Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

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Impact of Limited Field of View (FoV) on Human Behaviour in Virtual Reality (VR)

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Abstract

In this semester project, the goal was to examine human behaviour in VR with regards to limited FoV encountered in VR. The project primarily focused on evaluating potential differences in head movement trajectories between the VR and reality with regards to the limited FoV. To this end a user study was devised and conducted in three test environments, the first being reality (RB), the second being reality with limited FoV (LR) and the last being virtual reality (VR). Despite the significant individual variations in the behaviour of the user study participants, the results suggest variations in movement duration, speed, and angular offset depending on the test condition and type of specific movement. An interplay of head movement and eye rotation seems to be present in all test conditions. However, limitations in data recording, data labelling and study design may have influenced results, making it difficult to draw definitive conclusions. This semester project may provide a basis for further investigation into the matter.

Zusammenfassung

In diesem Semesterprojekt wurde das menschliche Verhalten in der virtuellen Realität (VR) im Hinblick auf das begrenzte Gesichtsfeld (FoV) in der VR untersucht. Das Projekt konzentrierte sich in erster Linie auf die Bewertung möglicher Unterschiede in den Kopfbewegungstrajektorien zwischen der VR und der Realität im Hinblick auf das begrenzte FoV. Zu diesem Zweck wurde eine Nutzerstudie konzipiert und in drei Testumgebungen durchgeführt, wobei die erste die Realität (RB), die zweite die Realität mit eingeschränktem FoV (LR) und die letzte die virtuelle Realität (VR) war. Trotz erheblicher individueller Unterschiede im Verhalten der Teilnehmer während der Benutzerstudie deuten die Ergebnisse auf Variationen in der Bewegungsdauer, der Geschwindigkeit und dem Winkelabweichung in Abhängigkeit von der Testbedingung und der Art der spezifischen Bewegung hin. Ein Zusammenspiel von Kopfbewegung und Augenrotation scheint in allen Testbedingungen vorhanden zu sein. Einschränkungen bei der Datenaufzeichnung, der Datenbeschriftung und dem Studiendesign könnten die Ergebnisse jedoch beeinflusst haben, so dass es schwierig ist, endgültige Schlussfolgerungen zu ziehen. Dieses Semesterprojekt kann als Grundlage für weitere Untersuchungen zu diesem Thema dienen.

Institut für Werkzeugmaschinen und Fertigung
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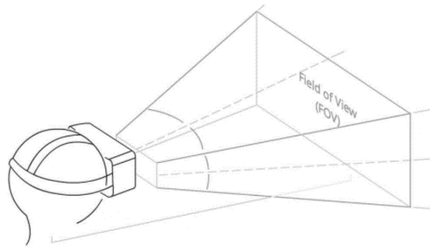
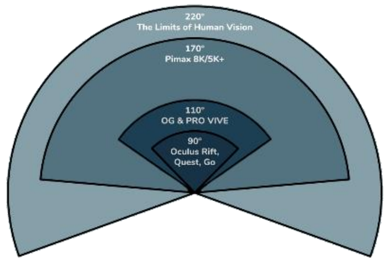
Impact of Limited Field of View (FoV) on Human Behavior in Virtual Reality (VR)

Keywords: Human behavior in VR, limited FoV, interactions in VR

Overview

Nowadays, one of the most popular and wide-spreaded technologies used for the VR experience is a combination of a head-mounted display (HMD) and a pair of controllers. HMD is a wearable device that displays the virtual environment. One of the main characteristics of an HMD is the FoV. Currently, most of the commercially available HMDs have a horizontal FoV around 110°, e.g. HTC Vive Pro 110°, HTC Vive Focus 3 120°, while people can see up to 200°-220°.





This limited FoV can have an impact on the human behavior in VR. Therefore, it's important to investigate how and in which situations it potentially affects the behavior. The comparison between a real-world scenario and a virtual one can be studied by measuring the rotational angles, the angular speed, and the trajectory of the head.

Tasks

Your task is to design and implement virtual and real setups to test if the current limitations in technology cause differences in behavior in virtual and real scenarios. You need to come up with an idea of how to limit the FoV in the real setup. Further, you set up a virtual testing environment, conduct a user study and evaluate your implementation. Finally, you present your findings to the ICVR lab and hand in a written report.

Workpackages

- Literature research on the impact of a limited FoV on user behavior
- Designing a suitable real and virtual environment
- Set up and conduct a user study, incl. data analysis
- Intermediate and final presentation
- Written report

Skills

- Basic programming skills, preferably in C#/C++
- Unity and VR experience is a plus
- Strong communication and interpersonal skills
- VRI lecture attendance is a plus

Results

The results of this thesis have to be summarised in a written report and will be presented to the ICVR in a 20min talk.

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I would furthermore like to voice my appreciation for all the participants of my user study who helped make this research project possible. We do what we must, because we can.

Contents

Glossary

CSV Comma-separated values.

FoV Field of view.

HMD Head-mounted display.

LR Limited Reality.

PC Personal Computer.

RB Reality Baseline.

SIM TLX Simulator Task Load Index.

SSQ Simulator Sickness Questionnaire.

VR Virtual reality.

1

Introduction

1.1 Motivation

Virtual reality (VR) technology has undergone steady development, leading to numerous potential uses in established fields, as well as enabling new applications. Such applications include educational uses, such as distance and language independent learning [1] or simulator training (e.g. machine training [2]), rehabilitation (e.g. physical therapy [3], occupational therapy [4]), entertainment (e.g. video games, movies) [5], as well as design and prototyping [6]. VR offers many advantages in such applications, allowing for cost reductions, or enabling the implementation of additional previously impossible or not viable scenarios. For example training in environments that would be too dangerous or expensive to physically simulate or otherwise not possible to implement in reality. VR can be used to simulate realistic scenarios, create immersive learning experiences, and facilitate the design and testing of products and structures in virtual environments.

With VR exposing users to an environment, that often differs from reality by a varying degree on both the physical and perceptional level, it might seem logical to assume that this might affect human behaviour. There are certain physical limitations in VR, such as the limited FoV, screen resolution, frame rate and lag in current HMDs, but also the composition and level of detail of the virtual environment, just to name a few, which might lead to a different sense of presence and immersion in VR, which in turn might affect user behaviour. Furthermore there are many perceived differences by the user, such as anonymity, the lack of real world consequences for actions, immersion, social influences and situational influences of the specific experiences. It is important to note, that behaviour is very individual and might be affected by many different factors. Hence the extent to which VR affects user behaviour may vary depending on the individual and the specific VR environment and experience. [7, 8, 9, 10, 11, 12, 13, 14]

There has been some research on specific topics on this and there is some evidence to suggest that people may behave differently in VR compared to reality. However, all of the underlying influences and mechanism of influence behaviour don't seem to be completely understood.

As previously mentioned, one of the main physical and perceptional differences in VR compared to reality, is the limited FoV of VR HMDs compared to normal human vision. The human field of view

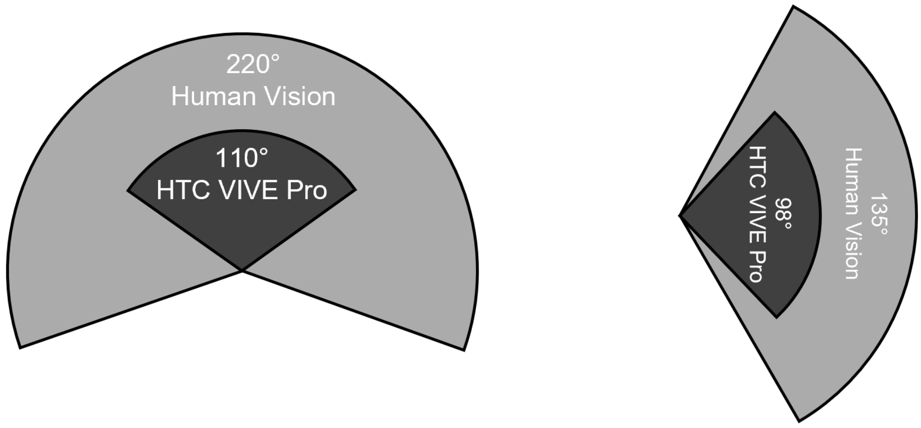

__Figure 1.1:__ Comparisons of horizontal (left) and vertical (right) FoV in VR using the HTC Vive Pro HMD and the FoV of normal human vision.

spans approximately 220 degrees horizontally and 110 degrees vertically [15], while for a VR, looking at the example of the HTC Vive Pro HMD, it is only 110 degrees horizontally and 98 degrees vertically [16], as seen in the comparison figure 1.1.

1.2 Related Work

Influences on user behaviour by limiting FoV (in reality) has been studied extensively. There have been several studies on how limited FoV affects user behaviour while maneuvering an obstacle course, which showed that with limited FoV users tend to maneuver more slowly and compensate for the limited FoV with more frequent head movements. [17, 18, 19, 20, 21]

Regarding search tasks, there have been both studies in VR and reality, looking on how FoV might affect user performance in search tasks. They found that with limited FoV search task performance, specifically the time needed for searching, drops, together with limiting the FoV. [22, 23, 24]

Looking at comparison studies of search tasks between VR and reality, some research has been done. This recent study compared the performance on visual search tasks in physical environments and VR, and found weak to moderate evidence that the search speed, accuracy, workload, and cognitive absorption were equal in VR and physical environments, but recommends further research. [25]

In VR with regards to FoV, research seems more limited and seems to be mainly focused on how artificially limiting FoV can be used in order to combat VR sickness. [26]

For much research in VR FoV is often taken in to account, be it as consideration or as a secondary condition, but often does not appear to be the main focus of research.

Looking at studies comparing user behaviour in reality and VR, much research there comes from the rehabilitation sector, where VR is used as a means for rehabilitation. Especially in research regarding the use of VR for rehabilitation of movements, there has been research to try and validate that movements in reality and VR are the same (what were the results? which papers?).

Such research has been done for grasping movements [27], walking [28] as well as more complex combinations, such as reach to grasp and transport as part of a device assembly task [29].

1.3 Task Formulation

The effects of FoV on human behavior in VR is an area of research that has not been extensively explored, given its complexity. While some studies have looked at behavioral differences for specific tasks and specific conditions, research remains limited comparing behavior in VR and reality with regards to limited FoV.

Research Question: How does user behaviour differ in VR compared to normal user behaviour in reality and how is it affected by the limited FoV in VR?

The purpose of this study is to examine the potential impact of FoV on user behaviour in VR compared to normal user behaviour in reality, with regards to user head movements. To this end a user study is to be designed and conducted as part of the project, as well its results analysed and discussed.

As part of the methodology, chapter 2, based on our literature research research, we have formulated our hypotheses in section 2.2, designed and prepared a user study as described in section 2.3 and Section 2.4, conducted the user study as shown in section 2.5, tidied and labeled the recorded trajectory data as specified in section 2.6 and analysed the results using the means described in section 2.7. We then present, compare and discuss the results from the user study, as well as the projects limitations in chapter 3 and eventually formulate our conclusion drawn from our results in chapter 4.

2

Methodology

In this chapter, a comprehensive overview of the methodology applied in the semester project is presented. Specifically, in section 2.1, detailed information on the software and hardware utilized throughout the project for both VR and the study design, as well as for the subsequent data analysis is provided. Additionally, in section 2.2, the hypotheses that guided the semester project are outlined. Furthermore, in section 2.3, the design of the user study is described and in section 2.4, the procedures that were employed in the conduct of the user study are presented. In section 2.5, information and statistics related to the user study are shown, and in section 2.6 the process of data transformation, tidying, and labeling and in section 2.7 the approach adopted for the data analysis is discussed.

2.1 Hardware and Software

2.1.1 Hardware

Given the nature of this semester project, the use of various hardware devices was imperative for the completion of the project. Throughout the duration of this project, the following hardware equipment was utilised.

HTC Vive Pro Eye

The provided HMD used during the semester project and in the user study was the HTC Vive Pro Eye as seen in Figure 2.1. The HTC Vive Pro Eye is a state-of-the-art VR headset developed by the HTC Corporation for enterprise and professional use in VR, with its dual 1440x1600 resolution AMOLED displays, 110-degree horizontal and 98-degree vertical field of view, and a 90Hz screen refresh rate.

The HTC Vive Pro HMD utilizes a combination of hardware and software to track the user's position and orientation. The HTC Vive Pro HMD uses the Steam VR 2.0 tracking system, developed by the Valve Corporation. This high-precision and low-latency tracking system uses a combination of infrared emitters and sensors to track the position and orientation of VR devices in a large-scale play area. In this tracking system, base stations, commonly referred to "lighthouses" are used. A rotating motor sends out the infrared beam which in itself has the clock time and rotation speed / angle encoded. This signal is then received by either the VR HMD or other VR components, such as controllers or trackers. Using triangulation the object can then calculate its own location and orientation. While it is possible to track using only one base station, usually at least two base stations are used for added precision. For further precision a gyroscope, G-sensor and proximity sensor are also integrated into the HMD. [30]

The Vive Pro Eye HMD also features integrated eye-tracking technology, powered by Tobii, that allows for precise tracking of the user's gaze. The system uses infrared cameras and an infrared light source to track the user's eye movement. By analyzing the reflection of the infrared light off the user's eyes, the system can determine the exact point of gaze with high precision. [31]

The HTC Vive Pro Eye HMD can be used in several different ways, the default being a tethered mode, where the HMD is connected to the link box via cable, allowing for the transfer of video signal and power, which in turn is connected to the PC via Display Port and USB, as well as connected to a power supply. Alternatively, the HMD can be operated in an untethered fashion, in which the device is not connected to the PC via cables, instead, the video signal is transmitted wirelessly from an antenna plugged into the PC to a receiver on the HMD. The device is powered by a mobile battery pack connected to the HMD via USB. This allows for unimpaired and free movement within the tracking space. [32]

HTC Vive Tracker

The HTC Vive Tracker, as seen in Figure 2.1, is a small, puck-shaped device, which can be attached to objects or body parts to enable them to be tracked in tracking space and therefore the VR environment. These trackers are connected wirelessly to the PC and use the same SteamVR Tracking technology described in subsection 2.1.1, allowing for tracking of the object or body part to which they are attached. The trackers make possible a more immersive and responsive VR experience, as well as enable further possible uses, such as data collection. The HTC Vive Trackers, later only referred to as trackers, were used during the course of this semester project for the location and orientation data collection of users in the test environment. [33]

Figure 2.1: *HTC Vive Pro Eye HMD, controllers and base stations (left) and HTC Vive Tracker 2.0 (right) [32]*

2.1.2 Software

During the course of this semester project the utilization of various software programs was necessary, which are presented hereafter.

Unity

Unity is a universal game engine developed by Unity Technologies. The Unity Editor is an integrated development environment (IDE), that facilitates the development of digital content for a varying degree of purposes, such as gaming, TV and architectural design, for various platforms, such as desktop, mobile and many more. For this purpose and to allow more complex interactions, Unity integrates an API for scripting in the programming language C#.

During the course of this project, the Unity Editor of version 2019.4.10f1 was used to assemble and design the technical parts of the user study, such as the data recording, as well as implementing the virtual environment for the VR-based test conditions. [34]

SteamVR

SteamVR is an applications developed by digital content distributor Steam, which was developed by the Valve Corporation. SteamVR enables VR, being the software component enabling VR to run, by not only running the SteamVR 2.0 tracking, but also by acting as the software interface between the PC and the VR HMD, allowing content to be transmitted and run in or as VR. During the course of this project, using the SteamVR plugin in Unity, SteamVR was used to enable the Unity project to be run and viewed on the HTC Vive Pro Eye HMD and to receive the tracking data from the VR test chamber.[30]

Blender

Blender is a free to use 3D software, which is commonly used for modeling, animation, compositing, and video editing. During the course of this semester project Blender was used for the composition of textures and the modelling of the virtual 3D environment and assets present therein. [35]

RStudio Server

In this project, a self-hosted RStudio Server was employed for data transformation, analysis and visualisation. RStudio is an integrated development environment (IDE), which together with is add-on packages facilitates the data science workflow using R and Python programming languages. It integrates with GitHub, providing a collaborative and reproducible workflow. [36]

GitHub

Github is a development platform that allows for easy collaboration from different work machines, as well as development control. GitHub was used during the course of this semester project for both the hosting of the Unity project, as well as the RStudio data and for the Overleaf project with which this report was written. [37]

2.2 Hypotheses

Based on our literature research and our subsequent project task specifications we have come up with the following hypotheses.

It is hypothesized that the velocity of the angular rotation movements in VR is slower compared to reality in terms of both movement duration and rotational velocity given similar surrounding in reality and VR. Furthermore, it is expected that there will be an increase in the number of movements made within VR compared to reality to compensate for limitations in FoV. Given identical FoV limitations and similar surroundings in VR and reality it is anticipated that the head movement trajectories are more comparable to the head movement trajectories in VR with regards to speed and duration, compared to reality without limited FoV.

2.3 User Study Design

To research and observe the specified user behaviours of interest and as called for in the project bid, a user study was to be conducted, the design of which is presented in this section.

2.3.1 Test Conditions

To be able to draw a comparison between the user behaviours in reality and VR and wether they are caused by the limitation of the user's FoV, the three test conditions listed in Table 2.1 were proposed.

Test Condition:	Reality (RB)	Limited Reality (LR)	Virtual Reality (VR)
Fov:	Normal human vision: 220 degrees horizontal 135 degrees vertical	Limited FoV: 110 degrees horizontal 98 degrees vertical	Limited FoV: 110 degrees horizontal 98 degrees vertical

Table 2.1: *The three test conditions and their FoVs proposed for the user study*

The *first* test condition was conducted in *reality*, as experienced in every-day life. This test condition serves as a point of reference and baseline to compare the other test conditions to and is hereafter referred to as Reality Baseline (RB).

The *second* test condition is also based in *reality*, however, the user's FoV is limited to the same level as experienced in VR. This test condition is hereafter redefferd to as Limited Reality (LR).

The *third* test was conducted entirely in *virtual reality* using the provided HTC Vive Pro Eye HMD to experience a virtual environment, which was custom designed using Unity and Blender. This test condition is hereafter simply referred to as Virtual Reality (VR).

2.3.2 Custom Designed Tracker Mounts and FoV Restriction Device

Reality Baseline (RB)

In the RB test condition a GoPro head-strap was used with a custom designed and 3D-printed attachment point, on which the HTC Vive Tracker was attached, using a standard tripod 1/4 inch mounting screw as

Test Condition:	Reality (RB)	Limited Reality (LR)	Virtual Reality (VR)
Fov:	Normal human vision: 220 degrees horizontal 135 degrees vertical	Limited FoV: 110 degrees horizontal 98 degrees vertical	Limited FoV: 110 degrees horizontal 98 degrees vertical

Table 2.2: *The three test conditions and their FoVs and employed tracking and perception alteration and enabling devices used in the user study*

seen in Figure 2.2. The mount was designed using the CAD modelling program NX1984.

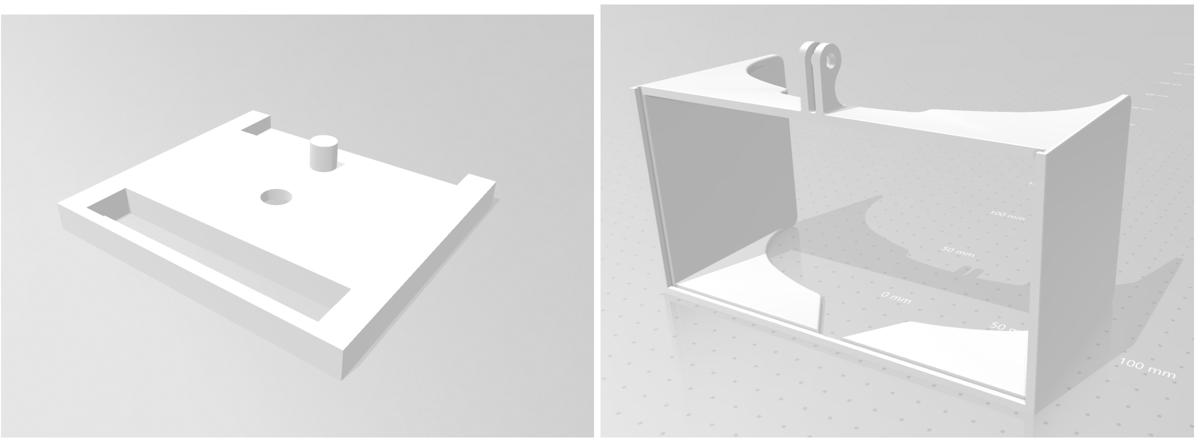

Figure 2.2: *Rendering of custom designed and 3D-printed Vive Tracker mount (left) and FoV restriction device (right)*

Limited Reality (LR)

The same head-strap used in the RB was also used for LR, with the addition of a custom designed and 3D-printed FoV restriction device. The FoV restriction device was designed using the CAD modelling program NX1984.

Figure 2.3: *FoV restriction device*

The device offers the same FoV as experienced while wearing the HTC Vive Pro Eye HMD, which was designed and validated iteratively in the following way.

Using the occlusion mesh sent to the HTC Vive Pro, an A4 paper with a grid was placed in an empty unity project at a specified distance in front of the unity camera, to match the distance where the FoV occlusion insert would be placed in the FoV restriction device.

The visible grid of the A4 paper in unity restricted by the occlusion mesh would be saved and transformed as the views of both eyes are overlapping, which then resulted in the following form being derived, which matches the FoV of the HTC Vive Pro Eye HMD.

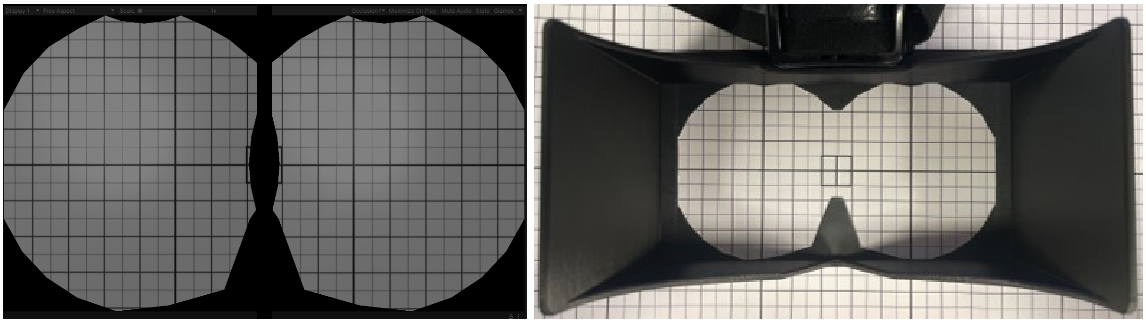

Figure 2.4: *Grid visible using the occlusion mesh for the HTV Vive Pro Eye HMD in unity (left) and using the FoV restriction device (right).*

Virtual Reality (VR)

The same custom designed and 3D-printed attachment point was also used to attach the HTC Vive Tracker to the HTC Vive Pro Eye HMD. While it was possible to record the location and trajectory of the HMD directly, to establish the same prerequisites for all test conditions, the data was also recorded using a Vive Tracker in VR, attached to a similar point as the tracker in reality.

2.3.3 User Study Environment

For the conduction of the user study a tracking space located on the basement floor *A* of the CLA building at ETH Center was chosen.

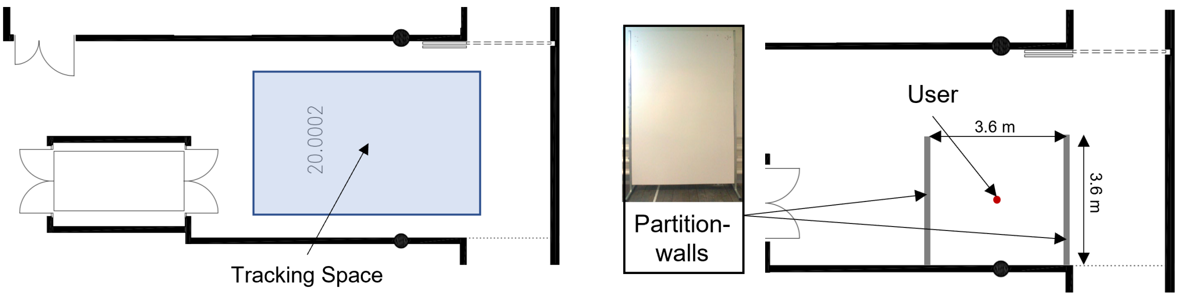

Figure 2.5: *CLA A floor tracking space test chamber floor plan (left) and layout for user study (right)*

The goal was to set up similar test chambers in both reality and virtual reality. The user was to be located in the middle of a square space, surrounded by three walls.

Reality

For the reality-based test conditions, RB and LR, the square test chamber was set up in the tracking space area using partition walls sourced from ETH Infrastructure. These partition wall panels had a height of 180 cm and a width of 120 cm and could be set up either vertically or horizontally between two metal stands, either 16 cm or 76 cm above the ground. Setting up the walls vertically at 76 cm above the ground, results in a total height of 256 cm. Three panels were used in their high vertical position for each wall, which including the metal stands, resulted in a wall length of 372 cm and a wall height of 256 cm. For the task, the user was to be located in the middle of this square room, at a uniform distance of 186 cm from all three walls.

Figure 2.6: *The empty CLA A floor tracking space (left) and with the partition wall setup (right)*

Virtual Reality

For the VR-based test, the test chamber was set up using unity, with the modelling and texturing of the assets having been completed in blender.

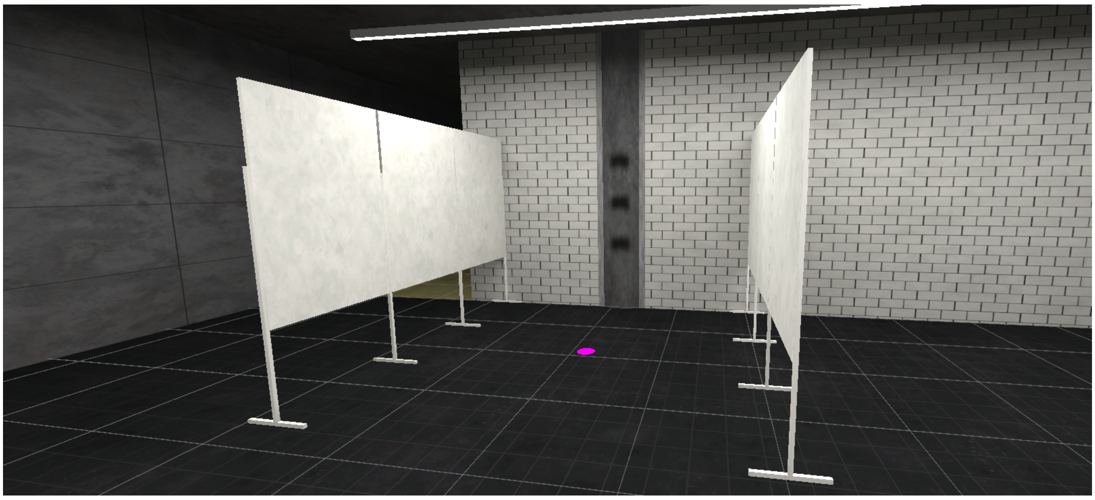

Figure 2.7: *Rendering of the VR test chamber*

2.3.4 Task Design

Given the test conditions and environments for the basic user study, each test condition required the participant to complete the task outlined below.

The three walls of the square test chamber are filled with nine focus targets each, for a total of 27 focus targets. These targets are composed of a combination of a letter and a number, with the letter depicting the wall, *A* for the left wall, *B* for the middle wall and *C* for the right wall, and the number standing for the location of the focus target. The focus target cards are ordered in a logical fashion as seen in Figure 2.8.

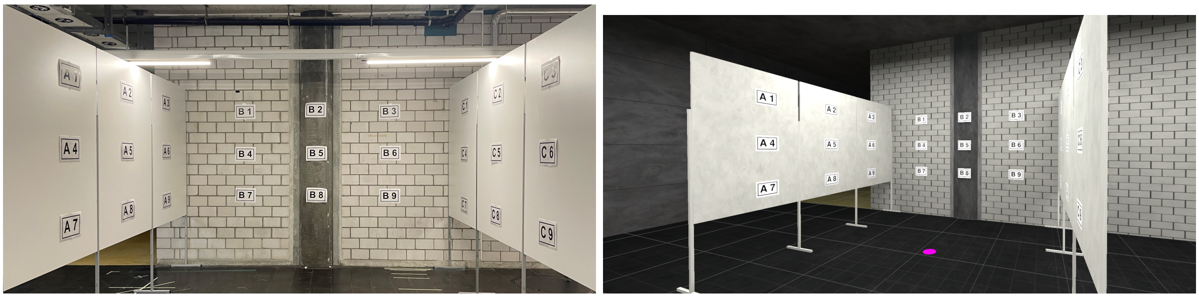

Figure 2.8: *Test chamber setup with focus targets in reality (left) and VR (right)*

The task starts with the user being located in the middle of the square test chamber in their resting position, which is looking at focus target B5 as seen in Figure 2.9.

Figure 2.9: *Resting position of the user looking at focus target B5*

The next focus target is called out by the test conductor with the user looking at the next focus target as seen in Figure 2.10.

Figure 2.10: *Example Looking Task Order*

The order of the looking task for the complete user study, depending on the test condition order, is shown in Figure 2.11.

Looking task order (RB-LR-VR)

1 R baseline:

- ☐ B5 -> B6 -> B9 -> B8 -> B5 -> B4 -> B1 -> B2 -> B5
- ☐ B5 -> B3 -> B1 -> B9 -> B3 -> B7 -> B1 -> B5 -> B7 -> B9 -> B5
- ☐ B5 -> A5 -> C5 -> B5 -> C2 -> B8 -> A2 -> A8 -> B2 -> C8 -> B5
- ☐ B5 -> B4 -> A4 -> C6 -> B6 -> B5

2 LR:

- ☐ B5 -> B4 -> B1 -> B2 -> B5 -> B6 -> B9 -> B8 -> B5
- ☐ B5 -> B7 -> B9 -> B5 -> B3 -> B1 -> B9 -> B3 -> B7 -> B1 -> B5
- ☐ B5 -> C5 -> A5 -> B5 -> C2 -> B8 -> A2 -> A8 -> B2 -> C8 -> B5
- ☐ B5 -> B6 -> C6 -> A4 -> B4 -> B5

3 VR

- ☐ B5 -> B6 -> B9 -> B8 -> B5 -> B4 -> B1 -> B2 -> B5
- ☐ B5 -> B9 -> B7 -> B5 -> B3 -> B1 -> B9 -> B3 -> B7 -> B1 -> B5
- ☐ B5 -> C2 -> B8 -> A2 -> A8 -> B2 -> C8 -> B5 -> A5 -> C5 -> B5
- ☐ B5 -> B4 -> A4 -> C6 -> B6 -> B5

Looking task order (RB-VR-LR)

1 R baseline:

- ☐ B5 -> B6 -> B9 -> B8 -> B5 -> B4 -> B1 -> B2 -> B5
- ☐ B5 -> B3 -> B1 -> B9 -> B3 -> B7 -> B1 -> B5 -> B7 -> B9 -> B5
- ☐ B5 -> A5 -> C5 -> B5 -> C2 -> B8 -> A2 -> A8 -> B2 -> C8 -> B5
- ☐ B5 -> B4 -> A4 -> C6 -> B6 -> B5

2 VR:

- ☐ B5 -> B4 -> B1 -> B2 -> B5 -> B6 -> B9 -> B8 -> B5
- ☐ B5 -> B7 -> B9 -> B5 -> B3 -> B1 -> B9 -> B3 -> B7 -> B1 -> B5
- ☐ B5 -> C5 -> A5 -> B5 -> C2 -> B8 -> A2 -> A8 -> B2 -> C8 -> B5
- ☐ B5 -> B6 -> C6 -> A4 -> B4 -> B5

3 LR

- ☐ B5 -> B6 -> B9 -> B8 -> B5 -> B4 -> B1 -> B2 -> B5
- ☐ B5 -> B9 -> B7 -> B5 -> B3 -> B1 -> B9 -> B3 -> B7 -> B1 -> B5
- ☐ B5 -> C2 -> B8 -> A2 -> A8 -> B2 -> C8 -> B5 -> A5 -> C5 -> B5
- ☐ B5 -> B4 -> A4 -> C6 -> B6 -> B5

Figure 2.11: *Looking order for the two test condition orders*

2.3.5 Data Recording

To record comparable data during all three test conditions, despite their different environments, HTC Vive Trackers were used, fixed to the users head. During all three test conditions, the unity program with the test chamber would run in the background, recording all the specified data from the Vive Tracker.

All of the following data points were recorded in Unity and saved in a CSV format.

- Time since Startup of the Tracking Script
- x-, y-, z-Location of Tracker
- x-, y-, z- and w-Quaternions of Tracker
- x-, y-, z-Rotation in Euler Angles

Additionally, in VR, due to the eye tracking capabilities of the HTC Vive Pro Eye HMD, eye tracking was set up and additionally, the following data was also recorded.

- x-, y-, z-Eye Gaze Direction
- x-, y-, z-Eye Gaze Origin
- Convergence Distance
- Focused Object (Focus Target A1 - C9)
- x-, y-, z-Location of Focused Object
- Left- and Right-Eye Blink

The Unity project was based and built up on the sample Unity project provided by ICVR. For the trajectory tracking the provided scripts were slightly adapted and updated to allow for the location and orientation of the HTC Vive Trackers to be recorded. Furthermore the scripts were improved to allow tracking of up to 50 Hz. In the case of the eye tracking, the functionality provided by the TobiiXR sample scenes and scripts were imported into the project. This was used to allow for the gaze-targeted focus object to be recorded as well.

2.3.6 Questionnaires

The following questionnaires were used in the user study:

- Demographics Questionnaire
- Simulator Sickness Questionnaire (SSQ)
- Simulation Task Load Index (SIM-TLX)
- Cognitive Absorbance Questionnaire
- VR Presence Questionnaire

Demographics Questionnaire

To get some basic information about the user study, as well as an insight and some basic information about the demographics of the user study participants, a demographics questionnaire, provided by the ICVR sample questionnaire, was used. The following questions were included (where applicable the answer options are provided in squared brackets):

- Date of study session
- Starting Time
- Gender
- Age
- Profession
- Are you currently wearing glasses or contacts? [Glasses / Contacts / None]
- Are you a student? [Yes / No]
- What degree are you pursuing? [BSc / MSc / PhD]
- Field of Study [Humanities / Social- / Natural- / Formal- / Applied Sciences / Other]

Simulator Sickness Questionnaire (SSQ)

To measure and quantify the users potential simulator sickness over the course of the user study, the simulator sickness questionnaire (SSQ) [38] was used. This questionnaire included questions about how severe the users are experiencing the following 16 different symptoms, which could be answered on a four step scale from *None (0)* to *Severe (3)*:

1: General discomfort

2: Fatigue

3: Headache

4: Eyestrain

5: Difficulty focusing

6: Increased salivation

7: Sweating

8: Nausea

9: Difficulty concentrating

10: Fullness of head

11: Blurred vision

12: Dizziness (eyes open)

13: Dizziness (eyes closed)

14: Vertigo

15: Stomach awareness

16: Burping

Simulation Task Load Index (SIM-TLX)

To measure the users task load during the different test conditions the SIM-TLX questionnaire [39] was used. This questionnaire included the following nine questions which could be answered on an eleven step scale from *very low (0)* to *very high (10)*:

1: How mentally fatiguing was the task?

2: How physically fatiguing was the task?

3: How hurried or rushed did you feel during the task?

4: How insecure, discouraged, irritated, stressed and annoyed were you?

5: How complex was the task?

6: How stressed did you feel while performing the task?

7: How distracting was the task environment?

8: How uncomfortable/irritating were the visual and auditory aspects of the task?

9: How difficult was the task?

2.3.7 Cognitive Absorbance Questionnaire

To measure the cognitive absorbance during the different test conditions, the following five questions, sourced from the template ICVR questionnaire, which could be answered in a seven step scale from *I do not agree (1)* to *I strongly agree (7)*, were used:

1: While using the VR equipment, I was able to block out most other distractions.

2: While using the VR equipment, I was absorbed in what I was doing.

3: While using the VR equipment, I was immersed in the task I was performing.

4: While using the VR equipment, I got very easily distracted by events unrelated to the task.

5: While using the VR equipment, my attention did not get diverted very easily.

VR Presence Questionnaire

To measure the presence during the VR test condition, the following five questions, sourced from the template ICVR questionnaire, which could be answered in a seven step scale from *1* to *7*, were used:

1: Sense of being in the training room, on the following scale, where 7 represents your normal experience of being in a place. I had a sense of being in the training room:

2: To what extent were there times during the experience when the training room was reality for you?

3: When you think back, do you think of the training room more as images that you saw, or more as a place that you visited?

4: During the time of the experience, which was strongest, the sense of being in the training room, or being somewhere else?

5: Consider your memory of being in the training room: How similar in terms of the structure of memory is this to the structure of memory of other places that you have been today? (...) Do you think of the training room as a place in a way similar to other places that I have been to today?

6: During the experience, did you often think to yourself that you were actually present in the test chamber?

2.4 User Study Procedure

During the user study, to prevent any bias induced by the test condition order, the order for the test conditions with the restricted FoV, LR and VR, was switched for half of the user study participants. Hence, the following two test condition orders were used:

- RB - LR - VR
- RB - VR - LR

An illustration of the user study procedures, including all questionnaires is seen in Figure 2.12.

2.4.1 Test Condition Procedure

Within each test condition the following procedures were used:

1. Familiarization Phase

During the beginning of each test condition the user is given some time to familiarize themselves with their environment until they feel ready to begin the task.

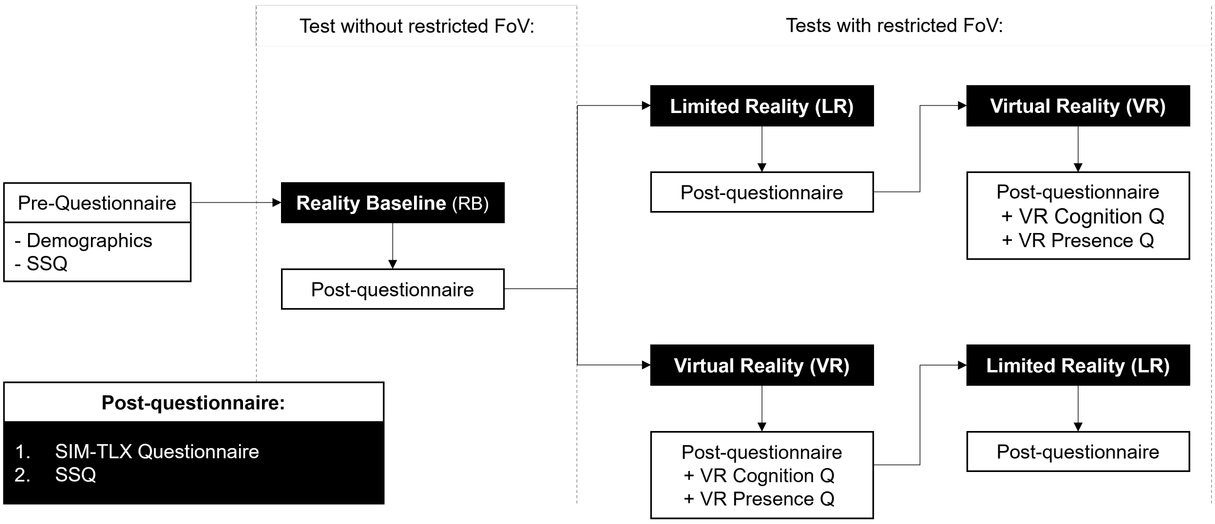

Figure 2.12: *User study procedures for both test condition orders*

2.1 Calibration

After the user has familiarized themselves with their test environment, the user is asked to look at the card B5 for calibration purposes before starting with the proper guided looking task.

2.2 Guided Looking Task

The guided looking task is completed with the test conductor calling out the focus targets and the user subsequently looking at them as described in section 2.3.4.

3 Waiting Task

After completion of the guided looking task, the user was then asked to remain in their spot for some time. The reason given was to give the data some time to save the recordings, however this was not quite accurate, as this was an excuse to potentially measure the users curiosity based on their head movement frequency during that time.

2.5 User Study Execution

The study was conducted between the 15th of December 2022 and the 23rd of December 2022. Participants were recruited by invitations in student chat-rooms in social media, as well as by distribution of posters at student study areas around ETH Zurich. A total of 31 participants with an average age of 24 were recruited. The age distribution ranged from 21 years to 33 years. Of the participants 13 identified as male and 18 identified as female. Most of the participants were students, nine of which were pursuing a Bachelor's degree, 20 pursuing their Master's degree and two pursuing the PhD. An overview of facts and figures of the participants of the user study can be found in Table 2.3.

Total Participants	Female	Male	Average Age	Age Standard Deviation	Age Range
31	13	18	24.613	2.531	21 - 33

Table 2.3: *User Study facts and figures*

Figure 2.13: *Satisfied user study participant*

2.6 Data Tidying and Labeling

To use the data collected during the user study, extensive post-processing was necessary. The recorded orientation had to be transformed into vectors for analysis and then transformed into spherical coordinates for visualisation.

To transform the rotation denoted by the quaternions or Euler Angles into a directional vector we need to take into account the orientation of the Vive Tracker worn by the user in the designated calibration position looking at B5, as the tracker is worn at an angle as seen in Figure 2.14.

To identify the calibration orientation a preliminary speed was calculated using the Euler Angle rotation differences using Formula 2.1. Furthermore, recording breaks were used to mark certain points during the recording, which can be identified by the larger difference between the recorded time since startup, which served as markers for the subsequent data tidying and labeling. Looking at the preliminary raw pitch and yaw angles and the calculated angular velocity and using the time-step markers as seen in Figure 2.15 left, the area with no to little movement could be identified as the calibration period, from which the calibration orientation could then be derived. As seen in Figure 2.15 right, the calibrated looking vector is calculated as the intersection vector between the plane spanned by the Vive tracker's local z-axis and

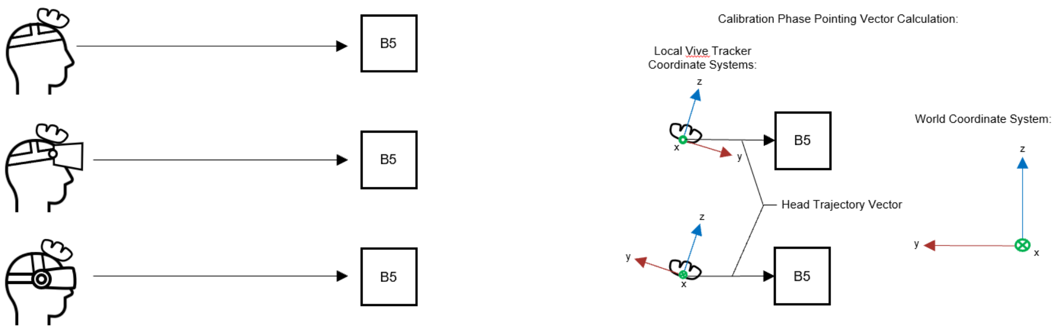

Figure 2.14: *Orientation of the Vive tracker while worn in test condition RB, LR and VR for the calibration (left) and orientation of the Vive tracker in depending on the two possible Vive tracker internal coordinate systems and the global world coordinate system (right)*

y-axis vector and the plane spanned by the global world y-axis and x-axis vector. Applying the inverse calibration rotation on the calculated head-trajectory vector results in a corrected head-trajectory vector to which all recorded rotations could then be applied to, resulting in a pointing vector corrected around the calibration orientation of the user looking at B5.

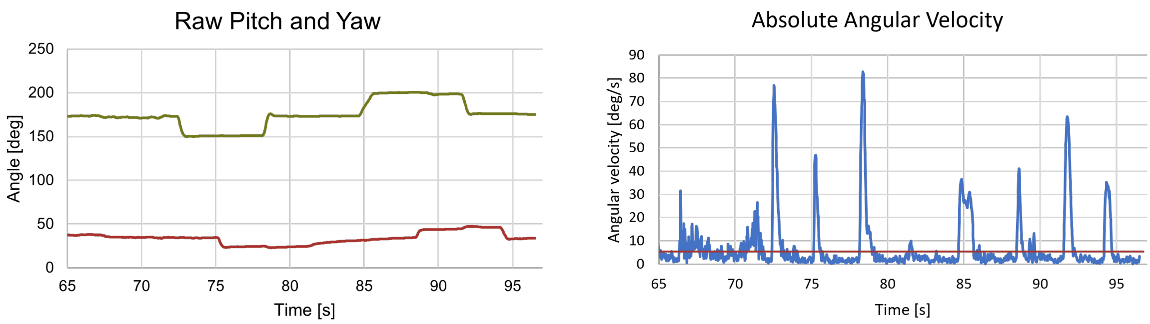

Figure 2.15: *Example raw pitch and yaw (left) and preliminary calculated angular velocity (right) for Phase 1 (B5-B6-B9-B8-B5-B4-B1-B2-B5) of the guided looking task of user study participant 20*

During the process of the the data tidying and transformation inconsistent results of the orientation of the Vive tracker were observed. These could be explained by an inconsistent internal coordinate system of the Vive tracker which was observed by chance during a test after the user study. Research has shown that the coordinate system of the Vive tracker might change depending on the role assigned in the SteamVR Tracker Settings, however, the coordinate system was observed to be different for some start-ups of unity, despite the role of the tracker not being changed. It appears that there is a bug that during the start-up of unity connection with SteamVR and the trackers, either one of two coordinates system may be used internally in the tracker. Fortunately, the coordinate system stayed consistent during the the run of the program and would only be randomly set at the start-up of the program or connection of the tracker. Two different coordinate systems were identified which are shown in Figure 2.14. This inconsistent coordinate system had to be accounted for as the calibration orientation was calculated using the plane spanned by the internal z-axis and y-axis vectors of the tracker, which due to the changing coordinate system sometimes resulted in values shifted by 180 degrees in subsequent spherical coordinate calculation.

The recorded rotation (in either Euler Angles or quaternions) was transformed into a rotational matrix and was applied to the head trajectory pointing vector using a transformation command provided by an R package, which enables transformation of rotations from one notation to another (EA to rotation Matrix or quaternions to rot Matrix), resulting in a head trajectory vector corrected around the orientation of the user looking at focus target B5. The transformation had to be then manually adjusted for the left-handedness of the Unity world coordinate system.

The angular rotation speed of each recorded time-point n was calculated using Formula 2.1, using the average of the angular difference over the duration of the time-step between the previous and latter recorded orientation, with the angle as the angle between the orientation vectors.

$$V_n = \frac{1}{2} * (\frac{\alpha_{pre}}{t_n - t_{n-1}} + \frac{\alpha_{post}}{t_{n+1} - t_n}) \tag{2.1}$$

In similar fashion to the angular rotation speed, the angular acceleration was calculated using Equation 2.2, using the average of the angular rotation speed difference over the duration of the time-step between the previous and latter recorded angular rotation speed.

$$A_n = \frac{1}{2} * (\frac{V_n - V_{n-1}}{t_n - t_{n-1}} + \frac{V_{n+1} - V_n}{t_{n+1} - t_n}) \tag{2.2}$$

Furthermore, to analyse the specific head movements, the movements had to be identified and labeled in the tracked data. This proved more difficult than expected as automatic labeling proved to be too tedious and inconsistent due to the messiness of the tracked data. Automatic labeling based on both movement speed threshold and head orientation proved inconsistent due to the vast differences between individual head orientations and movements.

Due to the complexity of the labeling operation and movement identification, the collected data was eventually labelled and identified by hand based on both orientation and movement speed, with a threshold of 5 deg/s being used to classify a data point as movement, while the specific movement was identified based on the orientation change. The threshold of 5 deg/s was chosen due to the fact that the noise of the calculated velocity was usually around $2-3$ deg/s depending on the user, as seen in Figure 2.15.

The labelling of the data was conducted using Excel, while the data tidying and transformation was completed using RStudio. In total 93 datasets, containing a combined total of 689’976 lines of code with a total of 28’289’016 individual data-points, were manually labelled. The data was labelled with three identifiers:

- *Phase*: Phase of the looking task, with entries ranging from 1-4, with each row of looking orders in Figure 2.11 representing one phase.
- *GFO*: Focus object on which the user should be focusing on in between the movements
- *Movement*: Denoting a movement between two focus objects and labelled with a number, to identify the specific movement in each phase.

There were a total of 33 movements for each user in each test condition.

The movement in Figure 2.16 represents a clean and ideal case for labelling, however, this was not always the case. The figure here is to provide and example of an easily identifiable movement to understand the concept employed for the labelling of the data.

Speed	Phase	GFO	Movement
0.484	1	B4	
1.207	1	B4	
2.994	1	B4	
5.800	1		2
9.143	1		2
12.704	1		2
16.321	1		2
19.935	1		2
23.318	1		2
26.078	1		2
28.340	1		2
30.514	1		2
32.789	1		2
34.737	1		2
35.734	1		2
35.471	1		2
34.268	1		2
32.542	1		2
30.279	1		2
27.592	1		2
24.633	1		2
21.711	1		2
19.246	1		2
17.375	1		2
15.700	1		2
13.741	1		2
11.821	1		2
10.178	1		2
8.7290	1		2
7.1251	1		2
5.404	1		2
3.880	1	B1	
2.638	1	B1	
1.736	1	B1	

Figure 2.16: *Example of labelled data of user study participant number 10, with colour-coded angular rotation speed and the three defined labels*

2.7 Data Analysis

After the data tidying, transformation and labelling the data into a usable format, the movement data was analysed and visualised using RStudio. Specifically, several key movements were identified and analysed in more detail, calculating the movement duration time, the average angular rotation speed, as well as the angular offset, the angular offset being the angle between the recorder head trajectory vector and the ideal vector between user and the focus target. Furthermore, the head movement trajectories were visualised for all movements of interest and in the case of the test conditions in VR, the eye trajectories were visualised as well.

Based on the above calculations, the overall movement duration of different movements, movement speed and angular offset for each test condition were calculated.

To account for individual behavioral differences, the individual differences for each individual user between the three different test conditions, with regards to head movement duration, head movement speed and angular offset were calculated, summarised and compared as seen in chapter 3.

3

Results and Discussion

In this chapter the derived results of the project are summarised.

3.1 Example Head Movement Comparison

A visualisation of the head movement trajectories of user 20 during phase 1 of the looking sequence (B5-B6-B9-B8-B5-B4-B1-B2-B5) is presented in Figure 3.1 for three distinct experimental conditions (RB, LR, VR) as an example.

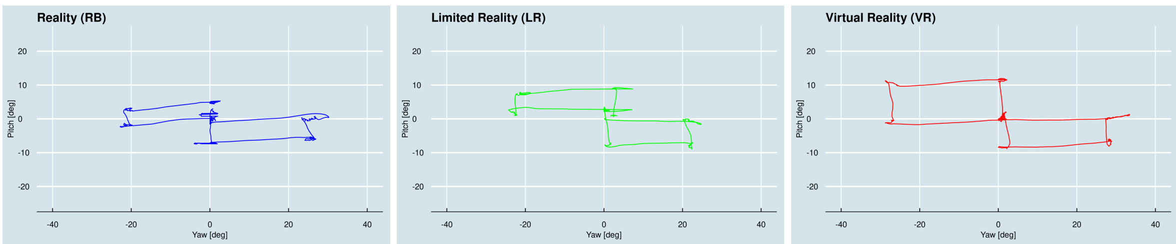

Figure 3.1: *Head movement trajectories for movement order B5-B6-B9-B8-B5-B4-B1-B2-B5 of user study participant 20 for RB (left), LR (middle) and VR (right)*

Figure 3.2 displays these same head movement trajectories over each other for easier comparison.

In the case of user 20, as seen in Figure 3.2, while all of the head trajectories are offset short of the focus target, in the case of RB and LR they appear more offset compared to the VR head trajectories. These example trajectories serves as a representation of what was found for most users, as detailed more in the following sections. Furthermore, this indicates that only a part of the rotation necessary in the aforementioned looking order is completed by turning the head. The rest of the distance is completed by eye rotation, as detailed in Section 3.2.

The examination of the head movement trajectories of individual 20, as depicted in Figure 3.2, reveals that while all of the head trajectories end short of the intended focus target, a greater deviation is observed in the test condition of RB and LR as compared to the test conducted in VR. These observations are generally consistent with the general trends noted among the study participants, which is why it was chosen as an example. The angular offset of the head trajectories compared to the focus object will be discussed in further detail for specific movements in subsequent sections. It is noteworthy that these findings suggest that only a portion of the rotation required to look at the focus target is achieved through head rotation, with the offset appearing to being compensated through eye rotation, as discussed in Section 3.2.

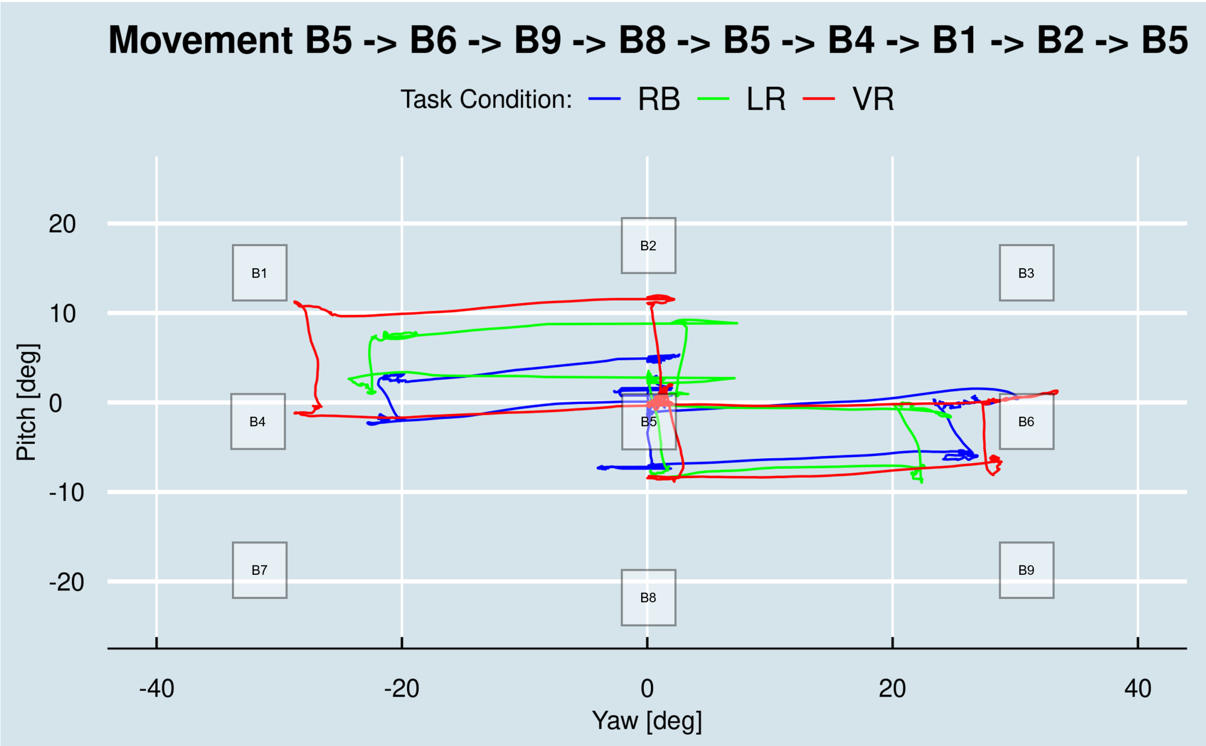

Figure 3.2: *Head movement trajectories for Phase 1 movement order B5-B6-B9-B8-B5-B4-B1-B2-B5 of user study participant 20 overlaid for all three different test conditions, including the location of the focus targets on wall B*

3.2 Comparison of Head Trajectories and Eye Trajectories in VR

By utilizing the built-in eye tracking functionality of the HTC Vive Pro Eye HMD, it was possible to record and analyse the eye movement trajectories of the participants during the VR test condition. In Figure 3.3, the comparison of head and eye trajectories for study participant 20 during Phase 1 (B5-B6-B9-B8-B5-B4-B1-B2-B5) of the looking task in the VR test condition is visualised.

The analysis of the head and eye trajectories revealed a consistent deviation of the head movement patterns from the intended focus target, while the eye movements were found to be accurately directed towards the focus target. This observation suggests that the angular offset of the head trajectory is compensated by rotation of the eyes towards the focus target, indicating the presence of an interplay between head and eye movements in the execution of the tasked shift between the focus objects.

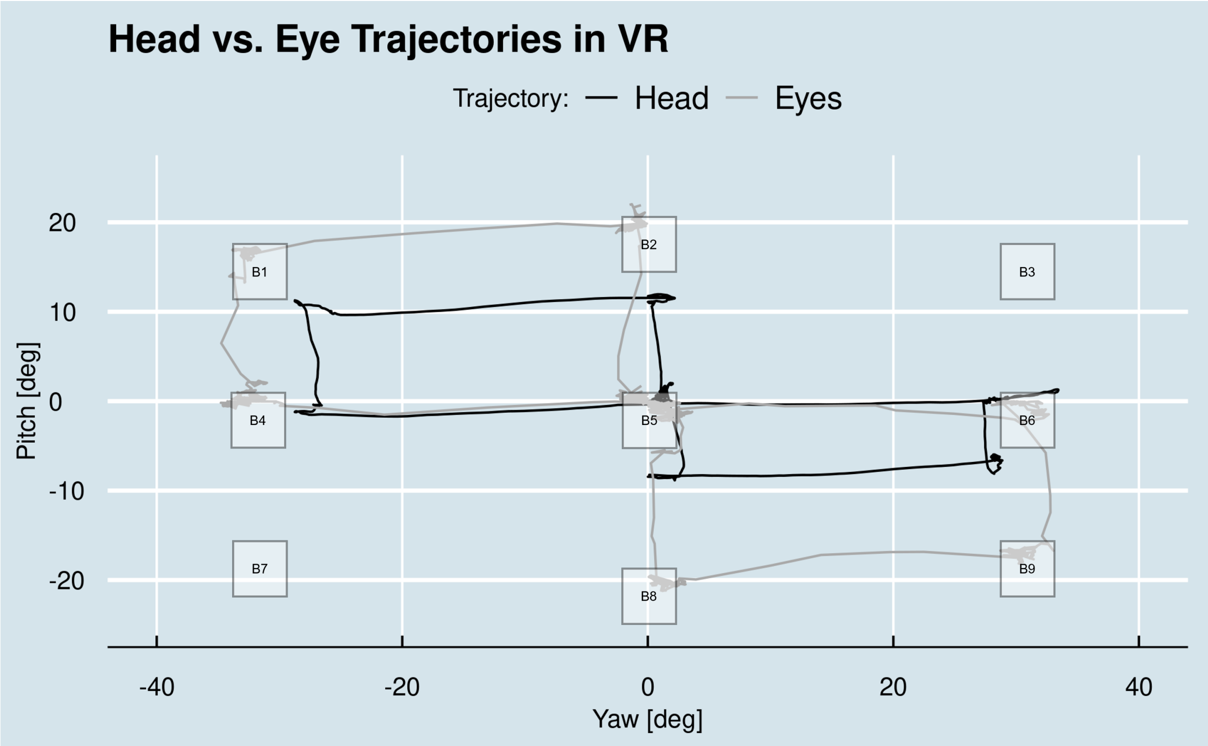

Figure 3.3: *Head and eye movement trajectories for Phase 1 looking order B5-B6-B9-B8-B5-B4-B1-B2-B5 of user study participant 20 during the VR-based test condition*

3.3 Detailed Head Movement Comparison

To account for the large number of recorded movements, the following movements were selected for further detailed analysis:

Short Movements:

- $B5 \rightarrow B6$
- $B5 \rightarrow B4$
- $B6 \rightarrow B9$
- $B4 \rightarrow B1$

Long Movements:

- $B5 \rightarrow A5$
- $C5 \rightarrow B5$

For the results analysis in this project, two distinct movement categories were considered: *short movements*, which are movements towards focus targets within the FoV of the participants, and *long movements*, which are movements towards focus targets outside of the FoV and thus necessitate a head rotation to some degree.

An analysis of several aspects of these movements is conducted in the following sections. The parameters evaluated include the duration of the movement, the average angular rotation speed, as well as the angular offset between the head trajectory and the focus target. Both the mean values across all users for the different test conditions, as well as the differences between the test conditions for each individual user, to account for individual behavioral differences, are being discussed.

3.3.1 Short Movements

B5 - B6

As seen in Figure 3.4 and Table 3.1 the movement duration (Time to Target) of the head is overall slightly higher in RB compared to LR and VR. Analysis of the differences for the individual users shows that the difference between RB and LR is twice as high compared to the differences between LR and VR. Focusing on the angular offset of the head trajectory compared to the focus target, these appear higher for LR, closely followed by RB, compared to VR. In this case the individual differences in angular offset for RB and LR are much more similar compared to VR. Focusing on the angular speed, this is the highest for VR, followed by LR and then RB, which are nearly identical. Here again, the differences between RB and LR are much smaller compared to the differences between RB and LR to VR.

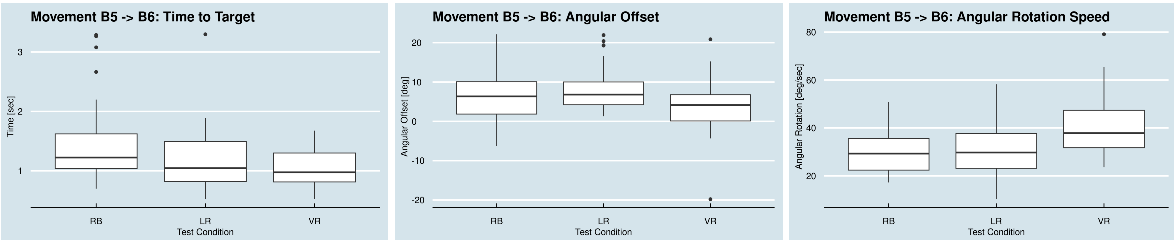

Figure 3.4: *Box plot of the mean values for Time to Target (left), Angular Offset (middle) and Angular Rotation Speed (right) of all user study participants for the three test conditions for movement B5 $\rightarrow$ B6*

Test Condition	RB	sd	LR	sd	VR	sd	ΔRB.LR	sd	ΔRB.VR	sd	ΔLR.VR	sd
Time to Target [sec]	1.481	0.716	1.187	0.552	1.058	0.313	0.295	0.647	0.423	0.693	0.128	0.526
Angular Offset [deg]	6.307	6.243	8.385	5.894	3.961	7.365	-2.072	8.048	2.77	9.694	4.842	7.307
Angular Rotation Speed [deg/sec]	29.916	9.098	30.678	11.062	40.516	13.72	-1.18	13.028	-10.472	15.166	-9.292	16.063

Table 3.1: *Table of mean values of all user study participants for the different test conditions (left) and the mean differences between the different test conditions for the individual users (right) for movement B5 $\rightarrow$ B6*

B5 - B4

As seen in Figure 3.5 and Table 3.2 the movement duration (Time to Target) of the head is overall again slightly higher in RB compared to LR and VR. Analysis of the differences for the individual users shows that the duration for LR and VR for individual users was nearly identical, while for RB it was longer. Focusing on the angular offset of the head trajectory compared to the focus target, these appear higher for RB, followed by RB and then VR. In this case the individual differences in angular offset for LR and VR are more similar compared to RB. Focusing on the angular speed, this is the highest for LR, followed by VR and then RB. The individual differences between RB and LR and LR and VR are similar.

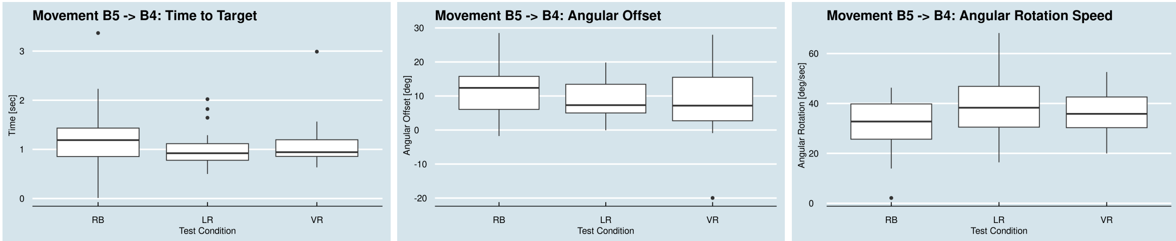

Figure 3.5: *Box plot of the mean values for Time to Target (left), Angular Offset (middle) and Angular Rotation Speed (right) of all user study participants for the three test conditions for movement B5 → B4*

Test Condition	RB	sd	LR	sd	VR	sd	ΔRB.LR	sd	ΔRB.VR	sd	ΔLR.VR	sd
Time to Target [sec]	0.863	0.693	0.802	0.434	0.687	0.336	0.287	0.613	0.209	0.727	-0.078	0.485
Angular Offset [deg]	11.806	7.392	9.332	5.677	8.896	9.892	2.768	9.721	3.0644	10.805	0.296	11.544
Angular Rotation Speed [deg/sec]	31.487	10.482	39.217	12.449	36.016	8.966	-8.212	16.799	-4.897	14.359	3.315	15.072

Table 3.2: *Table of mean values of all user study participants for the different test conditions (left) and the mean differences between the different test conditions for the individual users (right) for movement B5 → B4*

B6 - B9

As seen in Figure 3.6 and Table 3.3 the movement duration (Time to Target) of the head is overall very similar for all three test conditions. Same holds true for the differences between the test conditions for the individual users. Focusing on the angular offset of the head trajectory compared to the focus target, these appear higher for LB, followed by RB and then VR. In this case the individual differences in angular offset for LR and VR are more similar compared to RB. Focusing on the angular speed, this is very similar for all three test conditions. The individual differences between RB and LR and LR and VR are once again similar, however in this case the angular rotation speed for RB appears to be slightly higher.

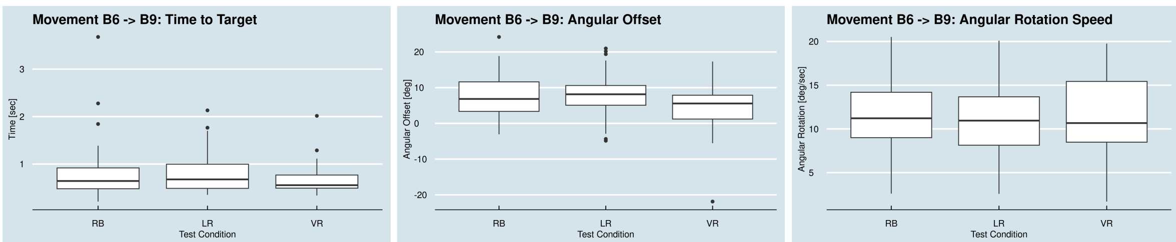

Figure 3.6: *Box plot of the mean values for Time to Target (left), Angular Offset (middle) and Angular Rotation Speed (right) of all user study participants for the three test conditions for movement B6 → B9*

Test Condition	RB	sd	LR	sd	VR	sd	ΔRB.LR	sd	ΔRB.VR	sd	ΔLR.VR	sd
Time to Target [sec]	0.863	0.693	0.802	0.434	0.687	0.336	0.05	0.766	0.17	0.663	0.12	0.541
Angular Offset [deg]	7.357	6.372	8.363	6.6	4.559	7.094	-0.738	9.514	3.481	9.938	4.219	8.363
Angular Rotation Speed [deg/sec]	11.841	4.867	11.054	4.389	11.528	4.396	1.089	5.426	0.285	5.662	-0.804	4.35

Table 3.3: *Table of mean values of all user study participants for the different test conditions (left) and the mean differences between the different test conditions for the individual users (right) for movement B6 → B9*

B4 - B1

As seen in Figure 3.4 and Table 3.4 the movement duration (Time to Target) of the head is overall very similar for all three test conditions. Same holds true for the differences between the test conditions for the individual users. Focusing on the angular offset of the head trajectory compared to the focus target, these are highest for RB, followed by LR and lastly VR. In this case the individual differences in angular offset for LR and VR are more similar compared to RB. Focusing on the angular speed, the results are once again very similar for all three test conditions. The individual differences between RB and LR and LR and VR are once again similar.

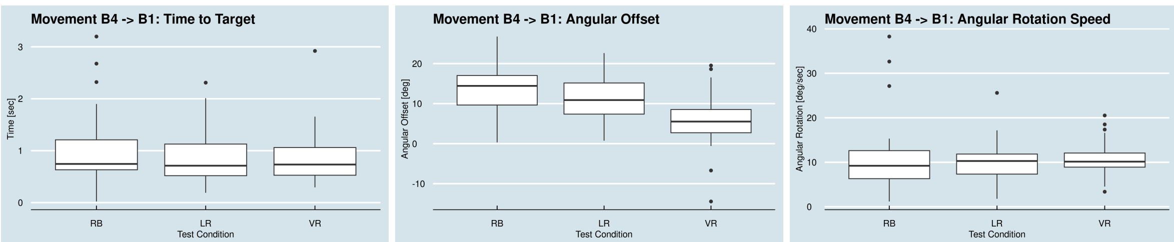

Figure 3.7: *Box plot of the mean values for Time to Target (left), Angular Offset (middle) and Angular Rotation Speed (right) of all user study participants for the three test conditions for movement B4 → B1*

Test Condition	RB	sd	LR	sd	VR	sd	ΔRB.LR	sd	ΔRB.VR	sd	ΔLR.VR	sd
Time to Target [sec]	1.043	0.697	0.919	0.548	0.861	0.5	0.124	0.859	0.182	0.933	0.058	0.593
Angular Offset [deg]	13.489	6.122	11.229	5.59	5.903	6.824	2.379	8.111	7.81	9.723	5.431	6.814
Angular Rotation Speed [deg/sec]	10.976	8.147	10.165	4.266	10.939	3.892	0.811	8.147	0.037	7.107	-0.774	4.226

Table 3.4: *Table of mean values of all user study participants for the different test conditions (left) and the mean differences between the different test conditions for the individual users (right) for movement B4 → B1*

Summary

Time to target appears to be similar in all four analysed movements, with RB being the slowest, followed by LR and lastly VR. The standard deviation for the time to target is rather vast for RB and only half as big for LR and slightly smaller even for VR. This indicates that there are big differences between the individual user study participants.

Overall, as seen in Figure 3.8, there appears to be an angular offset of head trajectories compared to the focus target. Overall the offset appears to be highest for RB, followed by LR and finally VR, however this differs for the individual movements. Looking at the standard deviation, this is similar for all three test conditions and rather high, once again indicating that also for the angular offset there are big differences between the individual user study participants.

With regards to the angular rotation speed there appears to be a difference between horizontal and vertical movements, with the horizontal speed being about three times as high compared to the speed of the vertical movements. With regards to the standard deviation this is similar for all test conditions and also rather big compared to the mean values, hinting at the vast difference between the individual user study participants.

Test Condition	RB	sd	LR	sd	VR	sd	$\bar{x}$ sd	sd	$\bar{x}$ sd	sd	$\bar{x}$ sd	sd
Time to Target [sec]	1.063	0.253	0.928	0.157	0.823	0.153	0.700	0.010	0.492	0.058	0.371	0.075
Angular Offset [deg]	9.740	2.991	9.327	1.166	5.830	1.905	6.532	0.504	5.940	0.397	7.794	1.226
Angular Rotation Speed [deg/sec]	21.055	9.667	22.779	12.542	24.750	13.611	8.149	2.069	8.042	3.746	7.744	3.977

Figure 3.8: *Table of averages of values and their standard deviation of all short movements (left) and well as the average of standard deviations and their standard deviation (right)*

3.3.2 Long Movements

B5 - A5 and B5 - C5

As seen in Figure 3.9 and Table 3.5 the movement duration (Time to Target) of the head is significantly lower for RB and similar for LR and VR. Similar holds true for the individual differences for each user between the task conditions. Focusing on the angular offset of the head trajectory compared to the focus target, these are lowest for RB, followed by LR and lastly VR. In this case the individual differences in angular offset for LR and VR are more similar compared to RB. Focusing on the angular rotation speed, this is highest for RB followed by VR and LR, which are very similar. The same holds true for the individual differences for each user between the task conditions.

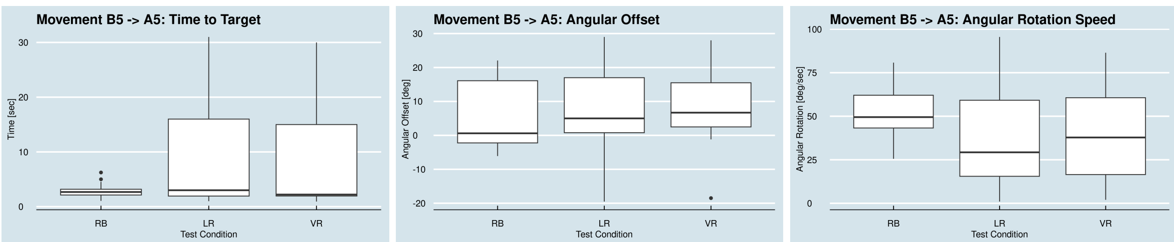

Figure 3.9: *Box plot of the mean values for Time to Target (left), Angular Offset (middle) and Angular Rotation Speed (right) of all user study participants for the three test conditions for movement B5 $\rightarrow$ A5 and B5 $\rightarrow$ C5*

Test Condition	RB	sd	LR	sd	VR	sd	ΔRB.LR	sd	ΔRB.VR	sd	ΔLR.VR	sd
Time to Target [sec]	2.818	1.145	9.118	9.395	8.671	9.583	-6.461	9.956	-5.853	9.439	0.204	16.63
Angular Offset [deg]	5.308	9.924	9.558	10.145	8.648	9.924	-2.481	16.852	-3.466	14.37	1.389	11.114
Angular Rotation Speed [deg/sec]	52.017	12.995	37.623	26.495	38.783	26.156	12.297	30.106	12.296	29.833	-1.816	32.441

Table 3.5: *Table of mean values of all user study participants for the different test conditions (left) and the mean differences between the different test conditions for the individual users (right) for movement B5 → A5*

C5 - B5 and A5 - B5

As seen in Figure 3.10 and Table 3.6 the movement duration (Time to Target) of the head is once again significantly lower for RB and similar for LR and VR. Similar holds true for the individual differences for each user between the task conditions. Focusing on the angular offset of the head trajectory compared to the focus target, these are lowest for RB, followed by vR and lastly LR. In this case the individual differences in angular offset for LR and VR are more similar compared to LR and RB. Focusing on the angular rotation speed, this is highest for RB followed by VR and then LR. In this case the individual differences between the test conditions for each user the difference between LR and VR is smaller compared to LR and RB.

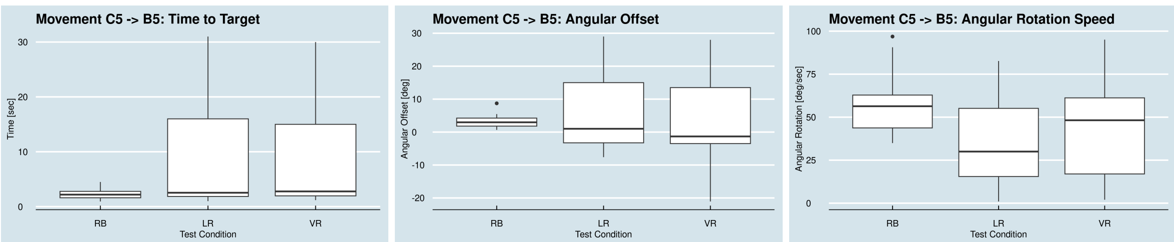

Figure 3.10: *Box plot of the mean values for Time to Target (left), Angular Offset (middle) and Angular Rotation Speed (right) of all user study participants for the three test conditions for movement C5 → B5 and A5 → B5*

Test Condition	RB	sd	LR	sd	VR	sd	ΔRB.LR	sd	ΔRB.VR	sd	ΔLR.VR	sd
Time to Target [sec]	2.246	0.845	9.055	9.556	8.975	9.613	-6.958	9.727	-6.551	9.319	0.08	16.785
Angular Offset [deg]	3.141	1.753	7.06	10.102	6.949	10.411	-2.93	12.302	-1.897	12.709	0.38	10.509
Angular Rotation Speed [deg/sec]	57.042	16.774	37.314	25.07	37.487	25.834	20.657	32.145	14.751	30.371	0.247	45.799

Table 3.6: *Table of mean values of all user study participants for the different test conditions (left) and the mean differences between the different test conditions for the individual users (right) for movement C5 → B5*

Summary

As seen in Figure 3.11 averaged over all the long movements, the time to target is fastest for RB by quite a margin, followed by VR and shortly after LR. As seen in the analysis of the short movements, also here the mean standard deviation is quite high, indicating differences between the individual users. Looking at the angular offset this is smallest for RB, followed by VR and LR. In this case the standard deviation is also quite high for RB and even higher for LR and VR, showing the difference between the different user behaviours with regards to the offset. With regards to the angular rotation speed this is the highest for RB, followed by VR and LR. The standard deviation is smallest for RB, but double the size for both LR and VR, once again indicating differences between the individual users.

Test Condition	RB	sd	LR	sd	VR	sd	$\bar{x}$ sd	sd	$\bar{x}$ sd	sd	$\bar{x}$ sd	sd
Time to Target [sec]	2.532	0.286	9.087	0.032	8.823	0.152	0.995	0.150	9.476	0.080	9.598	0.015
Angular Offset [deg]	4.225	1.084	8.309	1.249	7.799	0.850	5.839	4.086	10.124	0.021	10.168	0.244
Angular Rotation Speed [deg/sec]	54.530	2.513	37.469	0.154	38.135	0.648	14.885	1.890	25.783	0.713	25.995	0.161

Figure 3.11: *Table of averages of values and their standard deviation of all long movements (left) and well as the average of standard deviations and their standard deviation (right)*

3.3.3 Comparison of Long and Short Movement

The differences between long and short movements with regards to time to target appears to be that for the long movement the time to target tends to be longer, nearly double for RB and even higher for LR and VR, which seems logical, given that more rotation is necessary to reach the target. Furthermore, with regards to angular offset, the angular offset appears to be slightly higher for the short movements compared to the long ones with regards to RB and LR. One possible explanation for this might be that due to the fact that head rotation was necessary in the long movement, more head rotation was completed and hence less of the rotation was compensated with the eyes. However for VR it is higher for the long movements compared to the short movements. Looking at the angular rotation speed, higher speeds are generally reached for the longer movements, which seems sensible, given that more rotation had to be completed, giving more time for acceleration.

3.4 Questionnaires

Below, the results of the questionnaires can be found.

3.4.1 Simulator Sickness Questionnaire

The results of the SSQ are shown in Figure 3.12. There are no noteworthy differences between the two test condition orders.

In Figure 3.13 and Figure 3.14 the results for the individual simulation sickness for each test condition are shown for both test condition order RB - LR - VR and RB - VR - LR respectively. There are no

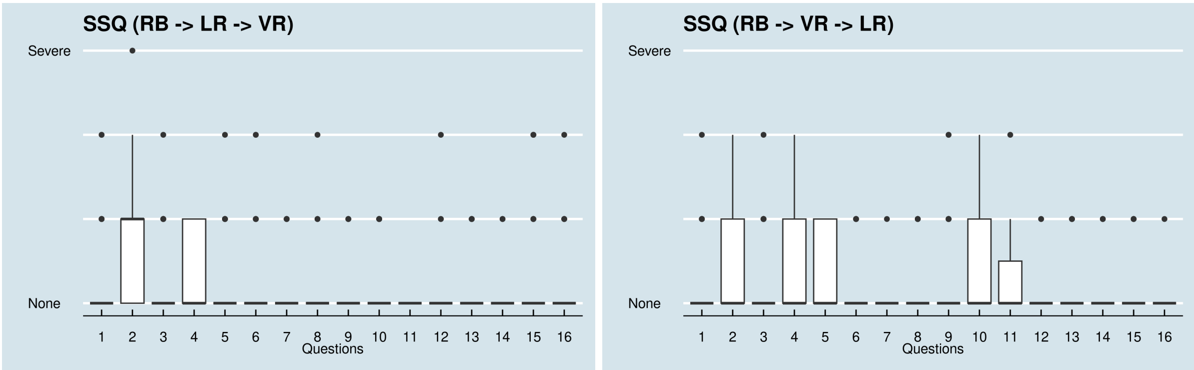

Figure 3.12: *SSQ results of all test conditions for each question in test condition order RB - LR - VR (left) and RB - VR - LR (right)*

noteworthy differences in the results.

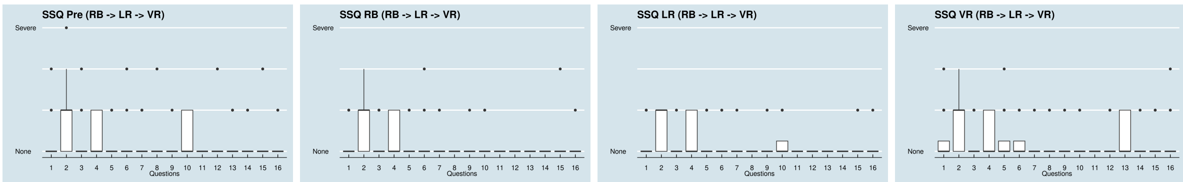

Figure 3.13: *SSQ results for each question in test condition order RB - LR - vR and each test condition: RB (left), LR (middle), VR (right)*

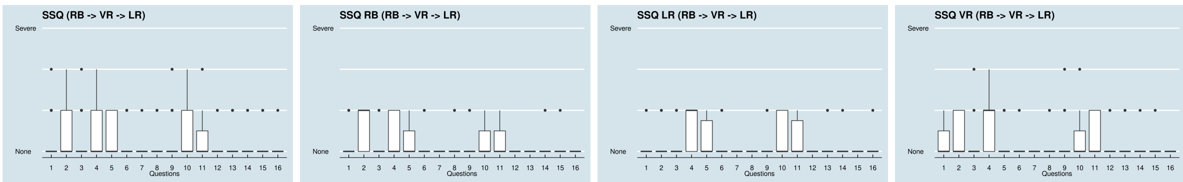

Figure 3.14: *SSQ results for each question in test condition order RB - VR - LR and each test condition: RB (left), LR (middle), VR (right)*

3.4.2 Simulation Task Load Index

The results of the SIM-TLX questionnaire are shown in Figure 3.15. There are no noteworthy differences between the two task conditions.

In Figure 3.16 and Figure 3.17 the results for the individual task loads for each test condition are shown for test condition order RB - LR - VR and RB - VR - LR respectively. There are no noteworthy differences in the results, except one outlier which had a higher task load in all test conditions compared to any other participant.

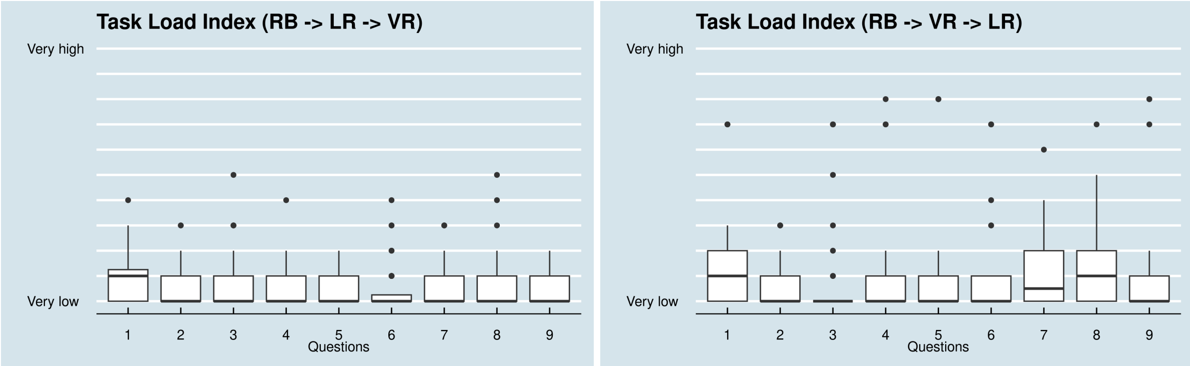

Figure 3.15: *SIM-TLX questionnaire results of all test conditions for each question in test condition order RB - LR - VR (left) and RB - VR - LR (right)*

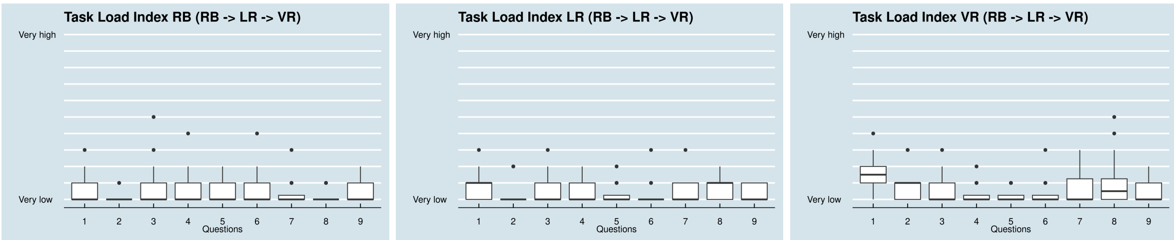

Figure 3.16: *SIM-TLX questionnaire results for each question in test condition order RB - LR - vR and each test condition: RB (left), LR (middle), VR (right)*

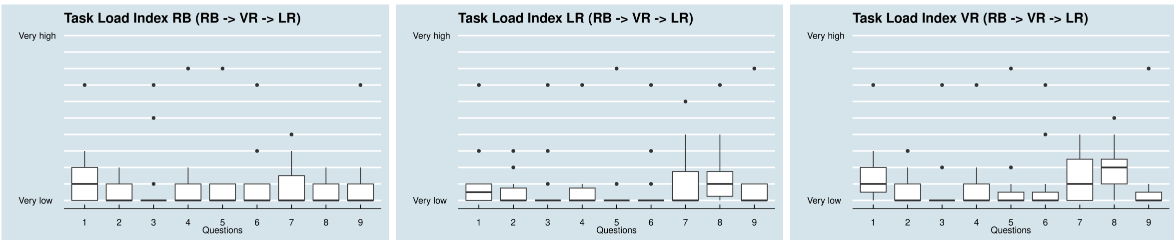

Figure 3.17: *SIM-TLX questionnaire results for each question in test condition order RB - VR - LR and each test condition: RB (left), LR (middle), VR (right)*

3.4.3 Cognitive Absorption Questionnaire

The results of the VR cognitive absorption questionnaire are shown in Figure 3.18. There are no noteworthy differences between the two task conditions.

3.4.4 VR Presence Questionnaire

The results of the VR presence questionnaire are shown in Figure 3.19. There are no noteworthy differences between the two task conditions.

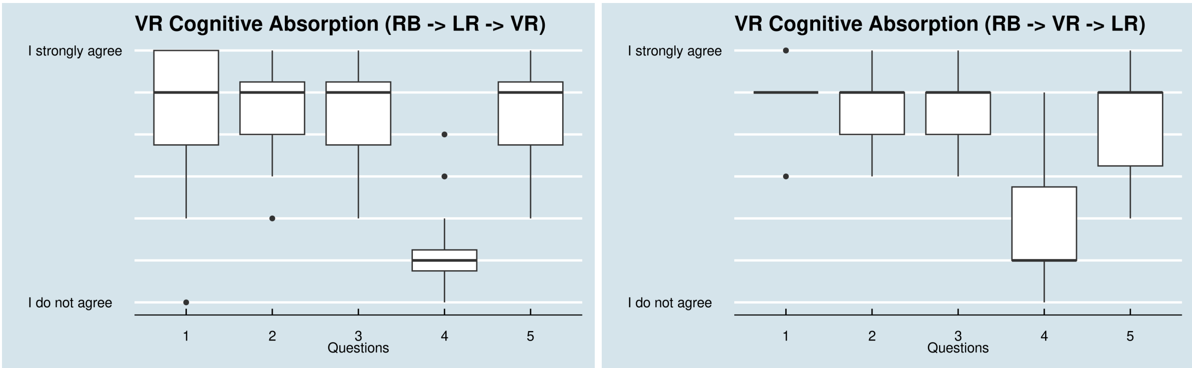

Figure 3.18: *VR cognitive absorption questionnaire results for each question in test condition order RB - LR - VR (left) and RB - VR - LR (right)*

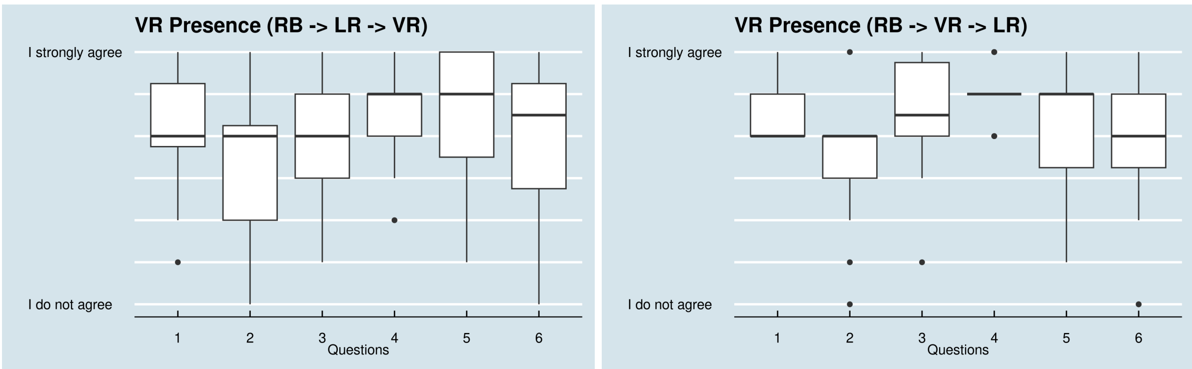

Figure 3.19: *VR presence questionnaire results for each question in test condition order RB - LR - VR (left) and RB - VR - LR (right)*

3.5 Further Observations

It is noteworthy that a number of participants (n=5) in the RB-VR-LR test condition reported experiencing mild to severe discomfort with regards to their perception of reality during the Limited Reality test condition. One participant noted that while wearing the FoV restriction device, they experienced a momentary uncertainty as to whether they were still in a virtual reality environment, as the limited FoV prevented them from seeing their own body. Another participant commented that the limited FoV seemed to be a defining characteristic of virtual reality and as a result, they felt slightly confused and unwell during the limited reality task as it this feeling did clash with their visual perception. Although this phenomenon was not the primary focus of the study and thus these findings should be considered anecdotal, it is nonetheless interesting and is hence mentioned here.

3.6 Limitations

The limitations of the semester project are numerous and raise some doubts about the validity of some of the received results. Firstly, the head movements of the participants were highly individual and differed greatly, which was not sufficiently accounted for in the tracking script design, which lead to difficulties during the post-processing of the data. This resulted in difficulties accurately tracking and identifying the specific head movements in the different task conditions and hence for interpreting the results. Secondly, the relation of head movements and eye movements was not taken into account enough during the design phase of the user study. They eye trajectories were only recorded during the VR test condition, leaving a gap in understanding the relationship in other conditions.

Additionally, there were instances where recorded trajectories appeared to have tracked incorrectly, possibly caused due to interference from the partition walls in the test chamber. This was in some cases also observed by the test conductor during the user study directly within the visual representation of the environment of the running the Unity program on the PC, where a shift of the trackers location and orientation could sometimes be observed. In the instances where this occurred, the head movements were simply repeated. However, to potentially mitigate this issue, more lighthouses were added to the tracking space, but this limitation remains a factor and some recordings were found to be scrambled during the data analysis and had to be removed from analysis.

Furthermore, the way the data tracking was designed was somewhat flawed, as the movements had to be identified and manually labeled in post-processing, which introduced another limitation, as the labelling of movements could have influenced the results. Calibration was also only applied during post-processing, which could have affected the results and should have been included in the tracking script design.

Moreover, the rotation of the trackers was recorded instead of instead of the actual head vectors, which could have been calculated by implementing a calibration in in the tracking design. This caused issues due to the inconsistent coordinate system of the trackers, leading to difficulties in the post-processing of the data as the different coordinate systems of the trackers had to be accounted for. The final limitation was the lack of synchronisation between the commands given by the test conductor and the actual head movements, which should have been implemented in the tracking script design to ensure accurate tracking and proper identification of the movements.

In conclusion, the limitations discussed above highlight the need for further research and refinement in the tracking design of this project.

4

Conclusion and Future Work

4.1 Conclusion

In this research project, the objective was to investigate human behavior in VR with respect to the limited field of view encountered in this environment. The project and the derived user study were centered on evaluating the difference in head movement trajectories among the three designated test conditions, (RB, LR, and VR).

The results, as outlined in Chapter 3, suggest that there may be some variations in movement duration, movement speed, and angular offset of the head compared to the target depending on the test condition.

Regarding the movement duration, for short movements, the results indicate that they were slightly longer for RB, followed by LR and then VR. The average time to target for each test condition are very similar to each other. The opposite holds true for long movements, where RB has by far the shortest movement duration, with LR and VR taking similarly long. This may indicate generally lower movement speed in LR and VR, however there was some variation of this between the specific movements analysed. The slower speed in RB for short movements on the other hand might be explained by the way the labelling was completed during the data tidying. As a combination of angular speed threshold and combination were used, there might be the reasonable possibility that bias was introduced to the data which was introduced as movements and hence the results were spoiled.

Looking at the angular rotation speed, the results varied once again depending on movement type, with the long movement inducing higher rotational speed compared to the short movement. For the long movement the speed for RB was highest while LR and VR were similarly slow. For the short movement however, while all average speeds were similar, VR was slightly faster, followed by LR and then RB. This might be explained by the shorter movement done in RB (measured by the higher offset) in combination with the way the movement speed was derived. The same labelling might have also directly influenced the received movement speeds.

Regarding the angular offset, tor short movements, the head was observed to rotate short of the focus target in all three conditions, generally more in RB, slightly less in LR, and the least in VR. However, this varied slightly for some specific movements. For long movements once again the opposite seems to be the case, as it is the lowest for RB, followed by VR and slightly higher LR. In terms of head trajectory offset, the results shown in Section 3.1 indicate that the degree of offset was compensated by eye rotation, indicating that the interplay between eye and head rotations is present in all three test conditions. Generally, the variation between the different test conditions were lower compared to the variation among individual participants for all three test conditions. Comparing the two analysed movement types, the offset was slightly higher for short movements compared to long movements, which could be explained by the need to induce head rotation for long movements.

It is important to note that the limitations in the recorded data and study design, as outlined in 3.6, may have influenced the results. Due to these limitations, as well as the very divergent and individual behaviour of the user study participants it is difficult to draw definitive conclusions. Further investigation is required.

4.2 Future Work

As this semester project is unable to provide definitive conclusions, continuation based on this work might be beneficial, as many of the limitations and potential problems were identified.

The design of the data tracking scripts should be reworked and improved. The calibration could be implemented directly in the script, allowing pointing vectors to be recorded, which remove the need for painstaking post processing in terms of data tidying, labelling, movement identification and more. This would also allow to circumvent the inconsistent coordinate systems within the Vive Trackers. Furthermore, the recorded data could be synchronised to the commands given by the test conductor, allowing for proper identification and measurements of movements, allowing for proper statistical analysis of the results.

An improved tracking script might also allow for measurements of more aspects of the movement, such as the time between the command and the beginning or end of the movement. Furthermore the eye tracking could be taken more into account when looking at head movement trajectories and should be looked at in combination. Other additional data might also be worth investigating, such as the acceleration and deceleration of the head and eye movement, as well as the interplay of head and eye movements in VR compared to reality. Furthermore the direction of movements left & right and up & down could be compared to see if there are any differences in horizontal and vertical movement. Results shown in Section 3.3.1 seem to indicate that the vertical angular movement is smaller compared to the horizontal one. It would furthermore also be interesting to see if there are any differences caused by the test condition order.

The user study task design and test condition design appears to be fit for purpose, but could be slightly improved and adapted to account for further details that might influence behaviour.

Furthermore, the findings outlined in Section 3.5 could potentially be of interest to further examine the feeling of presence in VR and what role the restricted FoV might play in it.

A

Appendix

A.1 Project Data and Code Access

A copy of the submitted thesis and most relevant files, including the complete unity project, all collected raw and transformed data, including the code used for transformation and visualisation, as well as various other additional data, can be accessed using the following link:

`http://gofile.me/3EjjZ/l9uQvCyNU`

Alternatively, the above data can also be accessed via the following open GitHub repository:

`https://github.com/NicK4rT/Unity-Projects`

A

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