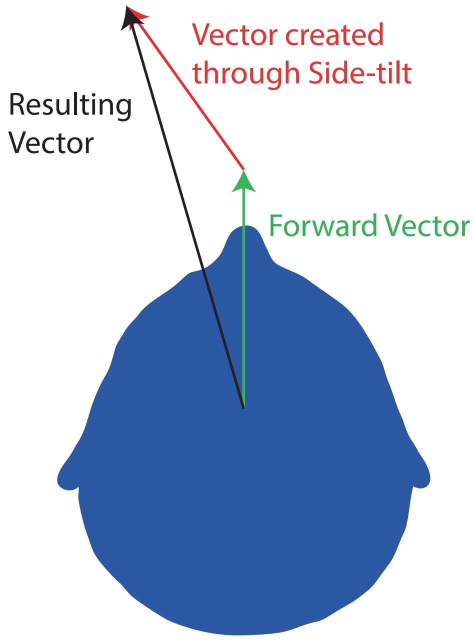

Figure 5.8: The forward-vector was used as direction-vector. If the angle α exceeded a threshold, the vector created through side-tilt was added to the direction-vector.

this vector as the direction vector to steer (see Figure 5.8). Further we are using the up-vector of the camera gameobject. This vector stands orthogonal on the forward vector and points up. We then calculate the angle α of side tilt between this up-vector and the y-axis, and the angle β of forward tilt between the up-vector and the y-axis. When α exceeds the threshold of $9°$ we projected the up-vector to the floor plane (dee Figure 5.10). Then we were adding this new vector to the direction/forward-vector (see Figure 5.8). We used the β angle to determine if we are travelling vertical. When β was lower $25°$ we set the y-component of the direction-vector to 0, to disable vertical travel (see 5.10). Otherwise, the user is simply following his gaze upwards.

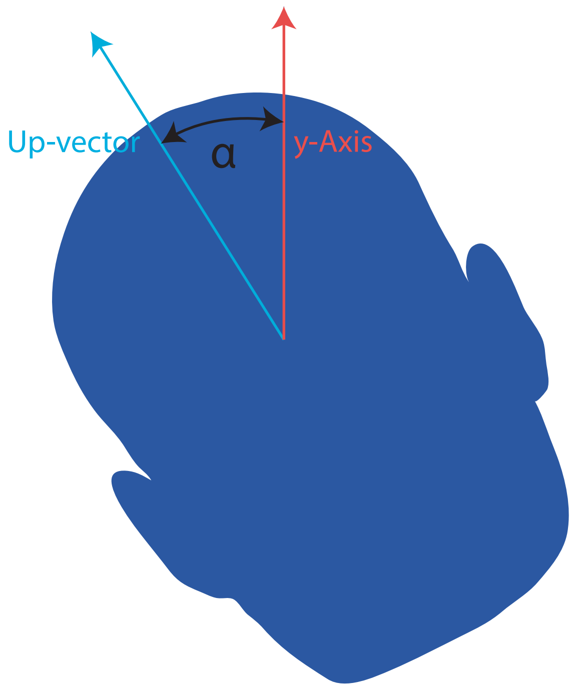

Figure 5.9: The angle α is the angle between the up-vector of the users head and the y-axis calculated from the front.

5.3.4 Implemetation of Platform-travel

We were using the implementation of Gaze-directed steering and were setting the y-component of the direction-vector to 0 to disable vertical travel by gazing. So participants could just locomote vertical. For the platform-travel we simply used two boxes which were animated in the Unity Animator. These squares had also a collider to lift the participant.

5.3.5 Implementation of Ladder-traveling

For Ladder-traveling we also used the implementation of gaze-directed steering and disabled the vertical travel by gazing. We added ladders with colliders to the virtual mu-

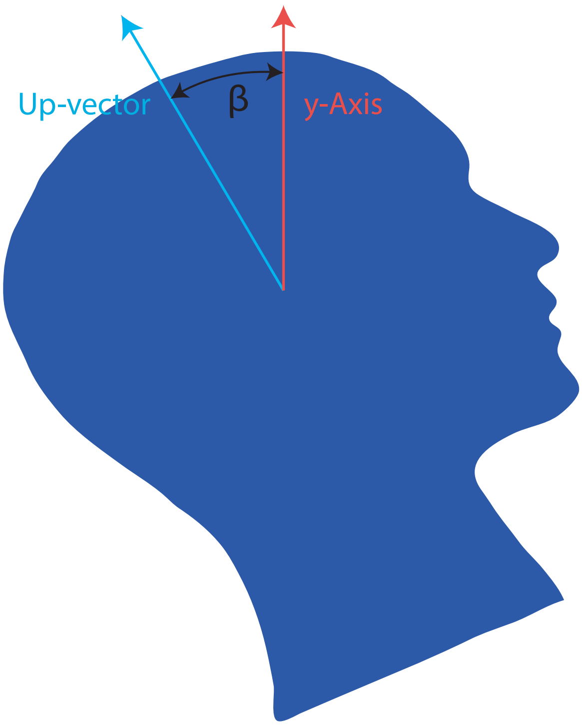

Figure 5.10: The angle β is the angle between the up-vector of the users head and the y-axis calculated from the side.

seum. On colliding, we were setting the direction-vector to either straight up or straight down, specified by whether the left hand of the participant was over or under his head.

5.3.6 Implementation of Hand-directed steering

For hand-directed steering we were simply obtaining the orientation of the left controller and used it as the direction-vector.

5.4 Study Design

We used a Usability Questionnaire and a Simulator Sickness Questionnaire to evaluate the locomotion methods.

We also raised other metrics like time, distance traveled, distance of head movement and the amount of errors made.

After an informed consent we are obtaining a baseline reading for the simulator sickness with the Simulator Sickness Questionnaire by Kennedy et al. [1993]. Then we made participants familiar with the HTC VIVE and explained them the search task they had to perform. Then we started the search task where participants had to find eleven treasures in fifteen different treasure chests. Before the trial of a method, we gave an explanation of how the locomotion method will work. Participants had also the ability to try a method before performing the search task. We had just 4 empty treasures in a trial to face lucky guessing. After a participant found eleven treasures or when a participant declared, that he is not able to remember where he hasn't been, we stopped the trial. Then we followed with a Simulator Sickness Questionnaire. After that, the participant was filling a usability questionnaire. We were repeating this procedure for every locomotion method and closed with a simple demographic survey and a ranking of the different locomotion methods. We used a latin square of five.

5.5 Results

We had ten participants in our study (3 female) with an average age of 24.7. We ran ANOVA tests for repeated measures on time, distance travelled, distance head movement, amount of head rotation and on the amount of errors made. We found significant differences in distance traveled, distance of head movement and the amount of rotation. Arm-cycling with gaze-directed steering had a significantly lower distance traveled compared to platform-travel. We saw the same outcome in terms of distance head movement, also when we compared it to ladder-traveling. In paired t-tests we could see that arm-cycling had a significant lower amount of head distance compared to every other locomotion method. When we compare the amount of rotation of ladder-travel and platform-travel to the other locomotion methods in paired t-tests, we saw a significant

Figure 5.11: This picture shows how a participants were performing arm-cycling in our user study.

higher amount of rotation.

Paired ANOVA testing revealed also that participants found arm-cycling significantly better to understand compared to hand-directed steering and ladder-traveling. Platform-travel performed also significantly better than ladder-travel. Participants found arm-cycling also the easiest to use with a significant better performance than ladder-travel. Participants felt also the most in control with arm-cycling with a significant better performance than ladder-travel and gaze-directed walking-in-place. Participants found arm-cycling not more tiring. With ladder-travel participants felt they couldn't go where there wanted significantly more often than with all other methods. Arm-cycling was the easiest to remember locomotion with significant difference to hand-directed steering. There was no significant difference between the required energy but participants found hand-directed steering to cause the lowest ef-

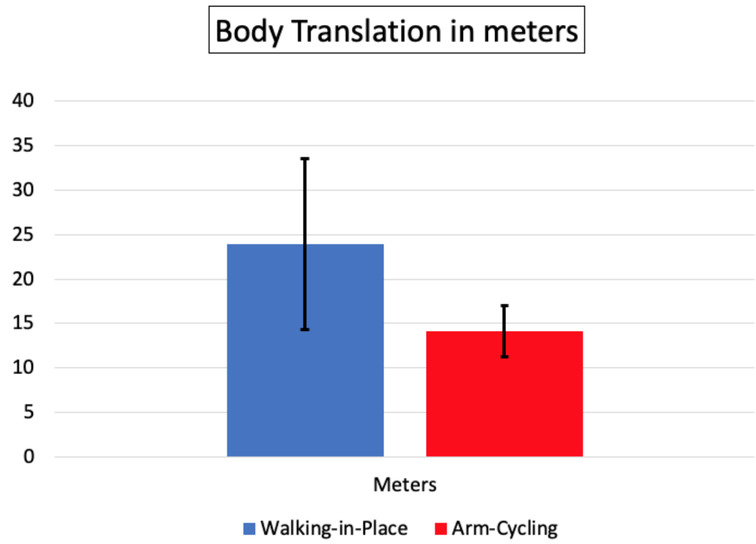

Figure 5.12: Mean of body translation. CIs are shown as error bars.

fort with a significant difference to platform-travel. Arm-cycling was described as more predictable and showed significant difference to ladder-travel, walking-in-place with gaze-directed steering as well as with hand-directed steering.

We could see intermediate Simulator Sickness for every method. There is a significant higher simulator sickness score compared to the baseline reading for every method. Arm-cycling had the lowest simulator sickness, while hand-directed steering had the highest.

Nine of our ten participants described their self as completely or more open to technology, while eight of them played often or more often video games. Two described their self as experienced with virtual reality. In the ranking arm-cycling got the best rates, while ladder-travel got the worst.

Table 5.1: Usability Questionnaire Results

Usability Questionnaire					
	WiP Hand-directed	WiP Gaze-directed	Ladder-travelling	Platform-travelling	Arm-Cycling
I thought this method was easy to understand	3.8*(1.135)*	4.3*(1.059)*	4.0*(1.054)*	4.6*(0.516)*	4.8 *(0.422)*
I thought this method was hard to use	2.4*(0.966)*	2.4*(1.174)*	2.6*(0.843)*	2.1*(1.197)*	1.8*(1.033)*
I felt like I had control over my actions	3.6*(0.843)*	3.3*(0.949)*	3.2*(0.789)*	3.8*(0.632)*	4.2*(0.632)*
I did not have a hard time visualising this movement in my head	3.1*(1.729)*	3.6*(1.430)*	3.4*(1.506)*	3.9*(1.197)*	4.4*(0.966)*
I understood how my movements translated to the environment	4.3*(0.823)*	3.9*(1.101)*	3.9*(0.994)*	4.4*(1.075)*	4.4*(0.699)*
This method made me tired	2.9*(1.370)*	2.9*(1.663)*	2.6*(1.506)*	2.7*(1.252)*	2.4*(1.265)*
I felt like I could go where I wanted to	4.2*(0.789)*	4.4*(0.843)*	3.4*(0.966)*	4.3*(0.823)*	4.3*(0.675)*
I liked using this method	3.2*(0.919)*	3.0*(1.333)*	3.2*(1.229)*	3.5*(1.354)*	3.7*(1.252)*
I had a hard time remembering the controls for this method	1.9*(0.876)*	1.8*(1.317)*	1.7*(0.823)*	1.4*(0.516)*	1.1*(0.316)*
I think that this method added to the virtual experience	3.2*(1.229)*	3.6*(1.174)*	3.3*(1.337)*	3.8*(1.317)*	3.2*(1.229)*
I think this method made the task harder to complete	2.3*(0.949)*	2.5*(1.269)*	2.9*(0.994)*	2.8*(1.398)*	2.4*(0.966)*
I did not get lost as I used this method	4.0*(1.155)*	4.4*(0.966)*	3.5*(1.434)*	4.2*(0.632)*	3.8*(1.476)*
I felt like this method required a lot of energy	2.9*(1.287)*	2.9*(1.287)*	2.9*(1.101)*	3.2*(1.033)*	3.2*(1.398)*
I felt like this method required a lot of effort	2.3*(0.949)*	2.8*(1.398)*	3.0*(1.333)*	2.9*(0.876)*	3.0*(1.414)*
I felt like this method was buggy	2.1*(0.876)*	2.7*(1.337)*	2.7*(0.949)*	2.4*(1.350)*	2.0*(1.247)*
I felt like there was not enough time when using this method	1.8*(0.632)*	1.7*(1.059)*	1.8*(0.632)*	1.6*(0.699)*	1.5*(0.972)*
I felt like this method was unpredictable at times	2.9*(0.876)*	3.2*(1.317)*	3.1*(0.994)*	2.7*(1.160)*	1.7*(1.252)*
I would not like using this method again	2.3*(0.949)*	2.8*(1.135)*	2.7*(1.494)*	2.3*(1.337)*	2.3*(1.567)*
I felt like I needed a break after using this method	2.9*(1.197)*	2.6*(1.350)*	2.4*(1.174)*	2.1*(0.994)*	2.4*(1.350)*
I would like to see this method implemented in a video game	3.1*(1.197)*	3.5*(1.354)*	3.3*(1.494)*	3.5*(1.269)*	3.1*(1.449)*
I felt overwhelmed when using this method	2.1*(0.738)*	1.9*(0.876)*	2.0*(0.943)*	1.7*(0.823)*	2.0*(1.155)*
This method made me frustrated	2.1*(0.994)*	2.7*(1.059)*	2.4*(1.265)*	1.9*(0.738)*	1.9*(1.101)*
means, standard deviation in italic 1 represents total disagree, 5 represents total aggree					

Table 5.2: Simulator Sickness Questionnaire Results

Simulator Sickness					
Baseline	WiP Hand-directed	WiP Gaze-directed	Ladder-travelling	Platform-travelling	Arm-Cycling
1.6*(1.506)*	6.7*(6.584)*	5.8*(5.808)*	5.1*(4.483)*	5.4*(3.627)*	4.5*(4.720)**
Means of summed symptom points, standard deviation in italic Range between 0 and 48 Significant values are marked with *					

Table 5.3: Body translation

Body translation				
WiP Hand-directed	WiP Gaze-directed	Ladder-travelling	Platform-travelling	Arm-Cycling
25.43*(13.9)*	223.9*(13.4)**	30.8*(13.2)**	33.5*(14.7)**	14.14*(4.07)**
Means of body translation, standard deviation in italic Significant values are marked with *				

Table 5.4: Time

Time				
WiP Hand-directed	WiP Gaze-directed	Ladder-travelling	Platform-travelling	Arm-Cycling
331*(25.8)*	310*(29.5)*	367*(29.0)*	377*(29.5)*	369*(33.142)*
Means of time, standard deviation in italic				

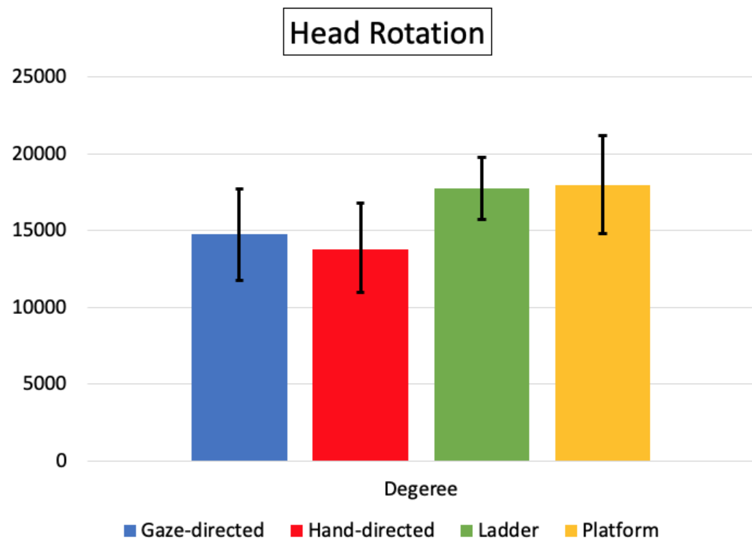

Figure 5.13: Mean of head rotation. CIs are shown as error bars.

Table 5.5: Distance

Time				
WiP Hand-directed	WiP Gaze-directed	Ladder-travelling	Platform-travelling	Arm-Cycling
608*(123.8)*	564.5*(40.4)*	638*(100.0)*	667*(102.0)*	548*(42.5)**
Means of distance, standard deviation in italic Significant values are marked with *				

Table 5.6: Rotation

Rotation in degree				
WiP Hand-directed	WiP Gaze-directed	Ladder-travelling	Platform-travelling	Arm-Cycling
13799*(3998)*	14760*(4163)*	17770*(2814)***	17961*(4462)***	13941*(2900)*
Means of Rotation, standard deviation in italic Significant values are marked with *				

Table 5.7: Means of sum of errors

Amount of Errors				
WiP Hand-directed	WiP Gaze-directed	Ladder-travelling	Platform-travelling	Arm-Cycling
0.70*(0.949)*	0.10*(0.316)*	0.40*(0.699)*	1.10*(1.853)*	0.10*(0.316)*
Means of sum of errors, standard deviation in italic				

Chapter 6

Evaluation

There was no significant difference in completion time. That means that we found the right trade-off when we decided on velocity in arm-cycling and walking-in-place. Also most participants haven't found themselves under time pressure with the different locomotion methods. There was also no significant difference between the amount of errors and platform-travel had the highest rate of only 1.1 Errors in average. We concluded, that users stayed overall orientated. Therefore Hypothesis H1 and H2 are rejected.

There was no difference in completing time. We conclude, that we decided on the right velocity

6.1 Velocity control

When we compare arm-cycling and walking-in-place directly, we could see that participants had a significant lower distance of body movement. So we accept hypothesis H8. We noticed that users tend to make little steps forward with walking-in-place. This might be a disadvantage with walking-in-place in crowded environments due to space restrictions. Participants felt more in control with arm-cycling. This is maybe a result of the more direct input of arm-cycling. Another explanation is that some participants felt walking-in-place unprecise, since this was stated a few times. Participants agreed also significantly more of-

With walking-in-place participants are still walking little steps forward

Arm-cycling got better results and users felt more in control

ten with the statement, that walking-in-place was unpredictable. However, walking-in-place was not experienced as buggy. Overall we saw better rankings with arm-cycling than with walking-in-place and also a lower simulator sickness. Therefore we reject hypothesis H5. Some participants stated that they found arm-cycling to slow. We assume, that arm-cycling would have got even better results if we would have made it faster. It was also the least tiring. Therefore we reject hypothesis H3 and H4. The main disadvantage of arm-cycling is the low technology acceptance of bystanders. Maybe this can be overcome, if one would use a movement more like arm-swinging, since this looks more like walking.

6.2 Steering Control

Gaze-control was liked the most while hand-directed steering is unintuitive

When we have a look at the four different steering methods we see the significant lower head rotation of hand-directed and gaze-directed steering compared to ladder-travel and platform-travel. We see also higher distances traveled for ladder-travel and Platform-travel. We assume that this is caused by the fact that participants can't use the direct way with these locomotion methods. Interestingly, there is also a higher distance traveled for hand-directed steering. Although it is not significant it shows that hand-directed steering has lower head rotation when we regard the rotation based on distance traveled. However, hand-directed steering was worse in terms of understandably, especially in comparison to ladder-travel. Participants found it also harder to visualize the movement of hand-directed steering in their head. hand-directed steering had also the worst Simulator Sickness Score. This led us conclude, that hand-directed steering is also for vertical travel unintuitive. Since hand-directed steering has a higher simulator sickness, compared to ladder- and platform-travel, yet gaze-directed steering has not, we can't accept hypothesis h6. Further ladder-travel was described as harder to use and participants found they had the least control. Interestingly participants found they weren't able to go where they wanted to with ladder-travel significantly more often than with every other steering control. It was possible to

Ladder-travel is maybe to complex and platform-travel was liked because of its realism climb to every height, while with platform-travel that was not. In our study design participants didn't have to climb to every height. This might explain that this fact was not apparent to the participants. Ladder-travel was maybe to complex. Platform-travel was described as the easiest to understand locomotion method. We assume this is due to the wide use of platforms in video games. It was also the most liked steering control. Some participants stated, that they liked Platform-travel because it was realistic and because of the ability to fall. Overall we recommend the use of Platform-travel over ladder-travel and the use of gaze-directed steering instead of hand-directed steering. Since gaze-directed steering got the best result in the ranking (see Figure **??**overallranking) , we found gaze-directed steering to be the best steering method.

6.3 Qualitative Feedback

As qualitative feedback we got the input, that ladder-travel was found to be hard to control. Also some participants stated that they liked falling with platform-travel. Therefore we can also reject hypothesis H7. Further none of the participants was using side-tilt to avoid obstacles. Some participants stated that they had tried it, but then still haven't used it. This corresponds to the findings of Tregillus et al. [2017]. Also some participants stated, that they found arm-cycling to slow.

6.4 Implications

Based on our findings we can't advise to use arm-cycling, but maybe arm-swinging performs as well as arm-cycling and has a better social acceptance. Further we can recommend gaze-controlled steering in vertical locomotion. Also platform-traveling can be a good advise, especially when realism is need.

We advise to use either platform-travel or gaze-directed steering

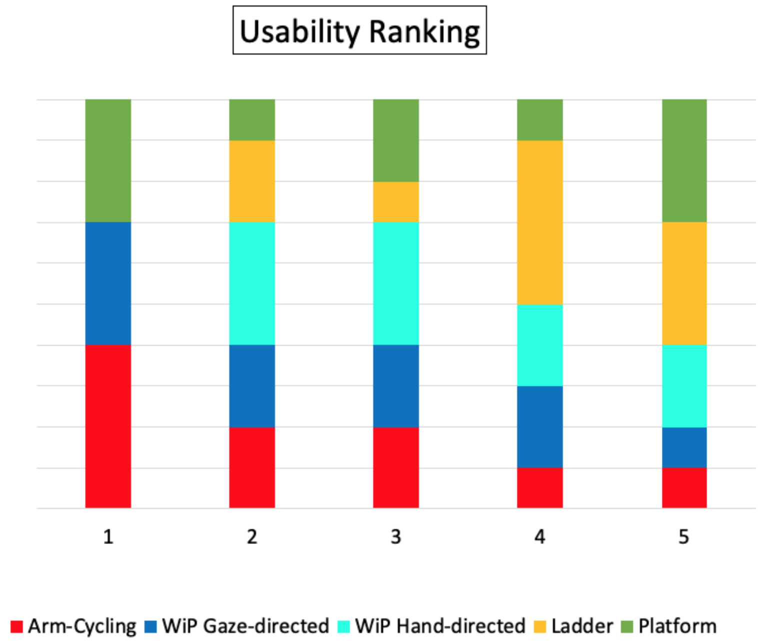

Figure 6.1: This chart shows the overall ranking of locomotion methods after the user study. arm-cycling and walking-in-place with gaze-control were liked the most.

Chapter 7

Summary and Future Work

In this thesis we evaluated locomotion techniques for VR in a mobile context. We could show that arm-cycling is a good locomotion method. However, one has to enhance to social acceptance of swimming-like motions. Further we could show that gaze-controlled steering and platform-travel are good ways to steer.

7.1 Summary and Contributions

Arm-cycling is good for our context, but the social acceptance is to low

We have shown, that arm-cycling is a suitable vertical locomotion method for mobile use cases. It is liked by users and was not disorientating. Users feel in control and can reach every point with as many effort as with walking-in-place. In a later implementation we are advising a higher velocity, but we want to bring up, that this could worsen simulator sickness. The benefit of arm-cycling in mobile applications is the lower need for space, which can be crucial in a crowded place. However people who watch arm-cycling can find it disconcerting which lowers the acceptance. The use of arm-swinging instead of arm-cycling may could bring a better social acceptance, since arm-swinging looks more similar to walking.

For the steering-control we found that gaze-directed steering performed best in our use case. It is liked by users and was not disorientating. Overall it is more intuitive than hand-directed steering. Also platform-traveling performed well and could be an option in use cases where the locomotion method needs to be realistic and users don't need to reach every height. Ladder-traveling wasn't liked by users, maybe because of the complexity.

7.2 Future work

Arm-swinging might perform as goog as arm-cycling and has better acceptance

For future work we suggest the evaluation of arm-swinging, since arm-swinging mimics walking and therefore the technology acceptance could be higher. Also Coomer et. al. stated, that there is a need for the comparison of arm-swinging and arm-cycling. In our study we were also the first to compare walking-in-place with arm-cycling. It might also be interesting, how good arm-cycling performs compared to walking-in-place for horizontal locomotion. Also the evaluation of arm-cycling with swim-directed steering would be interesting, since this would be a natural way to decouple gaze-direction and travel direction. Therefore swim-direction steering may be more intuitive than hand-directed steering. Further it could be interesting to evaluate arm-cycling with a higher velocity.

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