Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

innovation center virtual reality

Impact of Limited Field of View on Human Behaviour in Virtual Reality

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Abstract

In this semester project, the goal was to examine human behaviour in virtual reality (VR) with regards to limited field of view (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, the second being reality with limited FoV and the last being virtual reality. 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 im Hinblick auf das begrenzte Gesichtsfeld 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, die zweite die Realität mit eingeschränktem FoV und die letzte die virtuelle Realität 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.

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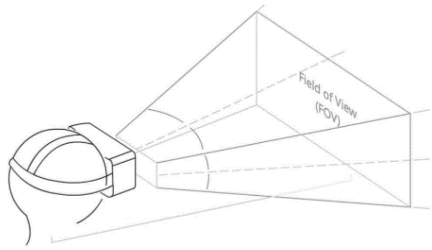
Impact of Limited Field of View (FoV) on Human Behavior in Virtual Reality (VR)

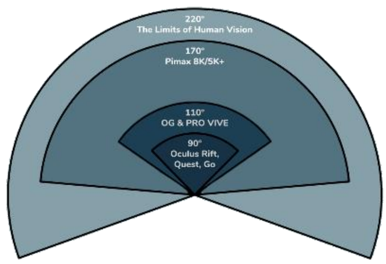
Keywords: Human behavior in VR, limited FoV, interactions in VR

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, 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. Furthermore the technology also enables completely new applications, for example training in environments that would be too dangerous or expensive to physically simulate or otherwise not possible to implement in reality. Examples of this would be firefighting, military operations or medical training. 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 in several aspects, which are discussed below.

To begin with, the are some biological aspects for which VR and reality differ: In reality the world is experience through all of the human senses: sight, touch, taste, sound and smell. In VR, given the current state of the technology, the experience is usually limited to sight and sound, even though there are attempts to simulate haptic feedback and smells in VR. [7]

Moreover, as VR is typically experienced using a HMD, there are certain technological constraints, including restricted Field of View (FoV), screen resolution, frame rate, and lag in present in HMDs. In addition, the virtual environment in VR is distinct from a real environment due to various factors, such as its artificial creation, which affects its composition and level of detail, which in turn might affect user perception and behaviour. [8, 9]

Given those technical limitations results in some differences in the physicality in the two different environments. In reality it is possible to touch and feel the surrounding environment and one is present in ones own physical body, which is again subjected to all the physical aspects of the environment, as

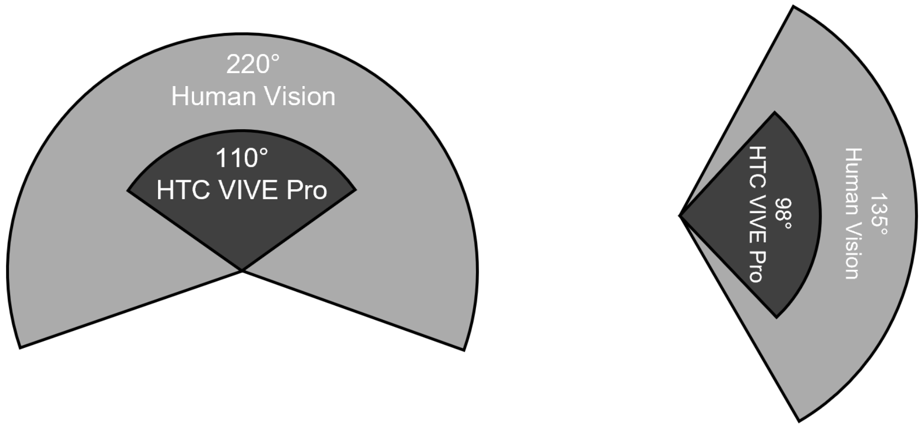


Figure 1.1: *Comparisons of horizontal (left) and vertical (right) FoV in VR using the HTC Vive Pro HMD and the FoV of normal human vision.*

well as the laws of physics. In VR this is not necessarily the case. Usually the interactions with the surroundings are limited to manipulating objects through a controller or using gestures are eye tracking, however, the actual physical interaction with the environment or the object is not felt the same way as in reality. [10]

Given the factors mentioned above, it seems reasonable to assume that they could affect the user's perception depending on the virtual environment, resulting in various differences regarding psychological aspects. These differences in realism may lead to a distinct sense of presence and immersion in VR, which can ultimately impact user behaviour. [11, 12, 13, 14] Additionally, users may experience various differences such as anonymity, lack of real-world consequences, immersion, social influences, and situational influences that are unique to the VR experience. [15] It is essential to note that user behavior is highly individual and may be influenced by several factors. Therefore, the extent to which VR affects user behavior may vary depending on the individual and the specific VR environment and experience.

Extensive research has been conducted on distinct aspects related to this matter, and some evidence has been found indicating that individuals may exhibit varying behaviours in virtual reality as opposed to reality. Nevertheless, despite the growing body of knowledge, the underlying reasons and complexities of the observed behaviour differences in VR remain somewhat elusive. Thus, further research is necessary to attain a more profound understanding of the causality and mechanisms affecting user behaviour in VR.

As mentioned before, one of the primary differences for users between VR and reality, is the limited FoV of VR HMDs compared to normal human vision. The human FoV spans approximately 220 degrees horizontally and 110 degrees vertically [16], while for a VR, looking at the example of the HTC Vive Pro HMD, it is only 110 degrees horizontally and 98 degrees vertically [17], as seen in the comparison figure 1.1.

1.2 Related Work

VR is being increasingly used in research as a powerful tool to create immersive and controlled environments that enable researchers to investigate human behaviour, cognition and perception in ways that were previously not possible. However, there are some concerns about the validity and reproducibility of behaviours in reality or VR. The extent to which behaviour in VR is similar to that in reality is a matter of debate. The validity, benefits and limitations of using VR for animal behaviour research is discussed in the following paper. [10]

The 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.

This study aimed to investigate the effects of FoV restrictions on human performance in a real-world manoeuvring task through an obstacle environment, finding that speed decreased linearly with decreasing FoV, while accuracy was consistently reduced for all restricted FoV conditions. [18] In a similar study, human locomotion through an obstacle environment with restricted FoV, finding that with restricted FoV, participants chose to prioritise safety by altering their path and step width. [19] The following similar study also investigated the effects of FoV restrictions on human performance while walking through an obstacle course. The results showed that all FoV restrictions increased the time to complete the course, with a smaller vertical FoV resulting in longer traversal time. [20] In this study the impact of FoV restrictions on human locomotion performance in complex environments was researched. The paper found that all FoV restrictions significantly reduced performance, with both time and the number of footsteps required to traverse the obstacle course increasing with decreasing FoV. [21] This last study examined how the restriction of the vertical FoV affects obstacle-crossing behavior, finding that a 40° or 90° vertical viewing angle increased step length and toe clearance compared to an unrestricted FoV, but a further decrease to 25° caused participants to slow down in addition to increasing step length and toe clearance, suggesting a shift in priorities from energy conservation to safety. [22]

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. The following study investigated the effects of display and scenario properties on the effectiveness of a virtual reality training system for a visual scanning task in a simulated urban environment. Results showed that FoV and visual complexity significantly affected target detection during training. The study also suggests that task performance during training may not always be an appropriate indicator of effectiveness for learning a prescribed strategy or skill. [23] This study examined the effects of FoV, target movement, and number of targets on visual search performance in virtual reality. Results show that search performance improved with a wider FoV, but decreased when targets were moving and with more visible targets. Neither FoV nor target movement affected the linear relationship between visual search time and number of items, but both negatively affected the perceived workload, with target movement being a more significant factor. [24] This paper presents an experimental evaluation of two information layout techniques for Information-Rich Virtual Environments, which provide different depth and association cues between objects and their labels. The study found significant advantages for the Viewport interface and a high FoV, and highlights the need for special design considerations to support search and comparison performance across different monitor configurations and projection distortions. [25]

Existing research has compared VR and reality, but none of these studies have specifically focused on limited FoV. This recent study for example 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. [26]

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. This study describes the development of a foveated FoV restrictor for VR systems, which dynamically moves the restrictor's center according to the user's eye gaze position. The study found that the foveated FoV restrictor did not result in increased virtual reality sickness compared to a head-fixed FoV restrictor, but did allow for a wider visual scan area and greater eye gaze dispersion. [27]

Examining more studies that compare user behaviour in reality and VR, many are focused on trying to utilise VR for rehabilitative purposes. 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. Such research has been done for grasping movements [28], walking [29] as well as more complex combinations, such as reach to grasp and transport as part of a device assembly task [30]. The first study compared movements made in physical and virtual environments by healthy individuals and those with motor deficits. Participants were asked to reach, grasp, transport, place and release a ball in both environments while their movements were analysed. Despite some differences in movement strategies between the two environments, both healthy individuals and individuals with motor deficits were able to complete the task using similar strategies, indicating that training in VR environments may be a valid approach to motor rehabilitation. [28] The second paper tests if VR walking produces realistic trajectories by comparing them to real-world trajectories. They use a framework of criteria and a model to generate reference trajectories and analyse the virtual paths. They test different virtual walking conditions and examine their impact on realism. Results show how each condition affects the realism of the virtual trajectories. [29] The purpose of this study was to determine if VR can aid in the recovery of upper limb function by retraining physiological movement patterns similar to those in the real world. The study compared the kinematics of reach-to-grasp and transport movements between VR and reality. Results showed that these movements took more time in VR, but joint angles and hand trajectory curvature were similar in both conditions. This suggests that VR may have the potential to retrain physiological movement patterns, but additional studies are necessary to determine how closely kinematics must match. [30]

It appears that in many studies about VR, the limited FoV in VR is acknowledged as a factor or a secondary condition to consider, but is usually not the primary focus of research.

1.3 Task Formulation

The study of the effects of FoV on human behaviour in VR represents an area of investigation that has yet to receive significant scholarly attention, due in part to its complex nature. While some prior research has examined behavioural differences in VR for specific tasks and under specific conditions, as seen in the paper comparing visual search in physical environments and VR [26], comparatively little research has been conducted on the comparative analysis of behaviour in VR and reality, especially in the context of limited FoV.

Thus, the overarching research question that motivates the present study is: *How does user behavior in VR differ from normal user behavior in reality, and to what extent is this difference influenced by the limited FoV in VR?*. This inquiry is novel and significant for several reasons. Firstly, it seeks to contribute to a deeper understanding of the ways in which VR technology affects human behaviour, with specific attention given to the impact of FoV limitations. Secondly, by comparing VR and reality, this study aims to identify the specific aspects of VR environments that might influence behaviour and how these differ from the physical world. Lastly, by providing a comprehensive analysis of possible user behaviour differences in VR caused by the limited FoV, this research can potentially inform the design and optimisation of VR technologies for its diverse applications, allowing them to account for these factors.

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 3.1, tidied and labeled the recorded trajectory data as specified in section 2.5 and analysed the results using the means described in section 2.6. 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 utilised throughout the project for the creation of the virtual environment, the running of the VR application and the preparation and conduction of the user study, 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 3.1, information and statistics related to the user study are shown. In section 2.5 the process of data transformation, tidying, as well as labeling is presented and in section 2.6 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 certain hardware devices was imperative for the completion of the project. During the project's timeline, a suite of HTC Vive VR products were employed, which included the HTC Vive Pro Eye HMD, two Vive Trackers, a wireless transmitter, up to six base stations and a personal computer (PC) to host and run the necessary software.

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 2.3. 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. With this information, along with the known positions of the base stations, the system can triangulate the position and orientation of the devices in 3D space. While it is possible to track the position and orientation using only one base station, usually at least two base stations are recommended for added precision in case of occlusion. [31, 32] For further precision, additional sensors, such as a gyroscope, G-sensor and accelerometer for measuring the angular velocity and rotation, are also integrated into the HMD. All of the data tracked by these sensors is processed and combined by the software to calculate the location and orientation of the devices. [33]

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 that track the movement of the user's pupils. The system can determine the exact gaze origin and gaze direction with high precision, given proper calibration. [34]

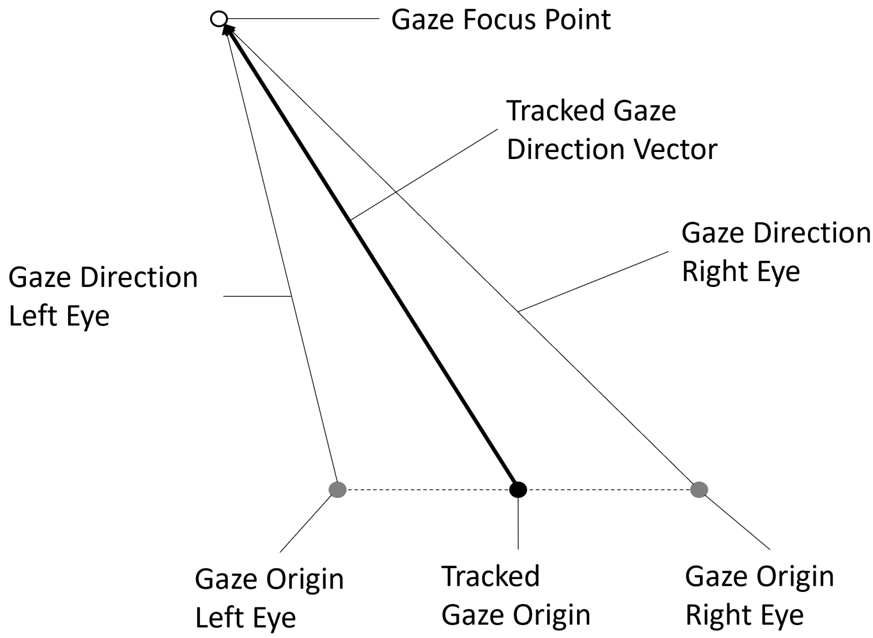


Figure 2.1: *Vector and calculations tracked by the TobiiXR, image inspired by documentation provided by Tobii [34]*

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. [35]

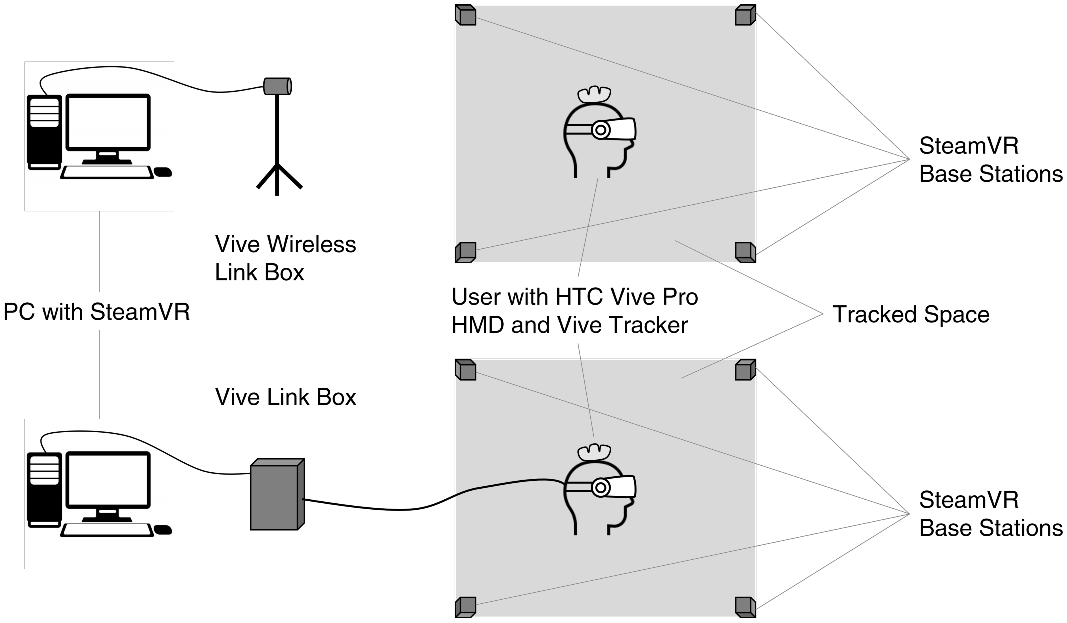


__Figure 2.2:__ Setup of the HTC Vive Pro Eye with four SteamVR base stations and either the link box (bottom) or the wireless link box (top)

HTC Vive Tracker

The HTC Vive Tracker, as seen in Figure 2.3, is a small, puck-shaped device, that is designed to track physical objects or body parts in the VR environment. These trackers are connected wirelessly to the PC and use the same SteamVR Tracking technology described in subsection 2.1.1. This allows for accurate tracking of the object or body part to which the trackers are attached, enhancing the VR experience. The trackers can enable, for example, full body tracking and consequently the animation of a virtual avatar, adding to the user's immersion and providing additional possibilities, such as for 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. [36]

__Figure 2.3:__ The full suite of HTC Vive VR devices used during the course of this semester project: The HTC Vive Pro Eye HMD (middle), several SteamVR Base Stations (top left and right) and two HTC Vive Trackers 2.0 (bottom left and right)

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. The development process is enabled to function seamlessly across a diverse range of platforms, including computers running different operating systems like Windows, MacOS or Linux, mobile devices such as Android and iOS devices and even gaming consoles and 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 compose and design the software-dependant parts of the user study, such as the data recording, as well as implementing the virtual environment for the VR-based test conditions. [37] This version of the Unity editor was chosen for the sake of convenience, as some of the supplied software and scripts were designed and implemented for this version of the Unity editor.

SteamVR

SteamVR is an application created by Valve Corporation, the developers of digital content distribution platform Steam. Its purpose is to enable VR by serving as the software interface between a computer and a VR headset, allowing VR content to be transmitted and run. SteamVR is also responsible for running the SteamVR 2.0 tracking system, which tracks the movement of the VR headset and controllers. In this project, the SteamVR plugin was utilised to enable a Unity project to be viewed and run on an HTC Vive Pro Eye HMD, while also receiving tracking data from the VR test chamber.[33]

Blender

Blender is a free 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 creation and composition of textures and the modelling and texturing of the virtual 3D environment and assets present therein. [38]

RStudio Server

In this project, a self-hosted RStudio Server was employed for data tidying, conversion, analysis and visualisation. RStudio is an integrated development environment (IDE) which, together with its add-on packages, facilitates the data science workflow using R and Python programming languages. It provides integration with GitHub, offering a collaborative and reproducible workflow. [39]

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. [40]

Siemens NX

Siemens NX is a software solution primarily used for CAD modeling in product design, engineering, and manufacturing. The software offers a comprehensive suite of tools for 3D modeling, simulation and analysis. In this project, Siemens NX version 1984 was utilised to model certain components for 3D printing. [41]

2.2 Hypotheses

Based on the literature research and the subsequent project task specifications, the following hypotheses were derived.

H1: It is hypothesized that the angular rotation movements in VR are slower compared to reality in terms of both movement duration and rotational velocity given similar surrounding in reality and VR.

H2: 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.

H3: 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 potential differences of user behaviours in reality and VR and whether they are caused by the limitation of the user's FoV, the three test conditions listed in Table 2.1 were proposed.

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).

Test Condition:	Reality (RB)	Limited Reality (LR)	Virtual Reality (VR)
Fov:	Regular FoV	Limited FoV	Limited FoV
Horizontal Fov:	220 degrees	110 degrees	110 degrees
Vertical Fov:	135 degrees	98 degrees	98 degrees

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

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

Test Condition:	Reality (RB)	Limited Reality (LR)	Virtual Reality (VR)
Fov:	Regular FoV	Limited FoV	Limited FoV
Used Devices:	GoPro Head-strap with Vive Tracker	GoPro Head-strap with Vive Tracker and FoV restriction device	HTC Vive Pro Eye HMD with Vive Tracker

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

GoPro Head-Strap and HTC Vive Tracker Mount

In the RB test condition a GoPro head-strap was used with a custom designed and 3D-printed attachment point, as seen in Figure 2.4, on which the HTC Vive Tracker was attached, using a standard tripod 1/4 inch mounting screw as seen in Figure 2.6. The mount was designed using the CAD modelling program NX1984.

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.

FoV Restriction Device

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, as seen in Figure 2.5, was designed using the same CAD modelling program as for the tracker mount described in the previous paragraph. It features a box like structure and is attached to the front mounting point of the GoPro head-strap. The

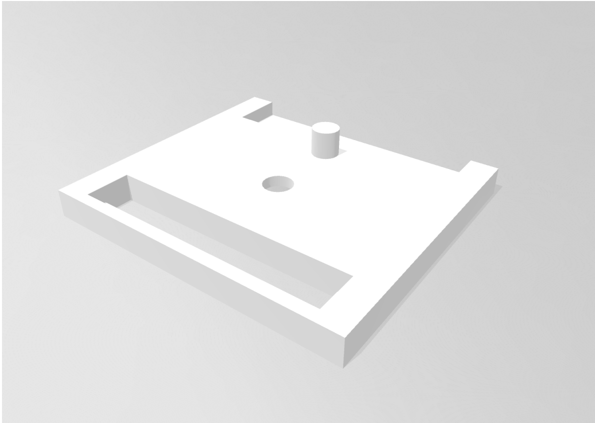


Figure 2.4: *Rendering and image of custom designed and 3D-printed Vive Tracker mount*

front of the FoV restriction device features a rectangular excerpt, where a rectangular card with a the accurately cut out FoV can be inserted.

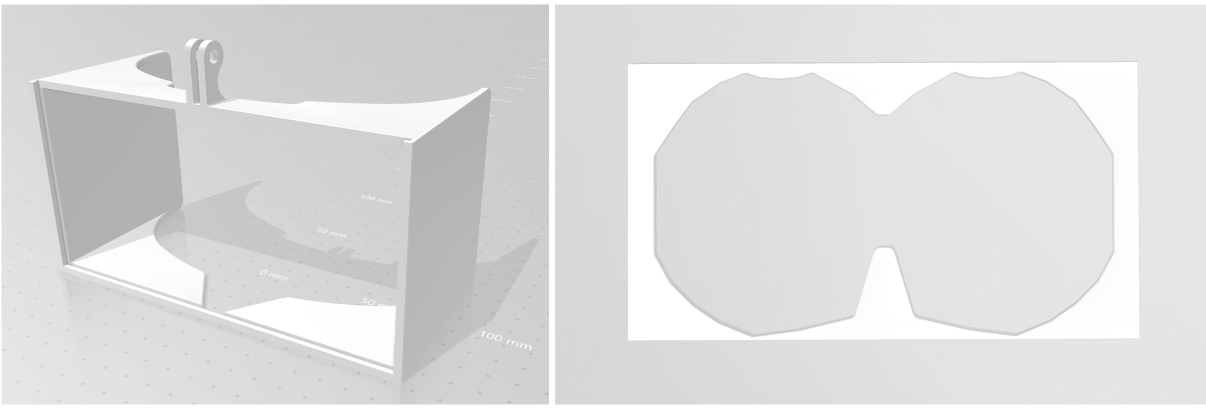


Figure 2.5: *Rendering of custom designed and 3D-printed FoV restriction device (left) and the FoV insert (right)*

Figure 2.6: *FoV restriction device*

FoV Restriction Device Calibration and Validation

The device is supposed to offer the same FoV as the HTC Vive Pro Eye HMD. To this end the rectangular card with the precise FoV restriction was designed and validated using a careful iterative process.

First, the occlusion mesh of the HTC Vive Pro had to be determined. Using a modelled A4 paper with a grid was placed at a specific distance in front of the Unity camera, which matched the position where the FoV occlusion insert would be placed in the FoV restriction device. This allowed for the creation of a reference point and visualization of the specific area that would be occluded.

The visible grid on the A4 paper, restricted by the occlusion mesh, was then displayed using a Unity preview viewer, saved and transformed to derive the specific form that would match the FoV of the HTC Vive Pro Eye HMD. This process involved combining the views from both eyes and ensuring they overlapped correctly.

This form was then used to model the FoV restricting insert for the FoV restriction device, which was then 3D-printed and validated using a real A4 paper with the same grid as used in Unity.

Overall, the iterative design and validation process of the FoV restriction device allowed for the creation of a device that closely mimics the FoV of the HTC Vive Pro Eye HMD, resulting in an accurate tool to mimic the FoV of the HTC Vive Pro HMD in reality.

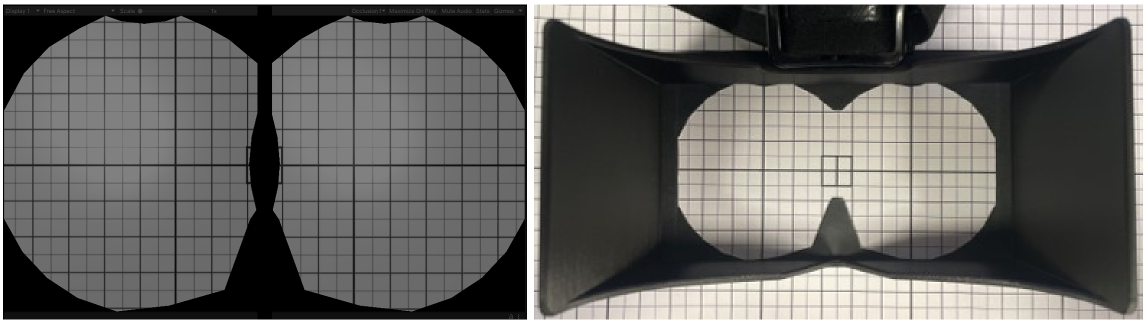


Figure 2.7: *Grid visible using the occlusion mesh for the HTV Vive Pro Eye HMD in Unity (left) and using the FoV restriction device (right).*

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.

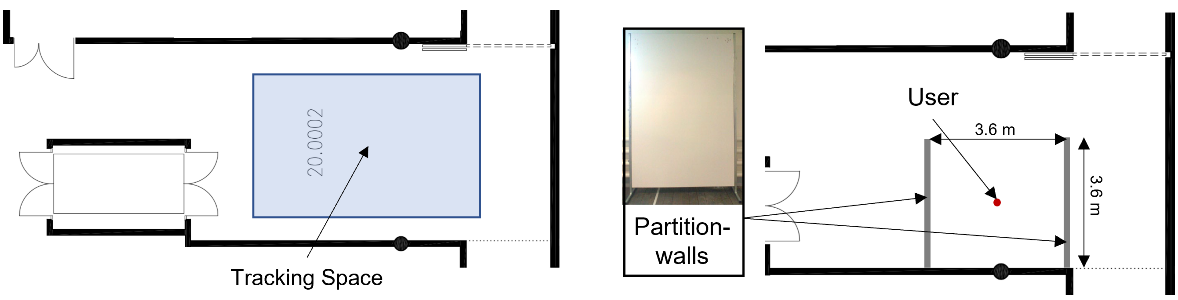


Figure 2.8: *CLA A floor tracking space test chamber floor plan (left) and layout for user study (right)*

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 2.9: *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, implementing the test chamber and its contents, which were modelled and whose textures where crafted in Blender.

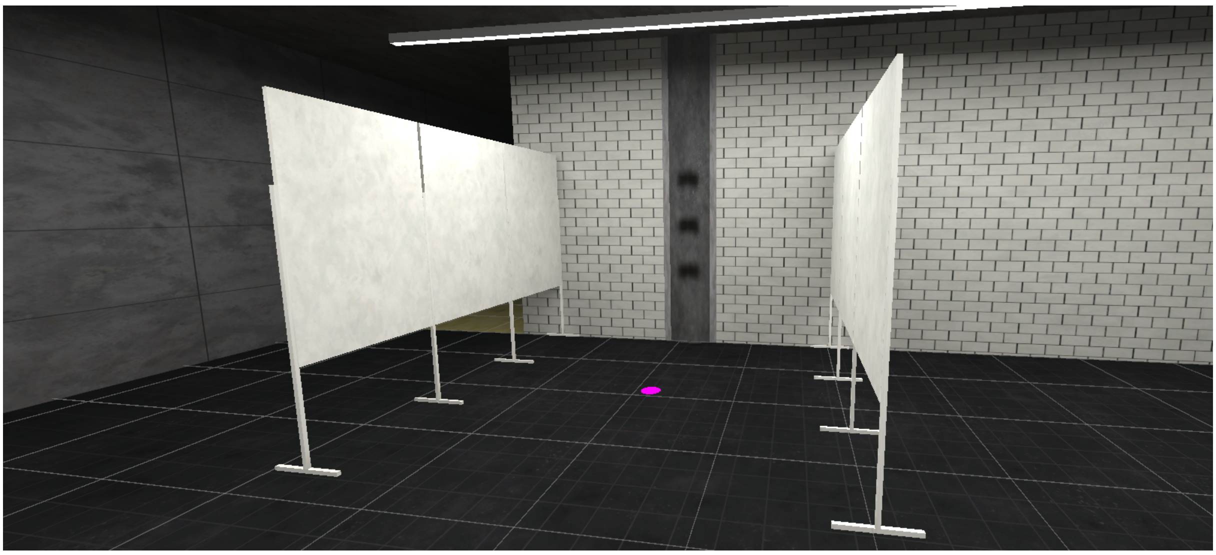


Figure 2.10: *Rendering of the VR test chamber*

2.3.4 Task Design

Given the test conditions and environments for the user study, each test condition required the participants 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 denoting the specific 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 2.11.

Figure 2.11: *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 2.12.

Figure 2.12: *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 called out target as seen in Figure 2.13.

Figure 2.13: *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 2.14. This order was chosen to progressively move from small movements limited to one wall to more advanced and complex movements over all three walls. There are four rows of movement, referred to as phase one through four. In the first phase only four vertical and four horizontal movements on wall B are induced, while in the second phase diagonal movements are also created for a total of ten movements. In the third phase ten movements across all three walls is induced, while in the fourth phase only five, but the largest rotations are induced. This was done to create a full set of different movements to analyse. The order of phases remains the same in all test conditions and in both test condition orders, however the order of movement is changed between the two test condition orders. It is important to note that in between all phases the users focus back on the focus target B5, which was used as a sort of calibration point.

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 2.14: *Looking order for the two test condition orders*

A summary of movements for each phase is listed below.

Phase 1: Shortest eight movements

Phase 2: Ten short movements

Phase 3: Ten longer movements

Phase 4: Longest five movements

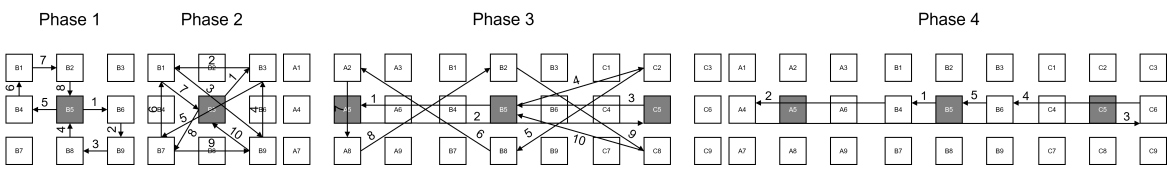


Figure 2.15: *Illustration of the looking task order for RB of the RB-LR-VR test condition order*

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 user's head. During all three test conditions, the Unity program with the virtual test chamber ran in the background, recording all the specified data from the Vive Tracker. The technical layout of the three test conditions can be seen in Figure 2.16, Figure 2.17 and Figure 2.18.

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 ruler angles

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, as the functionality for recording Vive Trackers was not present. To this end the script was enhanced and the trackers were hard coded into the script using their serial number to allow their tracking. 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.

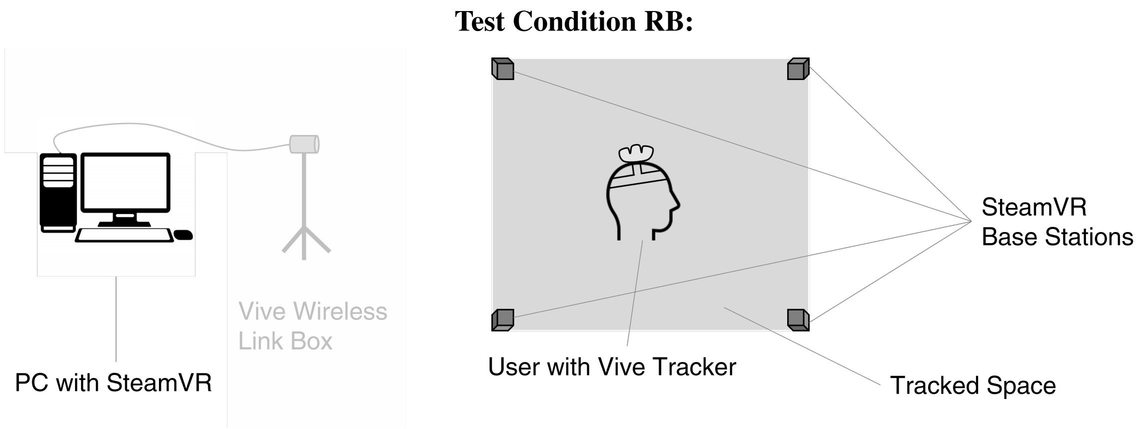


Figure 2.16: *Technical layout of test condition RB*

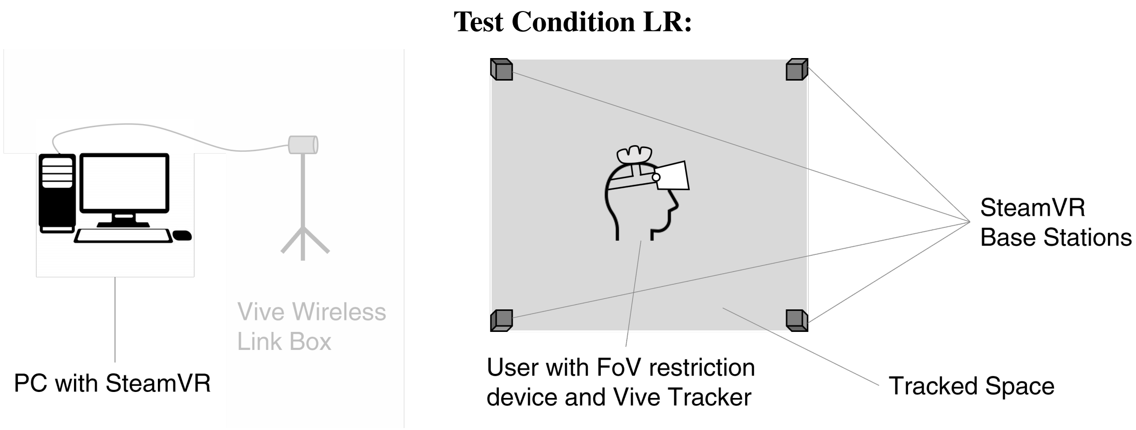


Figure 2.17: Technical layout of test condition LR

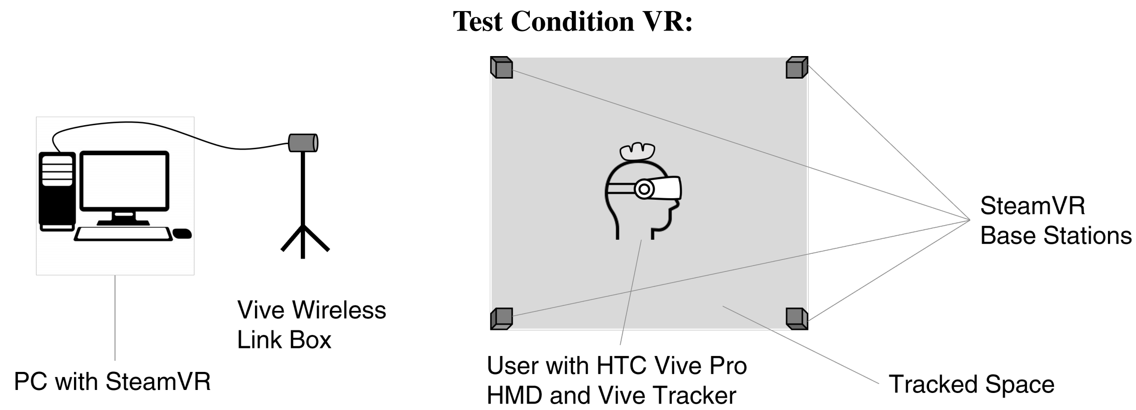


Figure 2.18: Technical layout of test condition VR

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) [42] 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 [43] 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?

Cognitive Absorption 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, such as for example the users progressively becoming more and more familiar with the test environment during the course of the user study, the order for the test conditions with restricted FoV, LR and VR, was changed 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 2.19.

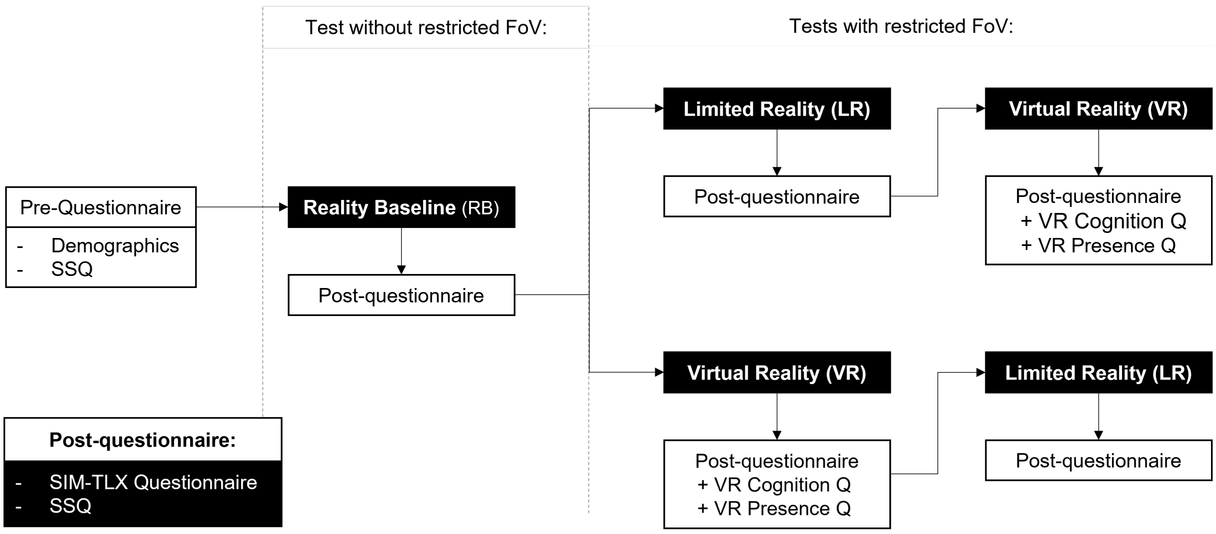


Figure 2.19: *User study procedures for both test condition orders*

2.4.1 Test Condition Procedure

Within each test condition the following procedures were used:

1. Environment Familiarisation

During the beginning of each test condition the user is given some time to familiarize themselves with their surrounding in the environment in which the test condition is conducted, so either reality or VR, until they feel ready to begin the task.

2. Guided Looking Task

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 true reason for this delay and the waiting time was to measure the users curiosity based on their head movement frequency during that time.

2.5 Data Labeling and Transformation

To use the data collected during the user study, extensive post-processing was necessary. The recorded orientation, which was recorded as a rotation from an defined initial position, had to be transformed into vectors for analysis and then transformed into spherical coordinates for visualisation.

2.5.1 Calibration

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 2.20.

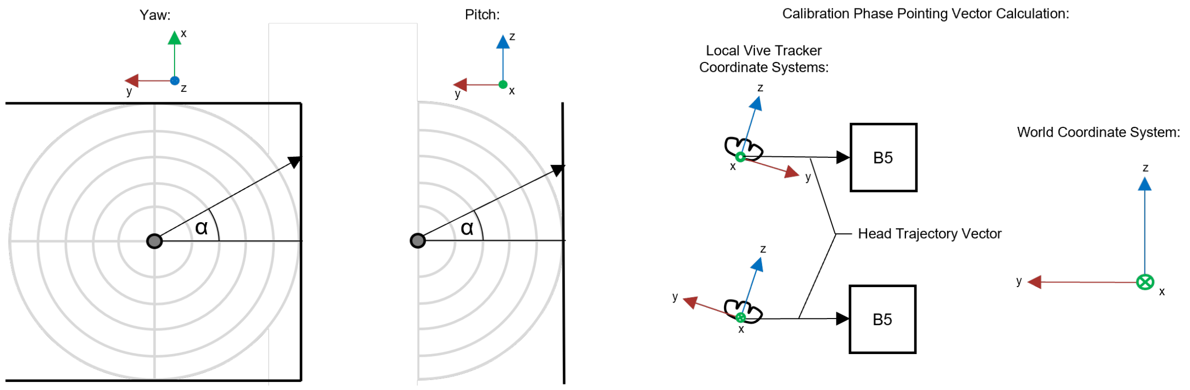


Figure 2.20: *Spherical coordinate system overlaid on the test environment from the top (left), the side (middle) and the orientation of the Vive tracker depending on the two possible internal coordinate systems and the global world coordinate system (right)*

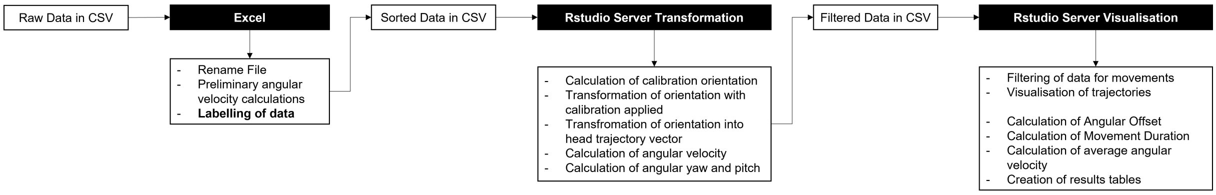


Figure 2.21: *The pipeline used for the post-processing of the recorded data*

To identify the calibration orientation a preliminary speed was calculated using the Euler Angle rotation differences using Formula 2.1. This formula calculates the average speed at every time-step by taking the average rotation speed between the next and the prior step by dividing the rotational change by the the time difference between the steps. Furthermore, to distinguish and mark certain points during the duration of the user study, recording breaks were used, which can be identified by the larger difference between the recorded time since startup between two points. These breaks served as markers for the subsequent data tidying and labeling to be able to identify the different lines and specific movements. Looking at the tentatively derived raw pitch and yaw angles and the calculated angular velocity, as well as using the time-step markers to identify the phase in which the calibration took place, as seen in Figure 2.22. The area with no to little movement could be identified as the calibration period where the angular rotation speed would be at the noise level of $2 - 3\ deg/s$ below our chosen threshold of $5\ deg/s$, from which the calibration orientation could then be derived. The labelled data is then imported into RStudio for the data transformation, analysis and visualisation. As seen in Figure 2.20, the calibrated head trajectory vector is calculated as the intersection vector between the plane spanned by the Vive tracker's local z-axis and 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. The order of post processing is visualised in Figure 2.21.

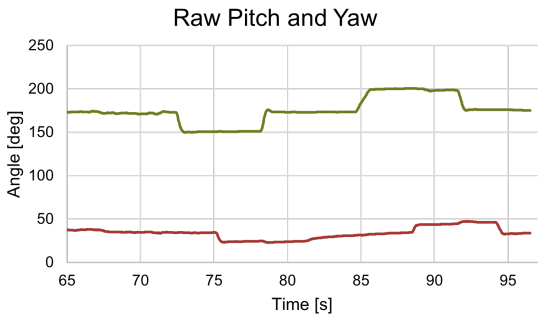


Figure 2.22: *Example raw pitch and yaw for Phase 1 (B5-B6-B9-B8-B5-B4-B1-B2-B5) of the guided looking task of user study participant 10*

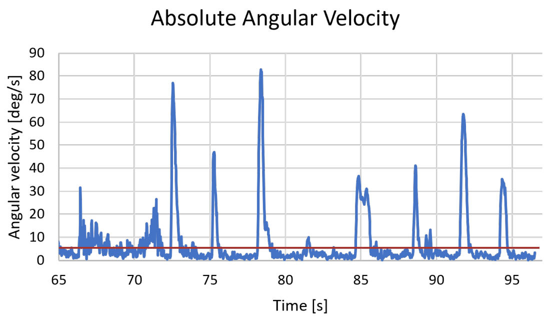


Figure 2.23: *Example preliminary calculated angular velocity for Phase 1 (B5-B6-B9-B8-B5-B4-B1-B2-B5) of the guided looking task of user study participant 10*

2.5.2 Data Tidying and Transformation

During the process of the the data sorting 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 [44]. The coordinate system for the roles *Held in Hand* is rotated by 90 degrees compared to all other roles and appears to occasionally change. However, despite using the other roles, 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 might be a bug that during the start-up of Unity connection with SteamVR and the trackers, which results in different coordinates systems 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 2.20. Reproduction of this issue is difficult, however some similar reports can be found in the HTC Vive and Unity support forums. [44] 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 resulting yaw and pitch are calibrated around the vector pointing at B5, as seen in Figure 2.20, with positive pitch being a rotation upwards, negative pitch being a rotation downwards. Positive yaw on the other hand is a rotation to the left, with negative yaw is a rotation towards the right.

The recorded rotation (which was both recorded in Euler Angles (EA) or quaternions) was transformed into a rotational matrix and was applied to the head trajectory pointing vector This was done 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 rotation matrix). The transformation was then adjusted to account for the left-handedness of the Unity world coordinate system. This way the rotation was derived taking into account the calibration orientation of the user looking at focus target B5, resulting in the derived rotations being the head movement rotations of the users starting from the center point of looking at focus target B5, with the rotation in relation to the initial position in the world coordinate system being accounted for.

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.

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

2.5.3 Data Labelling

Furthermore, to analyse the specific head movements, the movements had to be identified and labeled in the tracked data. This turned our to be 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. Different movement behaviour, the lack of synchronisation of the commands given and the recorded data, as well as large amount of irrelevant small movements users made during the user study were the main factors that prevented automatic labelling and classification of the recorded data into the desired movements. In the case of some users some small movements were barely noticeable, while in other cases the users movement was all over the place, as instead of directly looking at the target, they had forgotten its location and had to search for it.

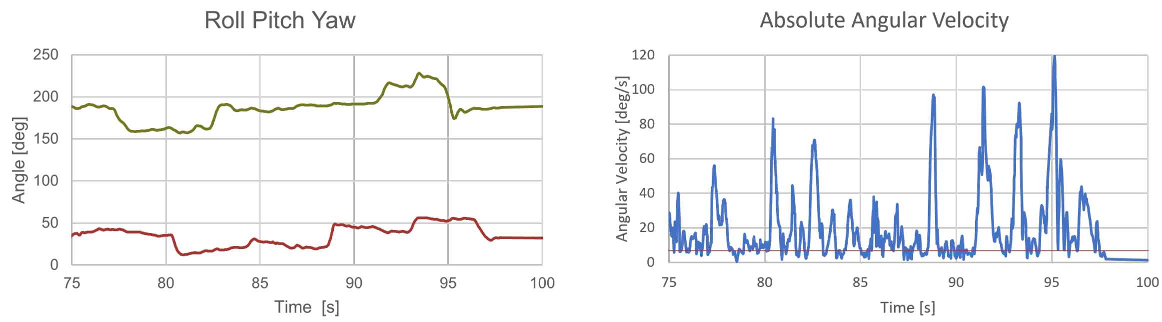


Figure 2.24: *Analogue to Figure 2.22 and Figure 2.23 a messy example of the recorded data is shown here*

Due to the complexity of the labeling operation and movement identification, the collected data was eventually labelled and identified manually 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 2.23. This ground noise is mainly caused by the trackers, however, on top of this noise some small movements are overlaid, which are possibly caused by slight movements of the users head. These slight head movements were, while different across different users, usually below $5\ deg/s$, which is why this threshold was chosen for the identification of proper movements.

The labelling of the data was completed 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 data with 41 different attributes, were manually labelled. The data was labelled with three identifiers listed below.

- *Phase*: Phase of the looking task, with entries ranging from 1-4, with each row of looking orders in Figure 2.14 representing one phase.
- *GFO*: Focus object which the user was asked to focus on
- *Movement*: Denoting a movement between two focus objects and labelled with a number (1 through 10, the maximum amount of movements in one phase), 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 2.25 represents a clean and ideal case for labelling, however, this was not always the case. Figure 2.25 is to provide and example of an easily identifiable movement to understand the concept employed for the labelling of the data.

2.6 Data Analysis

After the data tidying, transformation and labelling to a usable format, the movement data was analysed and visualised using RStudio. Specifically, several key movements were identified for analysis. The movements were chosen with the idea to have both shorter movements (on one wall) and larger movements (across all three walls). Furthermore for the shorter movements horizontal and vertical movements were chosen to be able to compare the results derived for those two categories. The data for these movements was 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.

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 2.25: *Example of labelled data of user study participant number 10 with colour-coded angular rotation speed (green < 5 deg/s < yellow < 10 deg/s < orange < 30 deg/s < red) and the three defined movement labels*

Based on the above the following attributes were calculated for each individual user within each test condition:

- Movement duration for each individual movement
- Average movement speed for each single movement
- Angular offset of the head trajectory vector compared to the direct vector between user and the focus target as seen in Figure 2.26

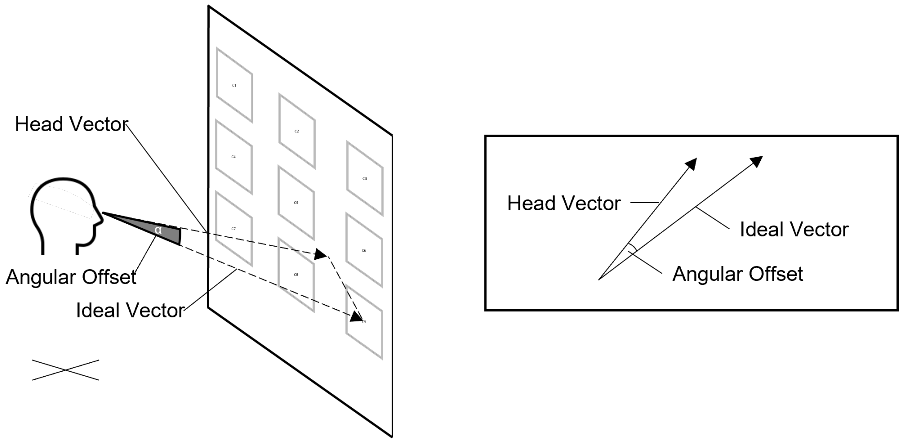


Figure 2.26: *Angular offset of head trajectory compared to optimal vector between user and focus target*

Based on the above results, the mean values across of all users for the different movements and the different test conditions were derived.

However, to account for individual behavioral differences (some users moving slower or faster), the differences between the head movement duration, head movement speed and angular offset in the three different test conditions were calculated for each individual user. This resulted in a delta for each of the mentioned attributes between the different test conditions, one delta being the difference between RB and LR, the second being the difference between LR and VR and the third being the difference between RB and VR. The mean of those deltas across all users for each of the different movements were calculated to get an indication of what differences of user behaviour between the different test conditions exist, for example if movements are generally slower in VR compared to RB for the individual users. These results are summarised, compared and discussed in Chapter 3.

3

Results and Discussion

In this chapter the derived results of the project are summarised. In Section 3.1 basic information about the conduction of the user study and its participants is provided. In Section 3.2 examples of the recorded head movement trajectories are visualised, while in Section 3.3 examples of the head trajectory and the eye gaze direction are visualised for the VR test condition. In Section 3.4 the results of all user study participants with regards to the duration of the movement, the speed of the head movement and the angular offset after the movement compared to the vector pointing directly at the focus target are analysed for several different movements.

3.1 User Study Participant Demographics

The user 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 a PhD. Table 3.1 provides a statistical summary of the demographics and other pertinent characteristics of the participants who have taken part in the user study.

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

Table 3.1: *Statistical summary of the demographics and other pertinent characteristics of user study participants*

Figure 3.1: *Satisfied user study participant*

3.2 Visualisation of Head Movement Trajectories

A visualisation of the head movement trajectories of user 10 during phase 1 of the looking sequence (B5-B6-B9-B8-B5-B4-B1-B2-B5) is presented in Figure 3.2 for three distinct experimental conditions (RB, LR, VR) as an example. User 10 was chosen as an example that illustrates general trends in user behaviours.

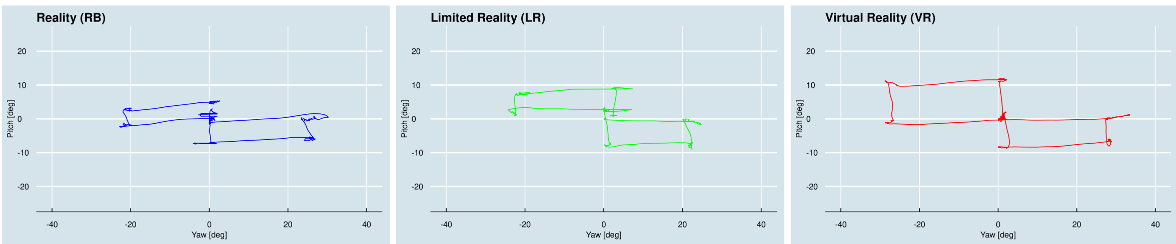


Figure 3.2: *Head movement trajectories for movement order B5-B6-B9-B8-B5-B4-B1-B2-B5 of user study participant 10 for RB (left), LR (middle) and VR (right)*

Figure 3.3 displays these same head movement trajectories over each other for easier comparison.

In the case of user 10, as seen in Figure 3.3, 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 the general trends in user behaviour, as detailed more in the following sections, however, it is important to note that differences between the different user behaviours were considerable. Furthermore, this indicates that only a part of the rotation necessary in the aforementioned looking order is completed by turning the head, as already shown in research. [45] The rest of the distance is completed by eye rotation, as detailed in Section 3.3.

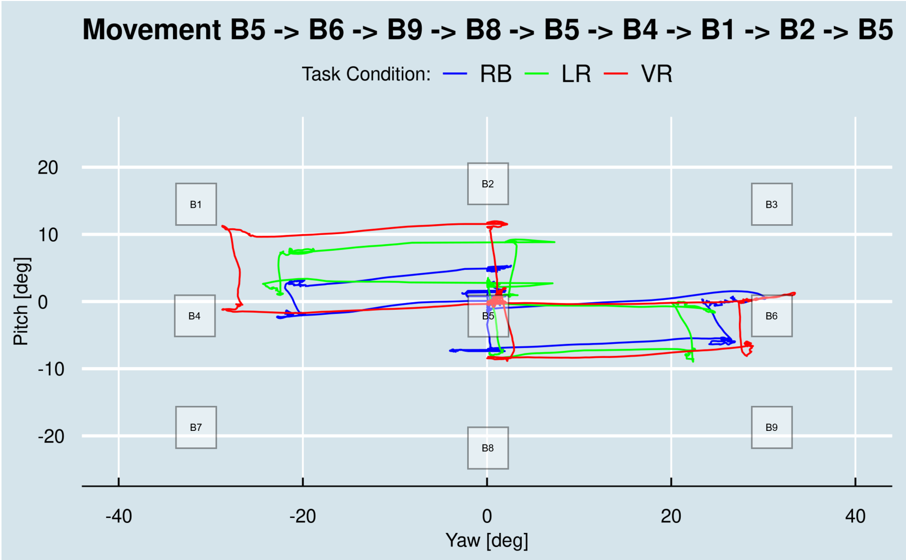


Figure 3.3: *Head movement trajectories for Phase 1 movement order B5-B6-B9-B8-B5-B4-B1-B2-B5 of user study participant 10 overlaid for all three different test conditions, including the location of the focus targets on wall B*

The examination of the head movement trajectories of individual 10, as depicted in Figure 3.3, 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. 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 part 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 3.3.

The comparison figures of all user study participants can be found in the appendix Chapter A.1.

3.3 Comparison of Head Trajectories and Eye Trajectories in VR

By utilising 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 3.4, the comparison of head and eye trajectories for study participant 10 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 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 was confirmed by the recorded focus target at which they eye gaze of the users was pointed at within the data recordings. 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. This was the case for many of the recorded eye trajectories, however, many of the recorded eye trajectories were also scrambled and offset, potentially due to a lack of synchronisation between the tracker and the HMD and its eye tracking. These example trajectories serves as a representation of the vastly generalised trends in user behaviour, as detailed more in the following sections, however, it is important to note that differences between the different user trajectories and behaviours were considerable.

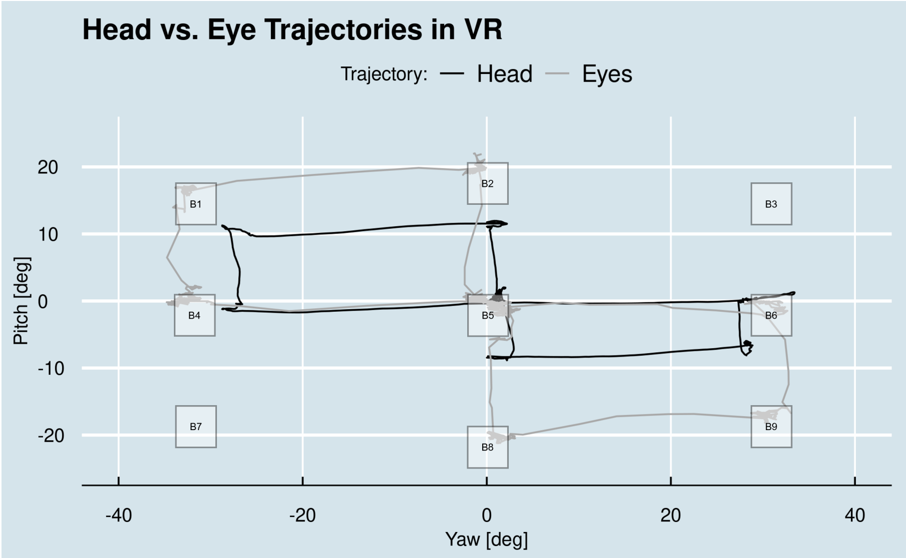


Figure 3.4: *Head and eye movement trajectories for Phase 1 looking order B5-B6-B9-B8-B5-B4-B1-B2-B5 of user study participant 10 during the VR-based test condition*

The comparison figures of all the user study participants can be found in the appendix Chapter A.1.

3.4 Head Movement Trajectories Results

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 (limited on one wall), and *long movements*, which are movements towards focus targets outside of the FoV (using all three walls) and thus necessitate a head rotation to some degree.

In order to manage the significant number of recorded movements, a subset of movements were chosen for more in-depth analysis. These particular movements were selected based on their comparability to one another, and were chosen specifically to enable the comparison of different aspects, with a preference for starting or ending at B5, which was the calibration point for the user study, whenever feasible.

Short Movements:

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

Long Movements:

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

An analysis of several parameters 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.

3.4.1 Short Movements

Movement B5 - B6

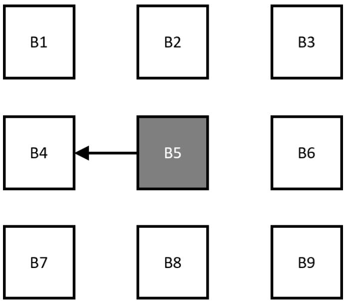


Figure 3.5: *Movement illustration B5 - B6*

Movement Duration
As seen in Figure 3.6 and Table 3.2 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.

Angular Offset
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.

Angular Rotation Speed
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.

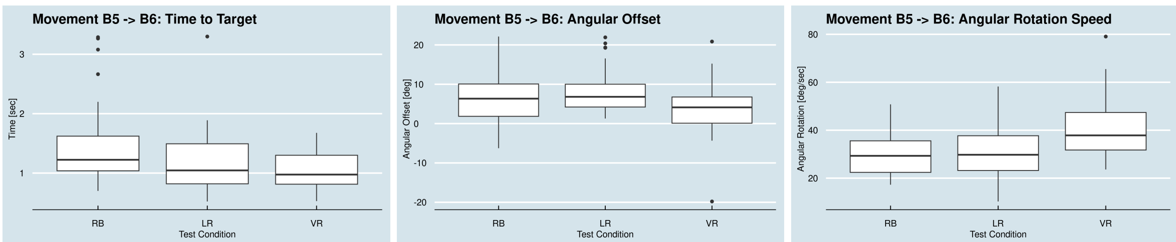


Figure 3.6: *Box plot of the mean values for Time to Target (left), Angular Offset (middle) and Angular Rotation Speed (right) of all user study participants for the three test conditions for movement B5 $\rightarrow$ B6*

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 3.2: *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 $\rightarrow$ B6*

Movement B5 - B4

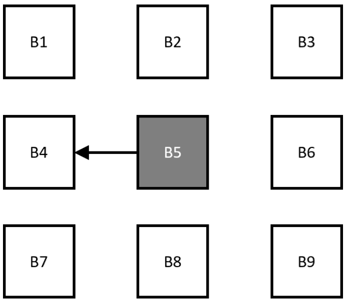


Figure 3.7: *Movement illustration B5 - B4*

Movement Duration

As seen in Figure 3.8 and Table 3.3 the movement duration 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.

Angular Offset

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.

Angular Rotation Speed

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.

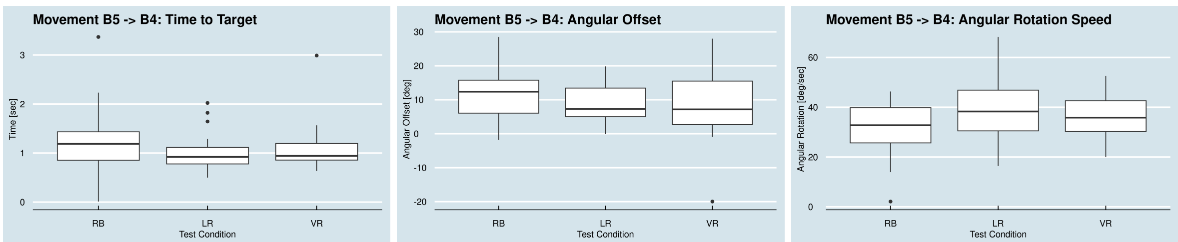


Figure 3.8: *Box plot of the mean values for Time to Target (left), Angular Offset (middle) and Angular Rotation Speed (right) of all user study participants for the three test conditions for movement B5 → B4*

Test Condition	RB	sd	LR	sd	VR	sd	ΔRB.LR	sd	ΔRB.VR	sd	ΔLR.VR	sd
Time to Target [sec]	1.28	0.608	0.993	0.344	1.071	0.426	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 3.3: *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 B5 → B4*

Movement B6 - B9

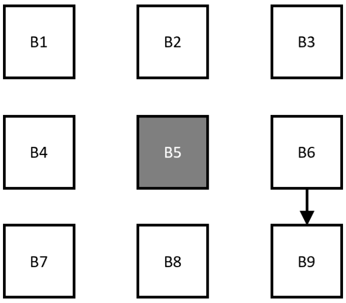


Figure 3.9: *Movement illustration B6 - B9*

Movement Duration
As seen in Figure 3.10 and Table 3.4 the movement duration 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.

Angular Offset
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.

Angular Rotation Speed
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.

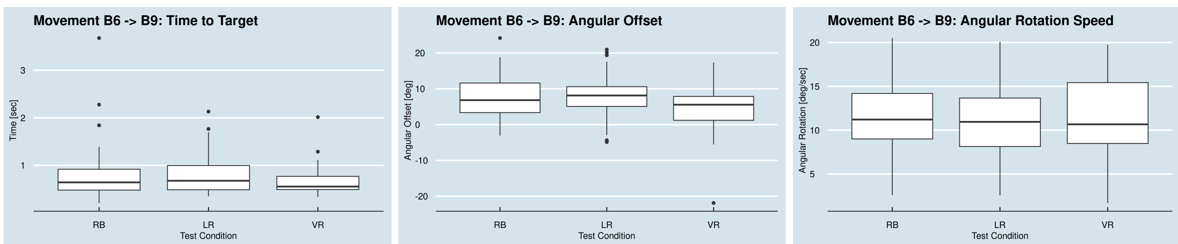


Figure 3.10: *Box plot of the mean values for Time to Target (left), Angular Offset (middle) and Angular Rotation Speed (right) of all user study participants for the three test conditions for movement B6 → B9*

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 3.4: *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 B6 → B9*

Movement B4 - B1

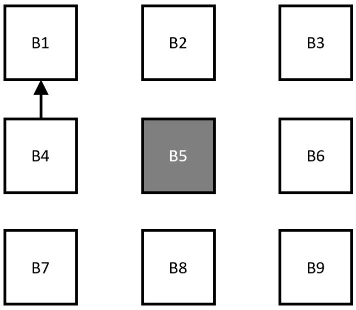


Figure 3.11: *Movement illustration B4 - B1*

Movement Duration
As seen in Figure 3.12 and Table 3.5 the movement duration 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.

Angular Offset
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.

Angular Rotation Speed
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.

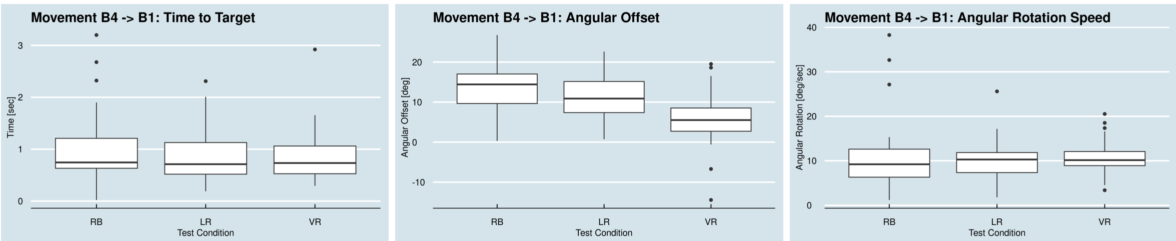


Figure 3.12: *Box plot of the mean values for Time to Target (left), Angular Offset (middle) and Angular Rotation Speed (right) of all user study participants for the three test conditions for movement B4 $\rightarrow$ B1*

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 3.5: *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 B4 $\rightarrow$ B1*

Summary of Results of Short Movements

Movement Duration
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.

Angular Offset
Overall, as seen in Figure 3.13, 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.

Angular Rotation Speed
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 3.13: *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)*

3.4.2 Long Movements

Movements B5 - A5 and B5 - C5

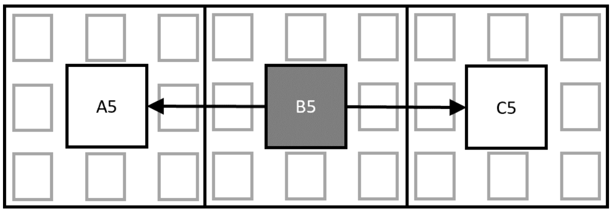


Figure 3.14: *Movement illustration B5 - A5 and B5 - C5*

Movement Duration
As seen in Figure 3.15 and Table 3.6 the movement duration of the head is lower for RB and similar for LR and VR. Similar holds true for the individual differences for each user between the task conditions.

Angular Offset
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.

Angular Rotation Speed
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.

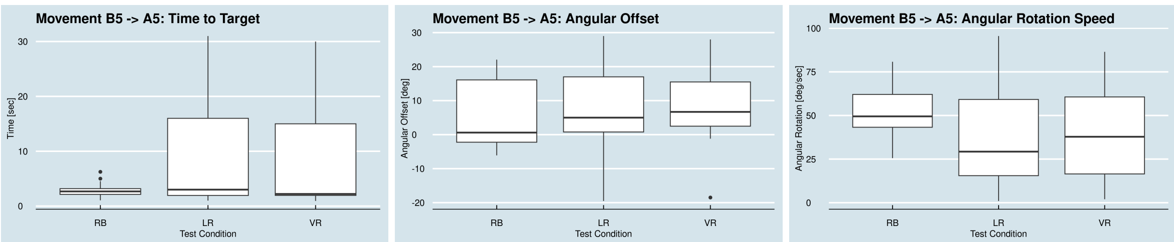


Figure 3.15: *Box plot of the mean values for Time to Target (left), Angular Offset (middle) and Angular Rotation Speed (right) of all user study participants for the three test conditions for movement B5 $\rightarrow$ A5 and B5 $\rightarrow$ C5*

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 3.6: *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 B5 $\rightarrow$ A5*

Movements C5 - B5 and A5 - B5

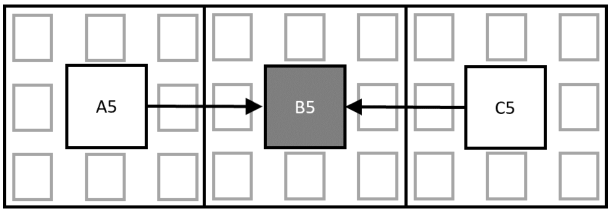


Figure 3.16: *Movement illustration C5 - B5 and A5 - B5*

Movement Duration

As seen in Figure 3.17 and Table 3.7 the movement duration of the head is once again lower for RB and similar for LR and VR. Similar holds true for the individual differences for each user between the task conditions.

Angular Offset

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.

Angular Rotation Speed

With regards to 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.

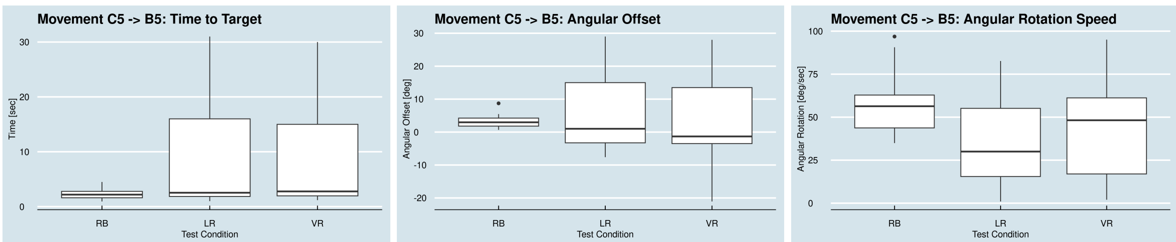


Figure 3.17: *Box plot of the mean values for Time to Target (left), Angular Offset (middle) and Angular Rotation Speed (right) of all user study participants for the three test conditions for movement C5 → B5 and A5 → B5*

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 3.7: *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 of Results of Long Movements

Movement Duration
As seen in Figure 3.18 averaged over all the long movements, the time to target is fastest for RB, 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.

Angular Offset
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.

Angular Rotation Speed
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 3.18: *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)*

3.5 Head Movement Trajectories Discussion

3.5.1 Short Movements

Movement B5 - B6

Movement Duration
Surprisingly the time to target is longest for RB, followed by LR and then VR. The reverse order was expected. A reason that might cause these results is the way the movements were labelled, based on which the movement duration was calculated. As a threshold was used, differences in acceleration and deceleration in the three different test conditions might result in counter-intuitive results, as seen here for the time to target.

Angular Offset
The offset of RB and LR is larger compared to VR, which seems sensible, as more of the rotation was completed with the eyes compared to head movements. The reason why the angular offset in VR is lower might be due to the fact that the edges of the FoV in VR become blurred due to the lenses present in the HMD. It is interesting to note that the offset of LR is slightly larger compared to RB.

Angular Rotation Speed
Looking at the angular rotation speed, interestingly the speed is slowest for RB, closely followed by LR and fastest for VR. The opposite was expected, but this might once again be explained by the way the movements were labelled, as different acceleration and deceleration in the different test conditions might cause these results. Furthermore, as seen in the angular offset, more rotation was completed in VR, which might also result in slightly faster speeds, as more time for acceleration and deceleration was possible.

Movement B5 - B4

Movement Duration
Similar to the previous movement, the time to target is longest for RB, followed by VR and then LR. The reason that might cause these results is the same as already mentioned previously, the way the movements were labelled, based on which the movement duration was calculated. As a threshold was used, differences in acceleration and deceleration in the three different test conditions might result in counter-intuitive results, as seen here for the time to target. Compared to movement B5 - B6, the time to target is slightly faster in the RB and LR test conditions, despite the movements having the same angular rotation, with VR yielding similar results.

Angular Offset
The offset of RB and LR is larger compared to VR, as was the case for movement B5 - B6. This seems sensible, as more of the rotation was completed with the eyes compared to head movements. The reason why the angular offset in VR is lower might be due to the fact that the edges of the FoV in VR become blurred due to the lenses present in the HMD. Compared to the previous movement, RB has the largest offset, with the offset in all three test conditions being slightly larger compared to the previous movement.

Angular Rotation Speed
For this movement, the rotation speed is fastest for LR, followed by VR and then slowest for RB. The opposite was expected, but this might once again be explained by the way the movements were labelled, as different acceleration and deceleration in the different test conditions might cause these results. It is, however surprising that LR has the largest movement speed. Given the fact that the movement speeds are somewhat similar, this might be explained as a fluctuation.

Movement B6 - B9

Movement Duration
Surprisingly, as in the previous movements, the time to target is longest for RB, followed by LR and then VR. The reason might again be the way the movements were labelled, based on which the movement duration was calculated. As a threshold was used, differences in acceleration and deceleration in the three different test conditions might result in counter-intuitive results, as seen here for the time to target.

Angular Offset
The offset of RB and LR is larger compared to VR, which seems sensible, as more of the rotation was completed with the eyes compared to head movements. The reason why the angular offset in VR is lower might be due to the fact that the edges of the FoV in VR become blurred due to the lenses present in the HMD. Interestingly the offset of LR is slightly larger compared to RB.

Angular Rotation Speed
Looking at the angular rotation speed, the speed is very similar for all test conditions, which stands in contrast to the previous two movements. A reason might be that in this case the movement was vertical, while in the previous cases the movements were horizontal.

Movement B4 - B1

Movement Duration
Once again, as in the previous movements, the time to target is longest for RB, followed by LR and then VR. As previously discussed, the suspected reason might be the way the movements were labelled, based on which the movement duration was calculated. As a threshold was used, differences in acceleration and deceleration in the three different test conditions might result in counter-intuitive results, as seen here for the time to target.

Angular Offset
The offset of RB and LR is larger compared to VR, which seems sensible, as more of the rotation was completed with the eyes compared to head movements. The reason why the angular offset in VR is lower might be due to the fact that the edges of the FoV in VR become blurred due to the lenses present in the HMD. Furthermore, the angular offset difference between RB and LR is very large for this movement.

Angular Rotation Speed
With regards to the angular rotation speed, the speed is very similar for all test conditions, as seen in the previous movement, but in contrast to the first two movements. The reason for this might be that the movement was vertical, while in the first two cases the movements were horizontal.

Overall Short Movements Discussion

Movement Duration
Concentrating on the movement duration for the short movements, the time to target is slowest for RB, followed by LR and fastest for VR. This is the case throughout the different small movements and seems counter-intuitive. The suspected reason for this might be way the movements were labelled, as based on the labelling the movement duration was calculated. As a threshold was used, differences in acceleration and deceleration in the three different test conditions might result in counter-intuitive results, as seen here for the time to target.

Angular Offset
Regarding the angular offset, for short movements, the head was observed to rotate short of the focus target in all three test conditions, generally more in RB, slightly less in LR, and the least in VR. However, this varied slightly for some specific movements. The angular offset are similar in RB and LR, but smallest for VR. This might be caused by to the fact that the edges of the FoV in VR become blurred due to the lenses present in the HMD.

Angular Rotation Speed
The angular rotation velocity is fastest for VR, followed by LR and then slowest for RB, but overall the angular rotation speed is very similar. These slight differences might be caused due to the larger rotation angle completed in VR, which allows more time for acceleration and hence leading to an overall slightly larger rotation speed.

Comparison of Vertical and Horizontal Movements

Movement Duration
With regards to the movement duration, horizontal movements tend to be generally longer compared to vertical movements. In both cases VR is the fastest, followed by LR and eventually RB. A reason for the different duration for horizontal and vertical movements could be the fact that the vertical movements required approximately 14 degrees less rotation compared to the horizontal movements (16 degrees vs 30 degrees.

Angular Offset
Considering the angular offset, this seems to be similar in both cases. The offset is slightly bigger for vertical movements compared to horizontal movements for RB and LR, while for VR it is slightly larger in the case of horizontal movements. However, considering that the rotation angle for vertical movements is nearly half as big compared to horizontal movements, the relative angular offset is much larger for vertical movements. This seems to indicate that there is less head rotation present for vertical movements compared to horizontal movements.

Angular Rotation Speed
Looking at the angular rotation speed, the speed is much larger for horizontal movements compared to vertical movements. This might once again be explained by the amount of rotation done for the two different movement types, which allows for more acceleration in the case of horizontal movements, as more rotation is completed. Furthermore, the variation between the different test conditions is much smaller in the case of vertical movements compared to horizontal movements. This could be due to the fact that the rotation for horizontal movements is slightly larger which allows for more divergence in user behaviour. Furthermore, this might also be explained by a potential difference in user behaviour regarding horizontal and vertical head rotations.

	Horizontal Movements						Vertical Movements					
Test Condition	RB	sd	LR	sd	VR	sd	RB	sd	LR	sd	VR	sd
Time to Target [sec]	1.381	0.662	1.090	0.448	1.065	0.370	0.953	0.695	0.861	0.491	0.774	0.418
Angular Offset [deg]	9.057	6.818	8.859	5.786	6.429	8.629	10.423	6.247	9.796	6.095	5.231	6.959
Angular Rotation Speed [deg/sec]	30.702	9.790	34.948	11.756	38.266	11.343	11.409	6.507	10.610	4.328	11.234	4.144

Figure 3.19: *Comparison of horizontal and vertical movements*

3.5.2 Long Movements

Movements B5 - A5 and B5 - C5

Movement Duration
Considering the time to target, it is lowest for RB, followed by VR and LR for which the time to target is higher. A reason for this could be the restricted FoV in both LR and VR, which might cause the users to rotate their head slower. Another aspect in LR and VR that might cause the users to rotate their head slower is the worn augmentation device, either FoV restriction device or HMD. While the users were

also wearing the tracker in RB, the HMD and FoV restriction device are heavier and impair the FoV of the users.

Angular Offset
Looking at the angular offset, it is highest for LR, closely followed by VR and eventually RB. Surprisingly the offset is lowest for RB, which might be explained by some users only rotating their head, instead of their complete bodies. In this case the head rotation could be impaired by the worn FoV restriction device or HMD which might cause the larger angular offset for LR and VR.

Angular Rotation Speed
With regards to the angular rotation speed it is highest for RB, followed by VR and LR which are similar. The faster angular velocity might again be explained by the fact that the user's rotate their heads slower due to the worn FoV restriction device or the HMD.

Furthermore the the frame rate might play a role in the case of VR, however given the similarities between LR and VR, it seems more likely this is caused by the restricted FoV or the fact that the users were wearing the augmentation devices.

Movements C5 - B5 and A5 - B5

Movement Duration
Considering the time to target, as in the previous movement, it is lowest for RB, followed by VR and LR for which the time to target is higher. The reason for this could once again be the restricted FoV in both LR and VR, which might cause the users to rotate their head slower. Furthermore, this might also be caused by the fact the users are wearing either the FoV restriction device or HMD.

Angular Offset
Looking at the angular offset, it is highest for LR, closely followed by VR and eventually RB, which is the same as in the previous movement. This might again be explained by some users only rotating their head, instead of their complete bodies. In this case the head rotation could be impaired by the worn FoV restriction device or HMD which might cause the larger angular offset for LR and VR.

Angular Rotation Speed
As is the case in the previous movement, with regards to the angular rotation speed, it is highest for RB, followed by VR and LR which are similar. The faster angular velocity might again be explained by the fact that the user's rotate their heads slower due to the worn FoV restriction device or the HMD.

Overall Long Movements Discussion

Movement Duration
In both cases of the long movements, the time to target is highest for LR, closely followed by VR and eventually RB. This could be explained by the restricted FoV in both LR and VR, which might cause the users to rotate their head slower. Another aspect in LR and VR is the worn augmentation device, either the FoV restriction device or the HMD. While the users were also wearing the tracker in RB, the HMD and FoV restriction device are heavier and additionally impair the FoV of the users. Furthermore in the case of VR, the HMD's frame rate might also contribute to the slower rotation. However, considering the similarities of results for LR and VR, it seems more likely this is caused by the restricted FoV or the fact that the users were wearing the augmentation devices, either the FoV restriction device or HMD.

Angular Offset
Looking a the angular offset, it appears that it is lowest for RB, followed by VR and LR. It is surprising that the offset is so much lower for RB compared to both LR and VR. A reason for this could be explained by users only rotating their head, compared to their whole bodies, and the rotation being impaired by the word FoV restriction device or HMD, causing the larger angular offset.

Angular Rotation Speed
With regards to the angular rotation speed, the results are similar for both long movements, with the speed being highest for RB, followed by VR and LR which are similar. This difference between RB and both LR and VR, might be explained by the different FoV in these test conditions, with the restricted FoV leading to a slower user head rotation. The fact the users are wearing augmentation devices, such as the FoV restriction device or HMD, might also affect their behaviour, for example due to the weight of the worn device. Furthermore the frame rate might play a role in the case of VR, however given the similarities between LR and VR, it seems more likely that the slower rotation speed is caused by the restricted FoV or the fact that the users were wearing the augmentation devices.

3.5.3 Comparison of Long and Short Movements

Movement Duration
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. For short movements on the other hand, time to target is more similar, however, compared to long movements where RB is always the fastest, for short movement RB is the slowest, followed by LR and then VR. Hence the order is reversed compared to long movements. One possible explanation for this could be the way the duration of the movement was measured, as only the movement above a certain speed threshold, to filter out the noise, was counted. A difference in angular acceleration and deceleration within the three test conditions might hence affect the time to target and could explain the reversed results for the short movements. Furthermore, for RB, more of the rotation is completed with eye movements, with the head potentially following the rotation at a short delay and at a slower speed, resulting in the higher time to target while only looking at the head trajectory.

Angular Offset
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. A reason why the offset in VR for short movements is lowest could be due to the lenses used in the HMD, which results in the edges of the FoV becoming blurred and hence the users are trying to focus on the objects in the middle of their FoV. On the other hand, the offset is larger for long movements in VR and LR, which might be caused due to the worn HMD and FoV restriction device, restricting the users freedom of head rotation, as not all users moved and rotated their body, a few only rotated their head. With regards to LR, for short movements, it is more similar to RB, while for long movements it is more similar to VR. A reason for this could be that in LR the restriction of FoV has not a big effect on short movements, as the movements are all within the current field of view, while for VR there are more differences which might affect the users, such as the blurriness at the edges of their FoV.

Angular Rotation Speed
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, allowing more time for acceleration. Furthermore, the speed is similar for short movements, while for long movements larger deviations are present. This might be explained by the divergence of differences scaling with the absolute angular rotation, with larger rotation angles leading to larger differences between the different users and the test conditions.

	Short Movements						Long Movements					
Test Condition	RB	sd	LR	sd	VR	sd	RB	sd	LR	sd	VR	sd
Time to Target [sec]	1.063	0.253	0.928	0.157	0.823	0.153	2.532	0.286	9.087	0.032	8.823	0.152
Angular Offset [deg]	9.740	2.991	9.327	1.166	5.830	1.905	4.225	1.084	8.309	1.249	7.799	0.850
Angular Rotation Speed [deg/sec]	21.055	9.667	22.779	12.542	24.750	13.611	54.530	2.513	37.469	0.154	38.135	0.648

Table 3.8: *Comparison of results for long movement and short movements for the three different test conditions, with regards to movement duration, angular offset and angular rotation speed*

3.6 Questionnaires

Below, the results of the different questionnaires can be found.

3.6.1 Simulator Sickness Questionnaire

The results of the SSQ are shown in Figure 3.20. There are no noteworthy differences between the two test condition orders.

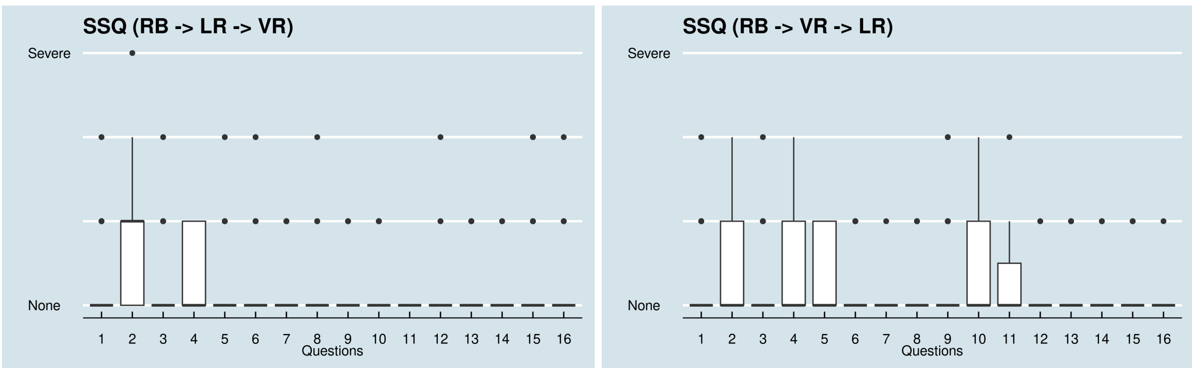


Figure 3.20: *SSQ results of all test conditions for each question in test condition order RB - LR - VR (left) and RB - VR - LR (right)*

In Figure 3.21 and Figure 3.22, as well as Table 3.9 and Table 3.10 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 noteworthy differences or outliers in the results.

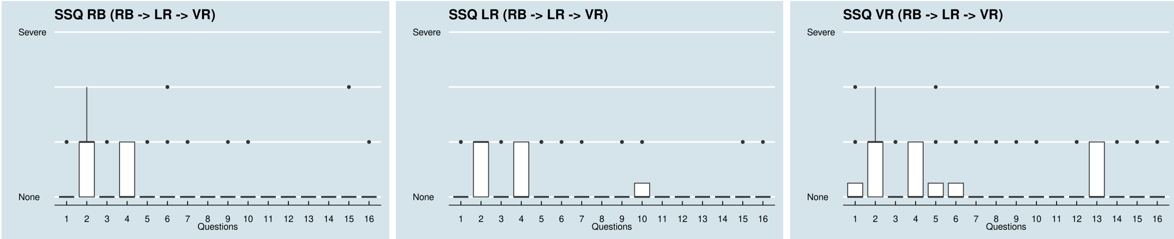


Figure 3.21: *SSQ results for each question in test condition order RB - LR - VR and each test condition: RB (left), LR (middle), VR (right)*

SSQ		Question															
RB-LR-VR		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
PRE	Mean	0.188	0.813	0.188	0.438	0.125	0.188	0.188	0.125	0.063	0.313	0	0.125	0.188	0.125	0.25	0.125
	Standard Deviation	0.544	0.834	0.544	0.512	0.342	0.544	0.403	0.5	0.25	0.479	0	0.5	0.403	0.342	0.683	0.342
RB	Mean	0.125	0.625	0.125	0.313	0.125	0.188	0.125	0	0.063	0.188	0	0	0	0	0.125	0.063
	Standard Deviation	0.342	0.619	0.342	0.479	0.342	0.544	0.342	0	0.25	0.403	0	0	0	0	0.5	0.25
LR	Mean	0.188	0.625	0.063	0.313	0.188	0.125	0.063	0	0.125	0.25	0	0	0	0	0.125	0.063
	Standard Deviation	0.403	0.5	0.25	0.479	0.403	0.342	0.25	0	0.342	0.447	0	0	0	0	0.342	0.25
VR	Mean	0.313	0.75	0.188	0.438	0.313	0.25	0.063	0.188	0.063	0.188	0	0.125	0.313	0.063	0.188	0.25
	Standard Deviation	0.602	0.775	0.403	0.512	0.602	0.447	0.25	0.403	0.25	0.403	0	0.342	0.479	0.25	0.403	0.577

Table 3.9: *Table with SSQ results for each question in each test condition for test condition order RB-LR-VR*

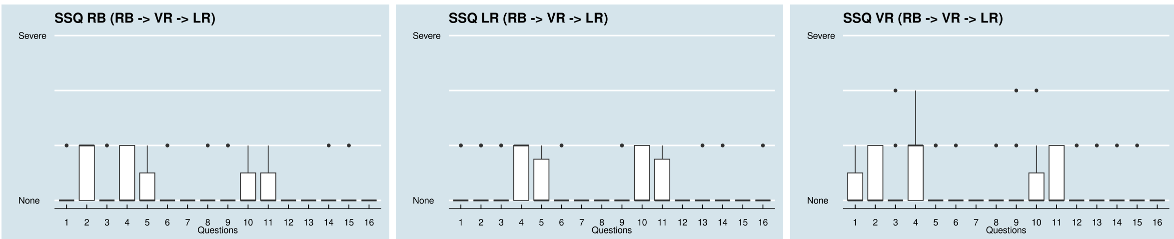


Figure 3.22: *SSQ results for each question in test condition order RB - VR - LR and each test condition: RB (left), LR (middle), VR (right)*

Taking into account the various aspects evaluated in the SSQ, it seems that there were no increases observed in the RB-LR-VR and RB-VR-LR test conditions, compared to the initial test conducted prior to the user study (referred to as PRE in the table). This suggests that the different test conditions did not have a negative impact on the user in terms of the parameters assessed. Furthermore, there appear to be no noteworthy differences between the two test condition orders.

SSQ		Question															
RB-VR-LR		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
PRE	Mean	0.2	0.667	0.2	0.4	0.333	0.2	0.067	0.2	0.333	0.333	0.2	0	0.133	0.067	0.133	0
	Standard Deviation	0.561	0.724	0.414	0.632	0.488	0.414	0.258	0.414	0.617	0.488	0.561	0	0.352	0.258	0.352	0
RB	Mean	0.133	0.533	0.133	0.333	0.267	0.133	0	0.133	0.2	0.267	0.267	0	0	0.067	0.067	0
	Standard Deviation	0.352	0.516	0.352	0.488	0.458	0.352	0	0.352	0.414	0.458	0.458	0	0	0.258	0.258	0
LR	Mean	0.214	0.179	0.393	0.464	0.214	0.071	0	0.107	0.286	0.321	0.143	0.071	0.107	0.036	0.036	0.071
	Standard Deviation	0.418	0.390	0.497	0.508	0.418	0.262	0	0.315	0.46	0.476	0.356	0.262	0.315	0.189	0.189	0.267
VR	Mean	0.267	0.467	0.2	0.733	0.2	0.067	0	0.133	0.267	0.333	0.333	0.133	0.133	0.067	0.067	0
	Standard Deviation	0.458	0.516	0.561	0.594	0.414	0.258	0	0.352	0.594	0.617	0.488	0.352	0.352	0.258	0.258	0

Table 3.10: *Table with SSQ results for each question in each test condition for test condition order RB-LR-VR*

3.6.2 Simulation Task Load Index

The results of the SIM-TLX questionnaire are shown in Figure 3.23. There are no noteworthy differences between the two task conditions.

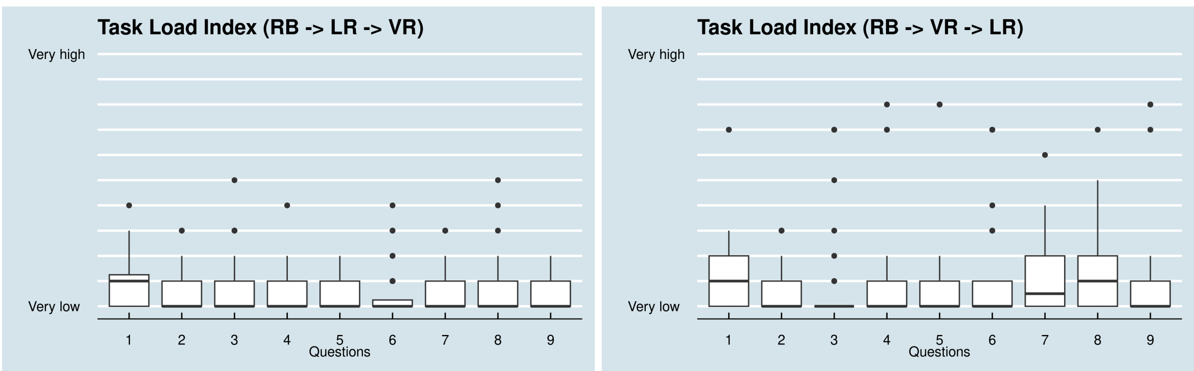


Figure 3.23: *SIM-TLX questionnaire results of all test conditions for each question in test condition order RB - LR - VR (left) and RB - VR - LR (right)*

In Figure 3.24 and Figure 3.25, as well as Table 3.11 and Table 3.12 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.

Considering the results for the SIM-TLX, there are no noteworthy increases or differences between the different test conditions or the two test condition orders to discuss. However, there is one outlier in the SIM-TLX with one user rating the the task load higher in all three test conditions as seen in Figure 3.25.

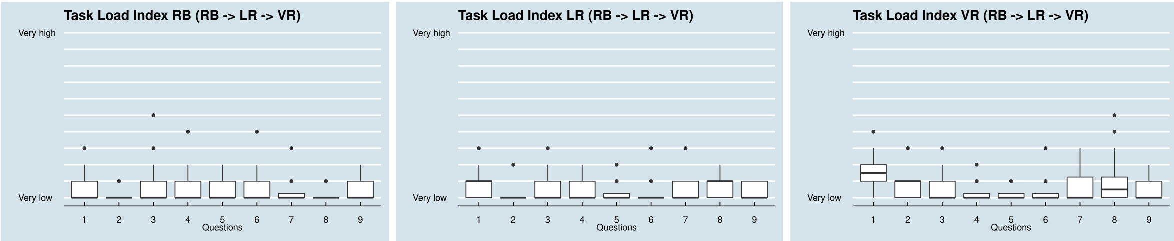


Figure 3.24: *SIM-TLX questionnaire results for each question in test condition order RB - LR - VR and each test condition: RB (left), LR (middle), VR (right)*

SIM-TLX		Question								
RB-LR-VR		1	2	3	4	5	6	7	8	9
RB	Mean	0.667	0.133	0.933	0.6	0.6	0.667	0.4	0.2	0.4
	Standard Deviation	0.9	0.352	1.438	1.121	0.737	1.175	0.828	0.414	0.632
LR	Mean	0.867	0.267	0.6	0.4	0.333	0.333	0.6	0.8	0.4
	Standard Deviation	0.834	0.704	0.91	0.737	0.617	0.816	0.828	0.775	0.507
VR	Mean	1.533	0.733	0.6	0.933	0.8	0.867	1.4	1.867	0.733
	Standard Deviation	1.807	1.1	1.844	1.831	2.077	1.995	1.352	1.457	2.052

Table 3.11: *Table with SIM-TLX results for all questions in each test condition for test condition order RB-LR-VR*

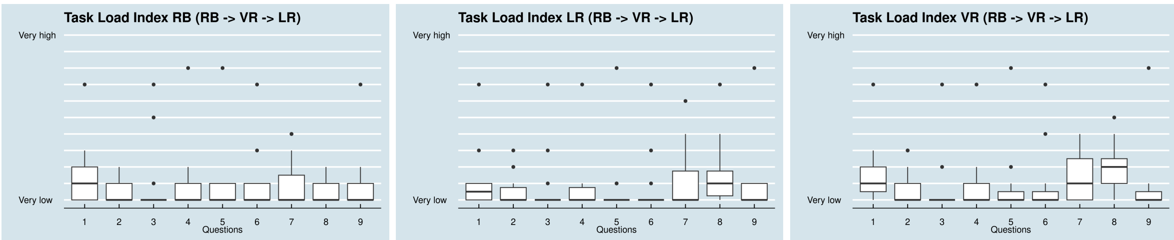


Figure 3.25: *SIM-TLX questionnaire results for each question in test condition order RB - VR - LR and each test condition: RB (left), LR (middle), VR (right)*

SIM-TLX		Question								
RB-VR-LR		1	2	3	4	5	6	7	8	9
RB	Mean	1.333	0.467	0.867	1	0.933	0.867	1	0.4	0.933
	Standard Deviation	1.915	0.64	2.134	2.07	2.017	1.885	1.512	0.632	1.831
LR	Mean	1.071	0.5	0.786	0.714	0.714	0.786	1.214	1.5	0.857
	Standard Deviation	1.9	0.941	1.968	1.858	2.128	1.968	1.888	1.912	2.107
VR	Mean	1.563	0.813	0.625	0.313	0.25	0.375	0.688	1.125	0.563
	Standard Deviation	1.153	0.981	0.885	0.602	0.447	0.806	1.014	1.586	0.727

Table 3.12: *Table with SIM-TLX results for all questions in each test condition for test condition order RB-VR-LR*

3.6.3 Cognitive Absorption Questionnaire

The results of the VR cognitive absorption questionnaire are shown in Figure 3.26 and Table 3.13. There are no noteworthy differences between the two task conditions.

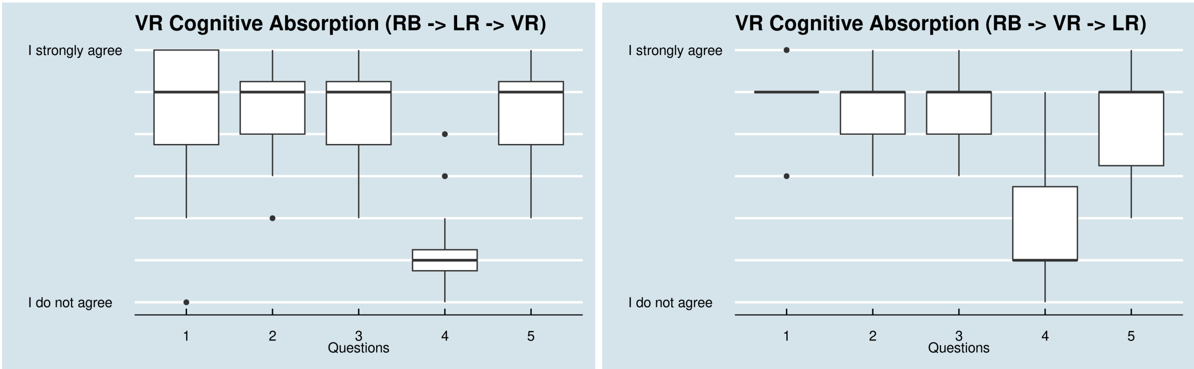


Figure 3.26: *VR cognitive absorption questionnaire results for each question in test condition order RB - LR - VR (left) and RB - VR - LR (right)*

VR Cognition Questionnaire	Question									
Test Condition Order	RB-LR-VR					RB-VR-LR				
	1	2	3	4	5	1	2	3	4	5
Mean	5.375	5.563	5.563	2.25	5.5	6.071	5.643	5.714	2.786	5.143
Standard Deviation	1.708	1.209	1.263	1.183	1.265	0.73	0.842	0.994	1.477	1.351

Table 3.13: *Table with VR cognition questionnaire results for each question in each test condition for both test condition orders*

Considering the results of the VR cognition questionnaire the results for all five questions appear to be similar in both test condition cases. The same holds true for the standard deviation. Considering the similar results, no link between user performance and the cognitive absorption was examined.

3.6.4 VR Presence Questionnaire

The results of the VR presence questionnaire are shown in Figure 3.27. There are no noteworthy differences between the two task conditions.

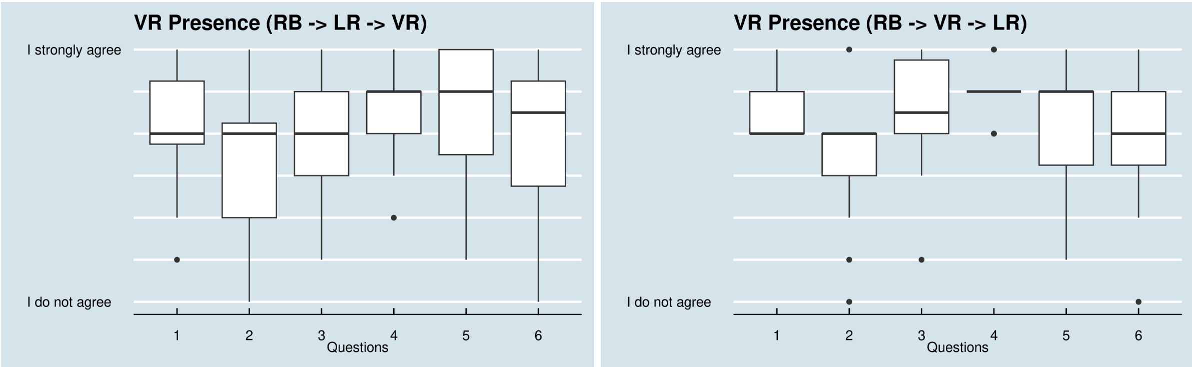


Figure 3.27: *VR presence questionnaire results for each question in test condition order RB - LR - VR (left) and RB - VR - LR (right)*

VR Presence Questionnaire	Question											
Test Condition Order	**RB-LR-VR**						**RB-VR-LR**					
	1	2	3	4	5	6	1	2	3	4	5	6
Mean	5.188	4.313	4.813	5.625	5.188	5	5.5	4.286	5.5	6	5.214	4.714
Standard Deviation	1.559	1.778	1.642	1.088	1.905	1.897	0.76	1.49	1.401	0.679	1.626	1.899

Table 3.14: *Table with VR presence questionnaire results for each question in each test condition for both test condition orders*

Looking at the results for the VR presence questionnaire the results for both test condition orders are once again similar. Furthermore the same seems to be the case for the standard deviation. As was the case for the cognitive absorption questionnaire, the same appears to be the case here. Hence no link between user performance and their sense of presence was examined.

3.7 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 LR 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.

3.8 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. The 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 temporary 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 could have been directly implemented in the tracking script. This could have been potentially mitigated either by giving the commands of which target to look at visually and record the timestamp when the command was given or by manually marking when the command was given, while for the end of the movement the user could potentially confirm the successful completion of the task by pressing a button themselves which would mark the end of the movement. This could have helped to identify the proper movements better and also take into account the reaction time of users. However some filtering based on movement speed might remain necessary still. The manual labelling introduced another limitation, as the labelling of movements could have influenced the results.

Moreover, the rotation of the trackers was recorded 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. Calibration of the orientation of the trackers compared to the global coordinate system was also only applied during post-processing, which could have affected the results and should have been included in the tracking script design. Furthermore, calibration could be completely skipped by directly recording the head trajectory vector, which could directly be calculated and recorded in the global coordinate system.

The final limitation was the lack of synchronisation between the oral 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. Currently the movements were only identified based on the head movement speed, which does not take into account reaction time or earlier movement of the eyes. Furthermore, in some cases of small users a small number of users barely moved their head and used only their eyes, which made identification of the head movements very difficult. This might also be mitigated by introducing the command of which target to look at visually and tracking the time when the command was given. Furthermore, some users gave feedback that it was difficult to convert the oral commands into which card to look at, furthermore, some users did not appear to be familiar enough with the environment and having a proper mind map of the focus target location, which resulted in the users having to search for the focus targets, which in turn might have affected the received trajectory results.

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 behaviour in VR with respect to the limited FoV encountered in this environment. Specifically, this semester project aimed to compare the head movement trajectories between reality and VR, with regards to FoV. To this end 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.

Results showed some individual variations in user behaviour, with differences in movement duration, speed, and angular offset depending on the test condition and type of specific movement, specifically when distinguishing between short and long movements.

For short movements, the time to target is slowest for RB, followed by LR and fastest for VR in short movements, which may be due to the way the movements were labeled and differences in acceleration and deceleration in the three test conditions. With the angular offset of the head trajectories, it is observed to rotate short of the focus target, with RB having the largest offset, followed by LR and VR, which might be due to the blurring of the edges of the FoV in VR. The angular rotation velocity is fastest for VR, followed by LR and then RB, with differences possibly due to the larger rotation angle completed in VR allowing more time for acceleration. With regards to short movements, specifically comparing horizontal and vertical movements, it is found that horizontal movements tend to be longer compared to short movements, with VR being the fastest, followed by LR and eventually RB. This could be explained by the fact that the vertical movements require less rotation compared to the horizontal movements. The angular offset is slightly bigger for vertical movements compared to horizontal movements in RB and LR, while for VR it is slightly larger in the case of horizontal movements, but the relative angular offset is much larger for vertical movements indicating less head rotation for vertical movements compared to horizontal movements. The angular rotation speed is larger for horizontal movements compared to vertical movements, which could be due to the amount of rotation and user behaviour. The variation between test conditions is smaller for vertical movements.

In both examined long movement cases, the time to target is highest for LR, followed by VR and then RB, which could be due to the restricted FoV, causing users to rotate their head slower. The angular offset is lowest for RB, followed by VR and LR, and the reason for the larger offset in LR and VR could again be due to the users' restricted FoV. RB had the highest angular rotation speed followed by VR and LR, which were similar, once again possibly due to the restricted FoV affecting user behaviour, although RB had the lowest angular offset compared to LR and VR, which may be explained by users only rotating their head rather than their whole body, leading to a more obstructed and offset rotation.

For long movements, time to target is longer, due to the larger required rotation; for short movements, time to target is more similar, but the order is reversed compared to long movements, which could be due to differences in angular acceleration and deceleration or the completion of more rotation with eye movements.With regards to the angular offset is higher for short movements than for long movements for RB and LR, possibly due to compensation with the eyes being less effective in long movements. However, in VR, the offset is higher for long movements, potentially due to blurred edges of the FoV. LR is similar to RB for short movements and similar to VR for long movements, potentially due to FoV restriction having less effect on short movements, due to the different focus targets being within the FoV. Higher angular rotation speeds were observed for longer movements, with larger deviations present for long movements. This could be explained by differences scaling with the absolute angular rotation.

It is important to note that the limitations in the recorded data and study design, as outlined in 3.8, 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

Given the limitations of this semester project to provide definitive conclusions, further research based on this work could prove valuable, as the findings obtained thus far show potential for continued exploration. Furthermore, many of the limitations and potential problems, as detailed in Section 3.8 were identified, improvements to which are presented subsequently.

Improved Data Tracking Script

Record Vectors instead of Orientations

The tracking scripts could be reworked and improved by directly calculating and recording the head pointing vector within the script. The necessary calibration for the head trajectory vector could also be implemented directly in the script. This could be achieved by drawing a vector between the recorded location of the tracker, taking into account a small offset of where the head of the user is actually located, and the fixed calibration point B5. The orientation of this vector could then be fixed to the location and orientation of the tracker, hence the vector would always remain attached to the same point of the tracker and the same orientation applied to it as to the tracker (which is moved in reality). This vector could then be recorded during the subsequent user study. This would remove the need for painstaking post processing in terms of data and orientation calibration and transformation. Furthermore, this would also allow to circumvent the inconsistent coordinate systems within the Vive Trackers, which were observed during this semester project.

Movement and Command Synchronisation & Visual Commands

Furthermore, the recorded vectors could be synchronised to the commands given by the test conductor directly within the script. The easiest way to achieve this would be to give the commands visually, recording the exact point in time when the command is given and what command was given directly within the tracking script. The command could be manually triggered directly by the test conductor by pressing a button for example. Marking the end of the movement would be more difficult, however, this could be measured as the point at which the angular rotation speed falls below a certain point. Another option would be to have the users confirm having completed the command by pressing a button themselves or by the having the test conductor observe the user and press a button to mark the end of the movement. This would however be very subjective and depend a lot on the subjective observation of either test conductor or the user in question. This would allow for proper identification and measurements of movements, allowing for proper statistical analysis of the results. Furthermore this would also allow to measure the time delay between command and the beginning of the user's movement. This would also remove the necessity of the rest of the painstaking post processing in terms of data tidying, labelling, movement identification and more.

Eye Tracking in all Test Conditions

Another important aspect for future work should be the eye tracking in all three test conditions. To this end the acquisition of a device to measure the eye trajectories in reality would be necessary. One of the conclusions of this semester project is that eye movement trajectories and head movement trajectories should be looked at in combination. It could be very interesting to see if the interplay of head and eye movements in VR compared to reality differs.

Further Data Analysis

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 and end of the movement and also the point when the user's eyes have focused on the target, if eye tracking is implemented in all test conditions. Also, even given the data recorded in this semester project, more aspects of the movements could be analysed. The direction of movements left & right and up & down could be compared to see if there are any differences in horizontal and vertical movements. Other additional data might also be worth investigating, such as the acceleration and deceleration of the head and eye movements. Results shown in Section 3.4.1 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. In addition it would be interesting to further research the relation on how the restricted FoV might affect the head movement speed and duration for longer movements.

User Study Design

The overall concept of the user study task design and test condition design appears to be fit for purpose, however some improvements could be made. For example, as mentioned before, the commands could be given visually, instead of orally. Also more aspects and details, such as the weight of the worn HMD or the screen refresh rate, which might influence user behaviour and which might differ between the test conditions could be taken into account in the study design and the subsequent analysis. Furthermore, the specific movements could be chosen better to fit the exact research purpose (for example horizontal versus vertical movements or long versus short movements). Some reservations regarding the goal of the user study trying to create comparable head trajectories were voiced as some users appeared to not be familiar enough with the environment and the location of the different focus targets, resulting in them having to search for the targets, which resulted in not so clear and comparable trajectories, which might have influenced the results.

Influence of Limited FoV on Further Aspects of User Behaviour and Experience

Furthermore, the findings outlined in Section 3.7 could potentially be of interest to further examine the feeling of presence in VR and what role the restricted FoV might play in it. Also the influence of limited FoV on other aspects of User Behaviour and Experience in VR could be pursued in future research.

A

Appendix

A.1 Individual User Head and Eye Movement Trajectories

In the following figures, the head movement trajectories for Phase 1 of the movement order (B5-B6-B9-B8-B5-B4-B1-B2-B5) are visualised for RB, LR and VR on the left, while on the right the head and eye trajectories in the VR test condition are shown.

User 1:

Figure A.1: *Head trajectories of user 1*

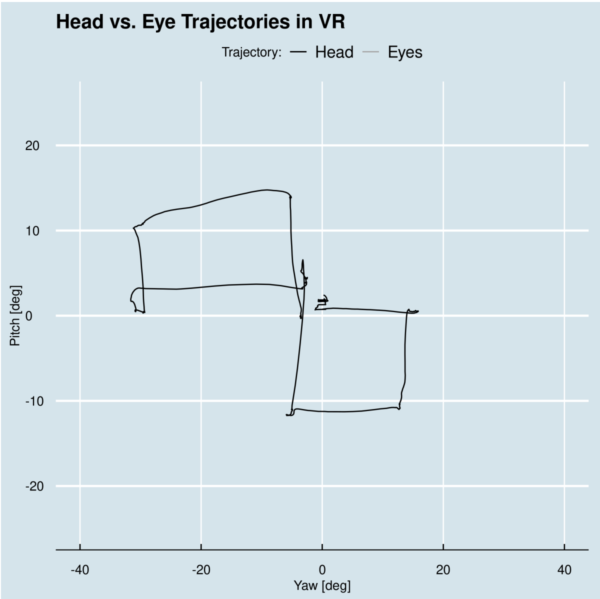


Figure A.2: *Eye and head trajectories in VR of user 1*

The eye trajectories for the VR test condition were unfortunately scrambled to such an extent that they could not be reconstructed.

User 2:

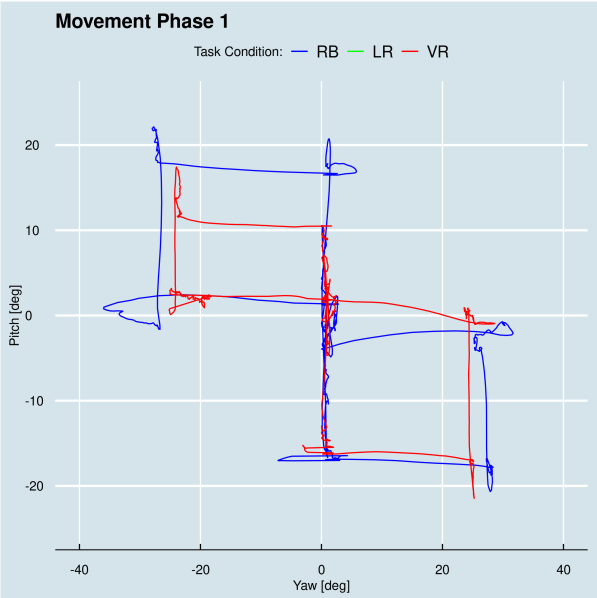


Figure A.3: *Head trajectories of user 2*

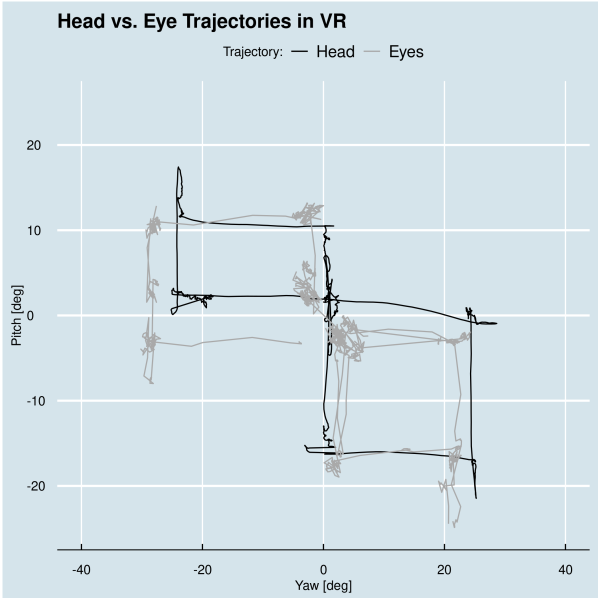


Figure A.4: *Eye and head trajectories in VR of user 2*

The head trajectories for the LR test condition were unfortunately scrambled to such an extent that they could not be reconstructed.

User 3:

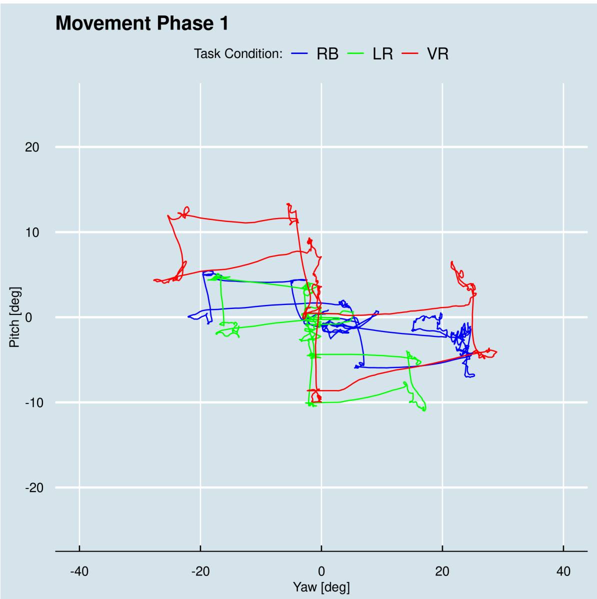


Figure A.5: *Head trajectories of user 3*

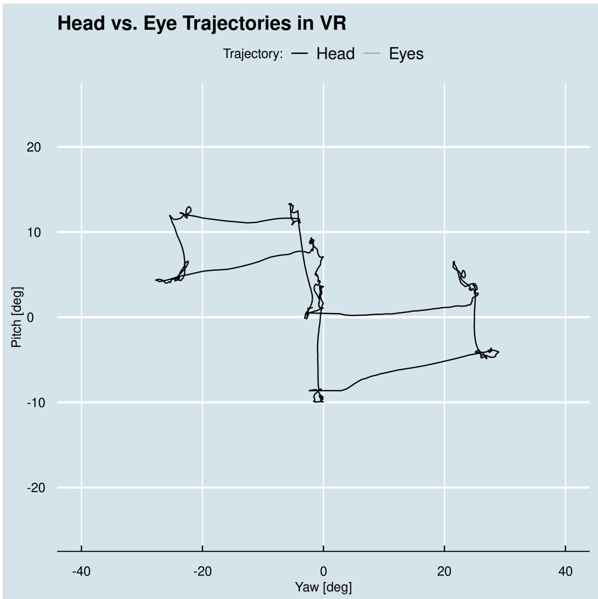


Figure A.6: *Eye and head trajectories in VR of user 3*

The eye trajectories for the VR test condition were unfortunately scrambled to such an extent that they could not be reconstructed.

User 4:

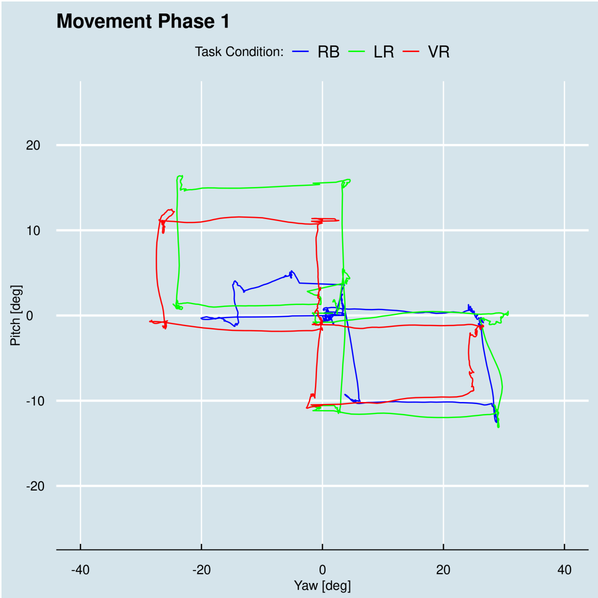


Figure A.7: Head trajectories of user 4

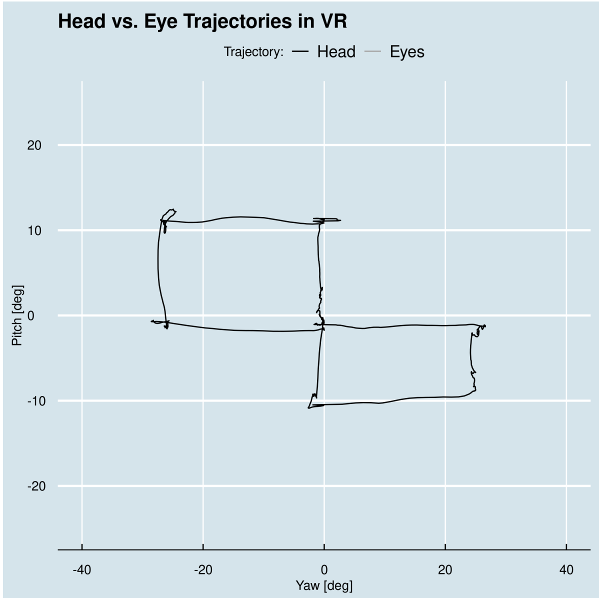


Figure A.8: Eye and head trajectories in VR of user 4

The eye trajectories for the VR test condition were unfortunately scrambled to such an extent that they could not be reconstructed.

User 5:

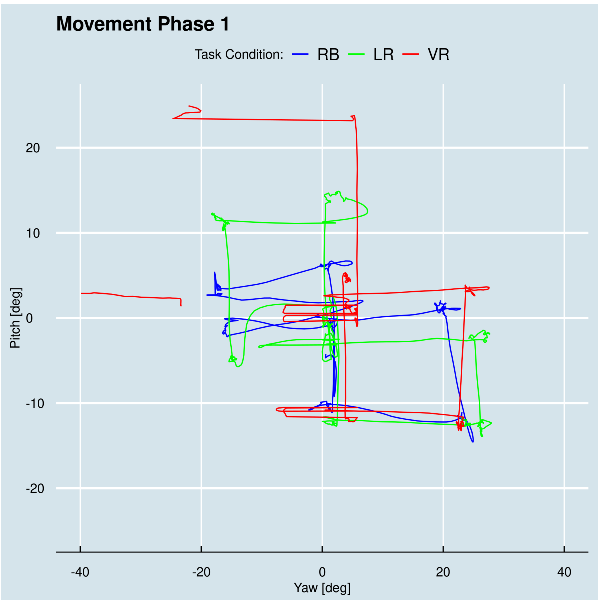


Figure A.9: Head trajectories of user 5

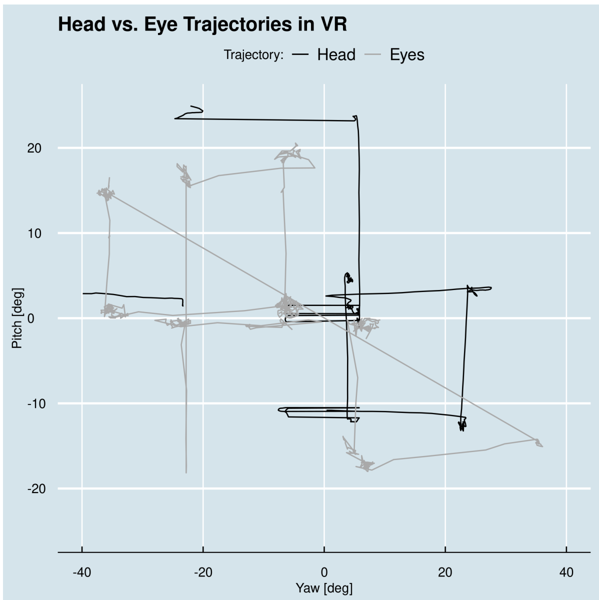


Figure A.10: Eye and head trajectories in VR of user 5

User 6:

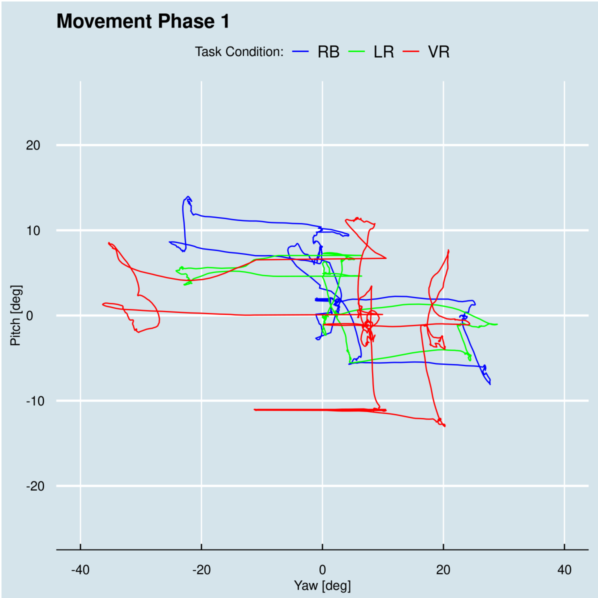


Figure A.11: Head trajectories of user 6

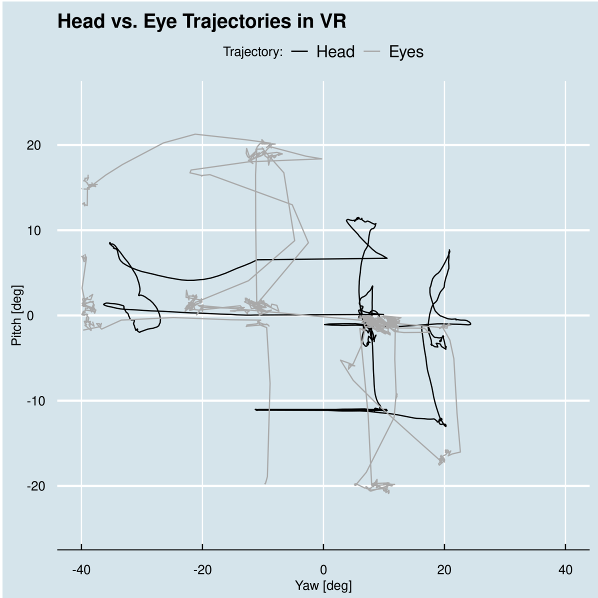


Figure A.12: Eye and head trajectories in VR of user 6

User 7:

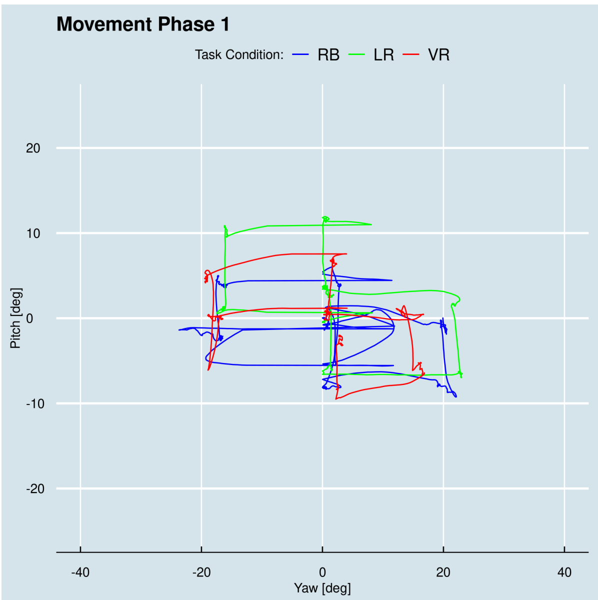


Figure A.13: Head trajectories of user 7

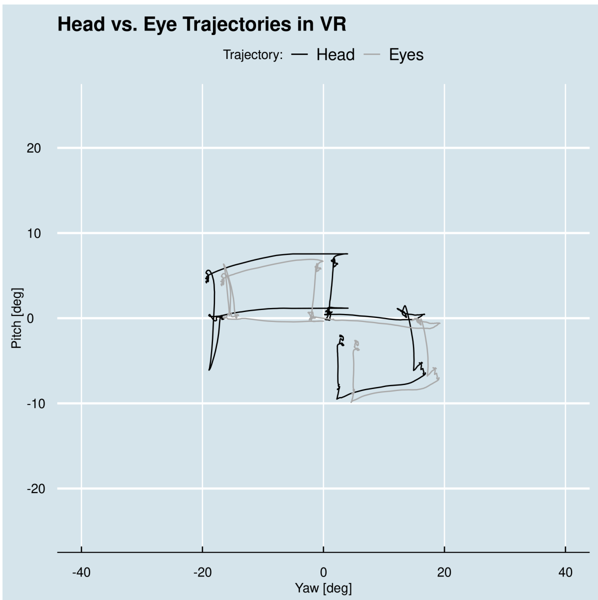


Figure A.14: Eye and head trajectories in VR of user 7

User 8:

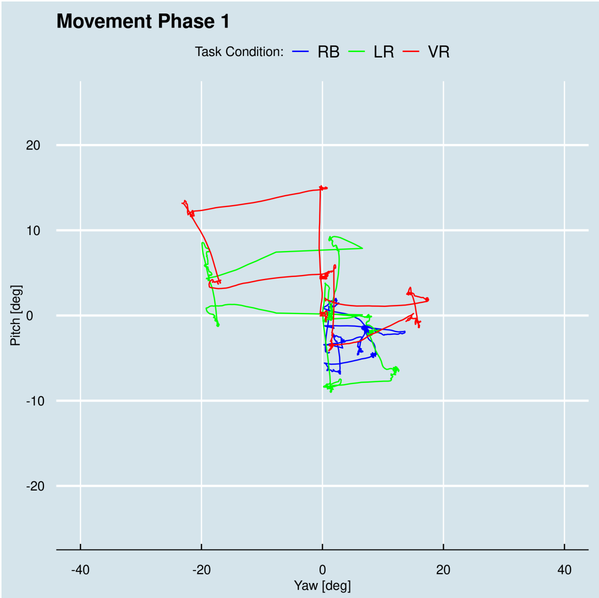


Figure A.15: *Head trajectories of user 8*

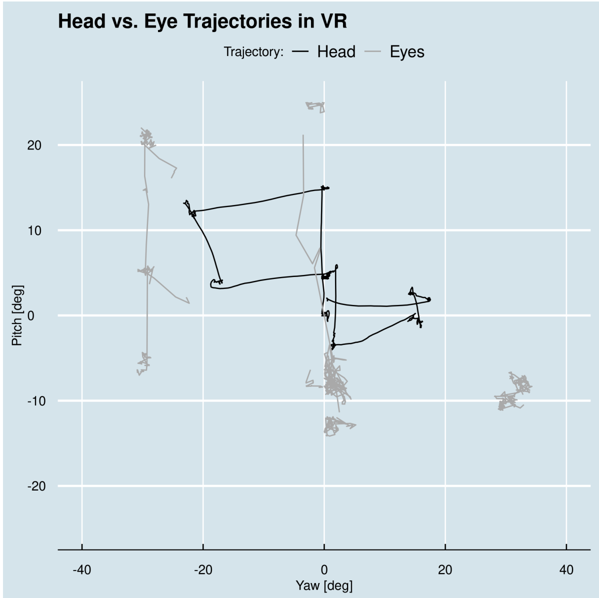


Figure A.16: *Eye and head trajectories in VR of user 8*

User 9:

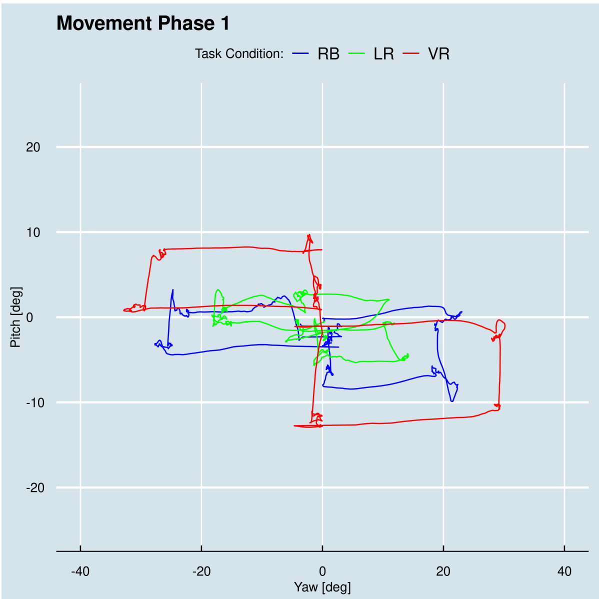


Figure A.17: *Head trajectories of user 9*

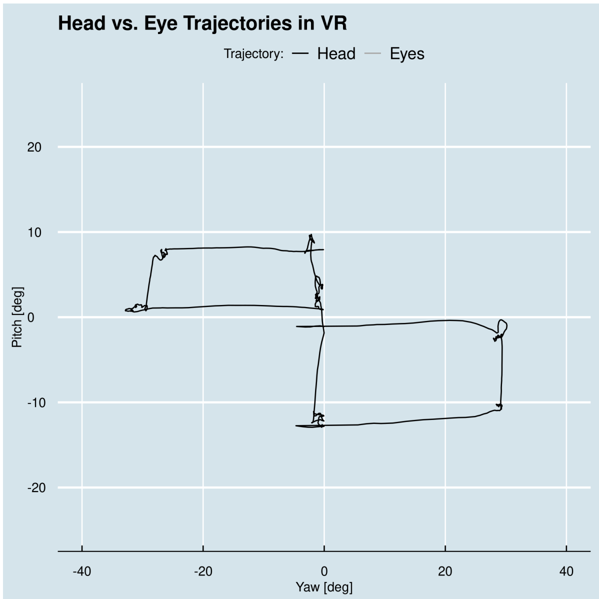


Figure A.18: *Eye and head trajectories in VR of user 9*

The eye trajectories for the VR test condition were unfortunately scrambled to such an extent that they could not be reconstructed.

User 10:

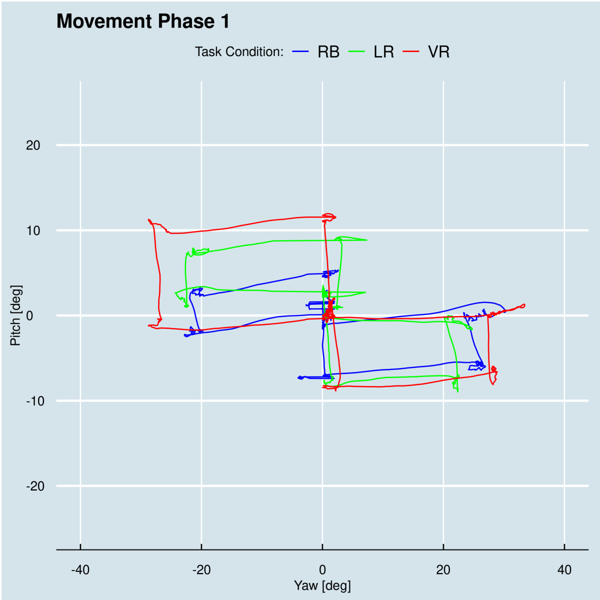


Figure A.19: *Head trajectories of user 10*

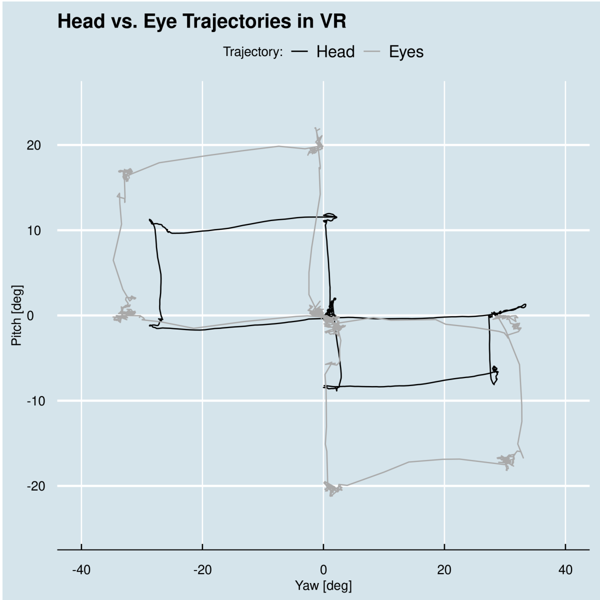


Figure A.20: *Eye and head trajectories in VR of user 10*

User 11:

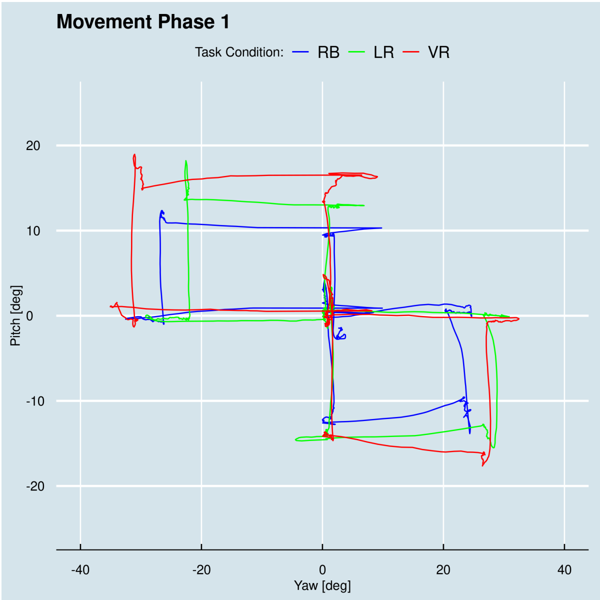


Figure A.21: *Head trajectories of user 11*

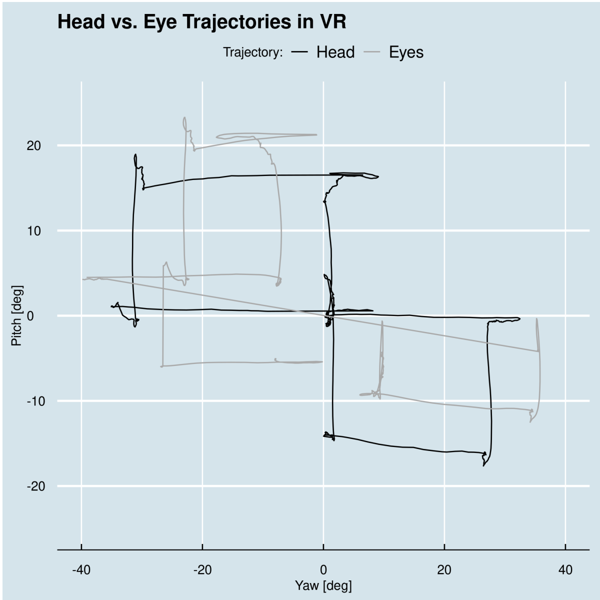


Figure A.22: *Eye and head trajectories in VR of user 11*

User 12:

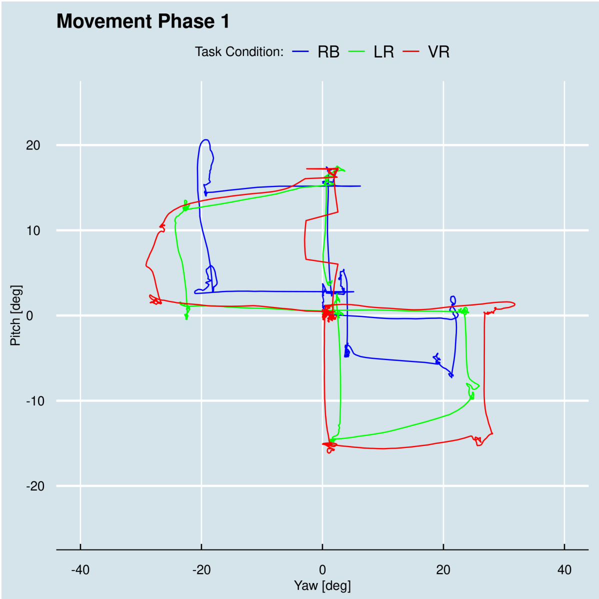


Figure A.23: *Head trajectories of user 12*

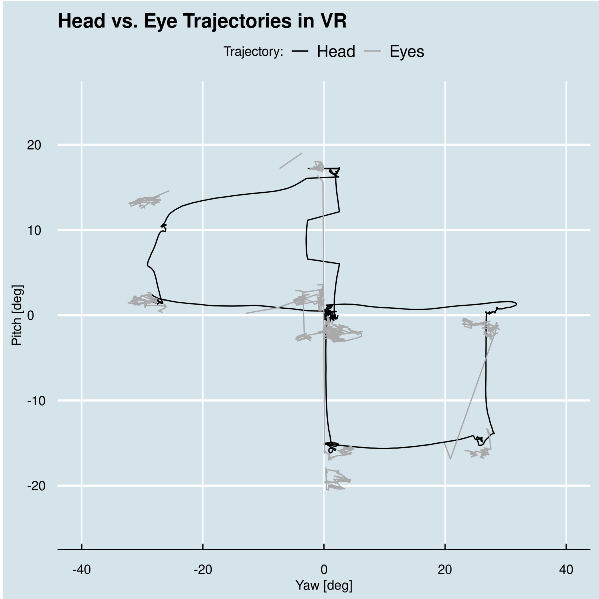


Figure A.24: *Eye and head trajectories in VR of user 12*

User 13:

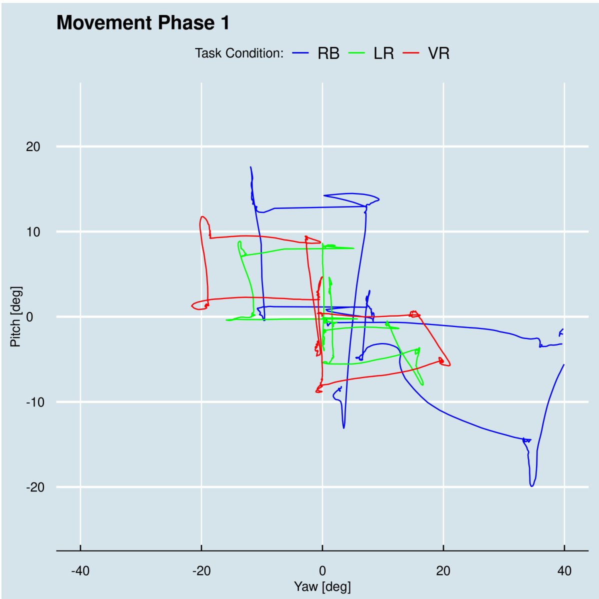


Figure A.25: *Head trajectories of user 13*

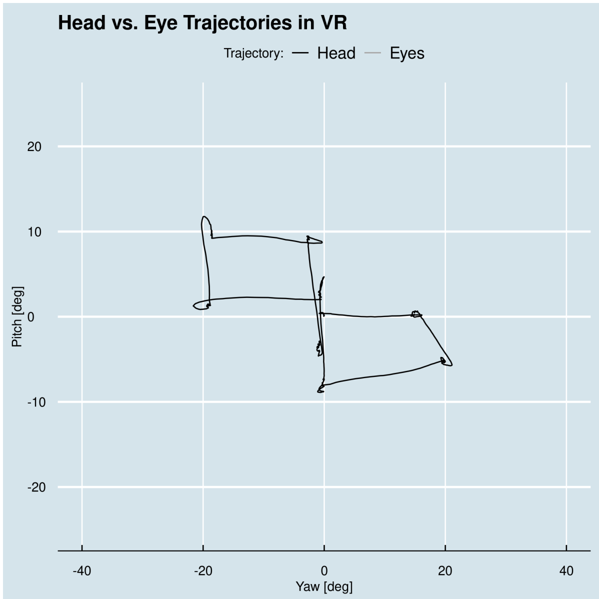


Figure A.26: *Eye and head trajectories in VR of user 13*

The eye trajectories for the VR test condition were unfortunately scrambled to such an extent that they could not be reconstructed.

User 14:

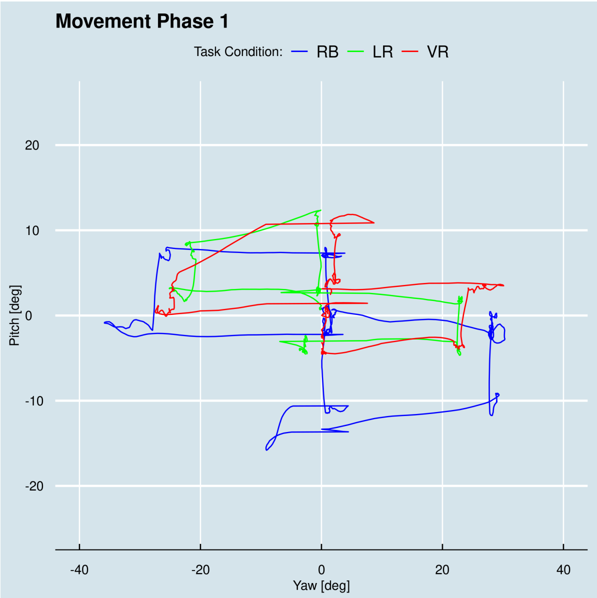


Figure A.27: *Head trajectories of user 14*

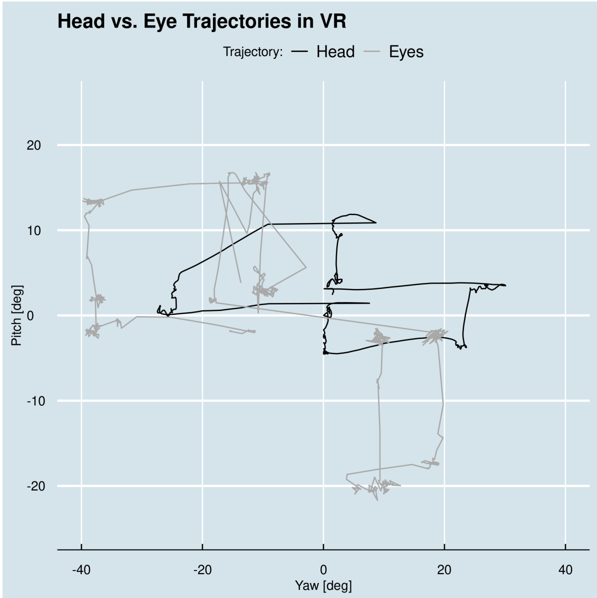


Figure A.28: *Eye and head trajectories in VR of user 14*

User 15:

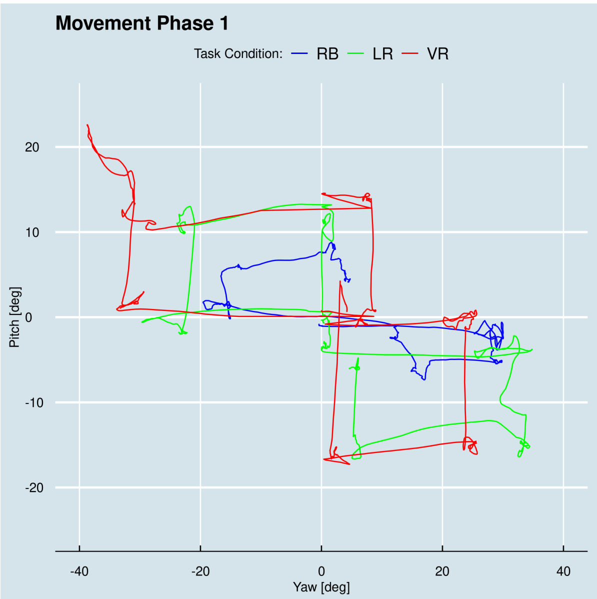


Figure A.29: *Head trajectories of user 15*

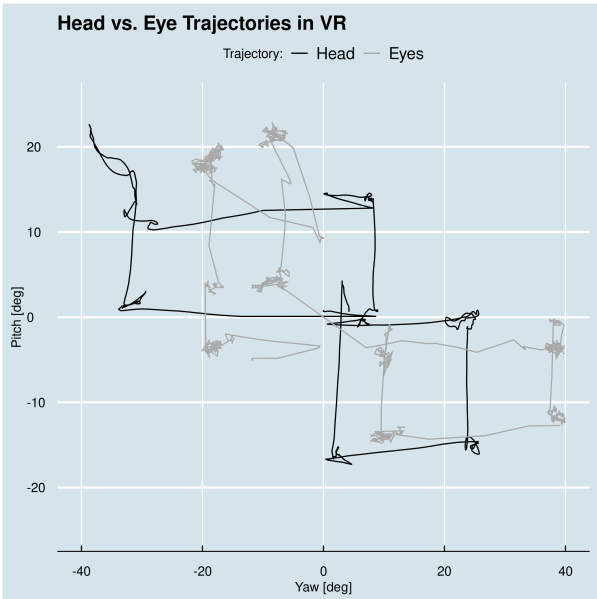


Figure A.30: *Eye and head trajectories in VR of user 15*

User 16:

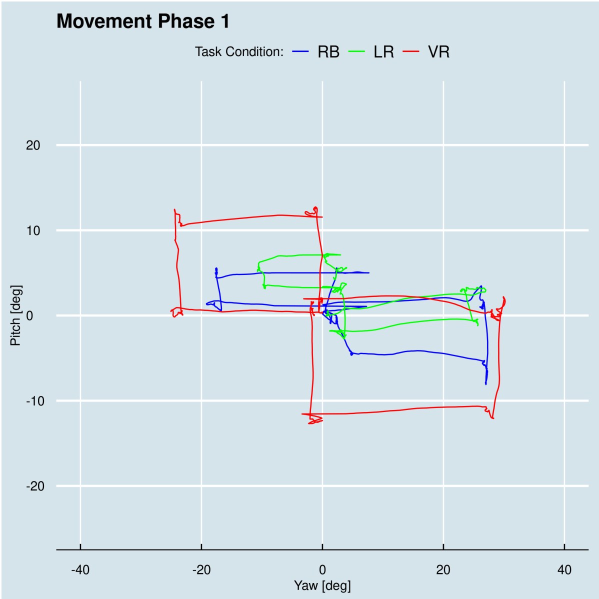


Figure A.31: *Head trajectories of user 16*

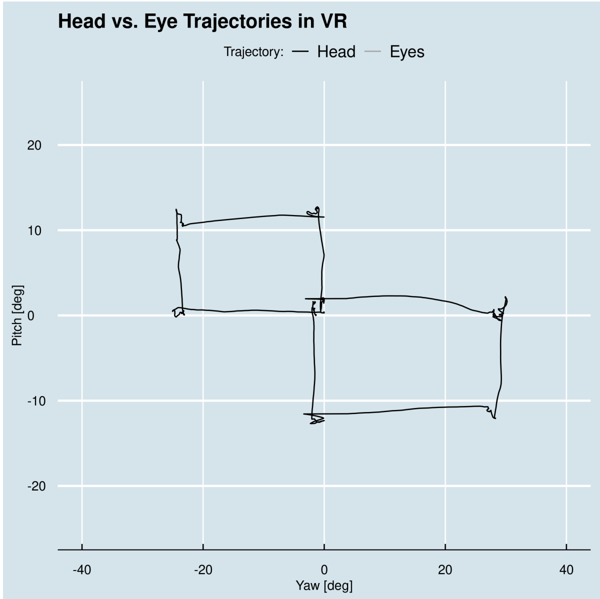


Figure A.32: *Eye and head trajectories in VR of user 16*

The eye trajectories for the VR test condition were unfortunately scrambled to such an extent that they could not be reconstructed.

User 17:

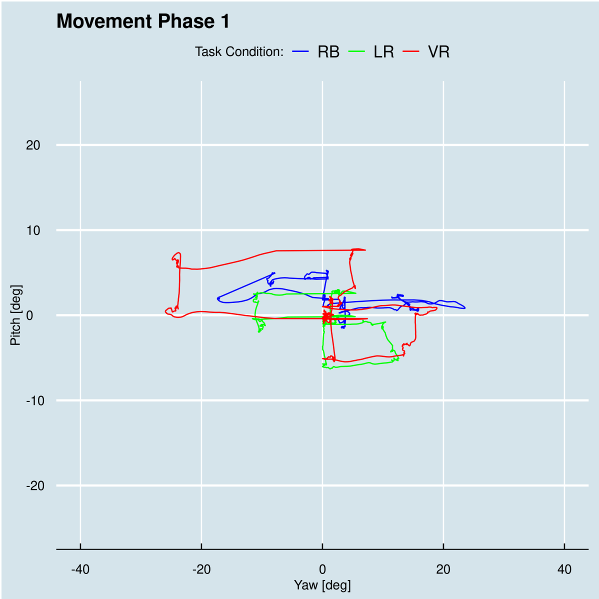


Figure A.33: *Head trajectories of user 17*

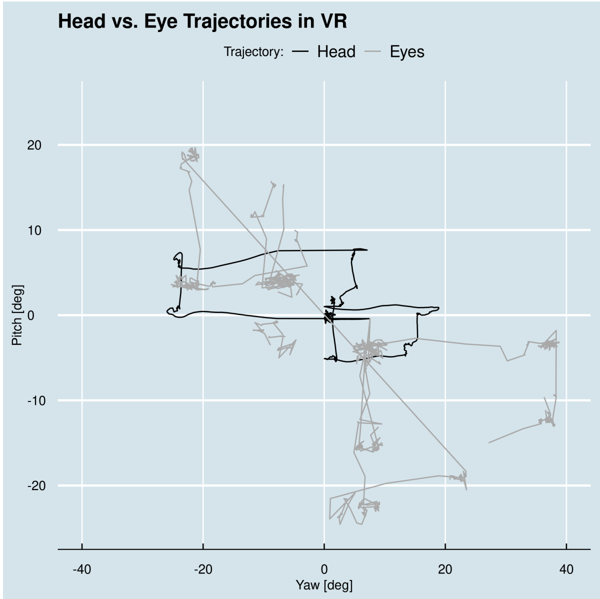


Figure A.34: *Eye and head trajectories in VR of user 17*

User 18:

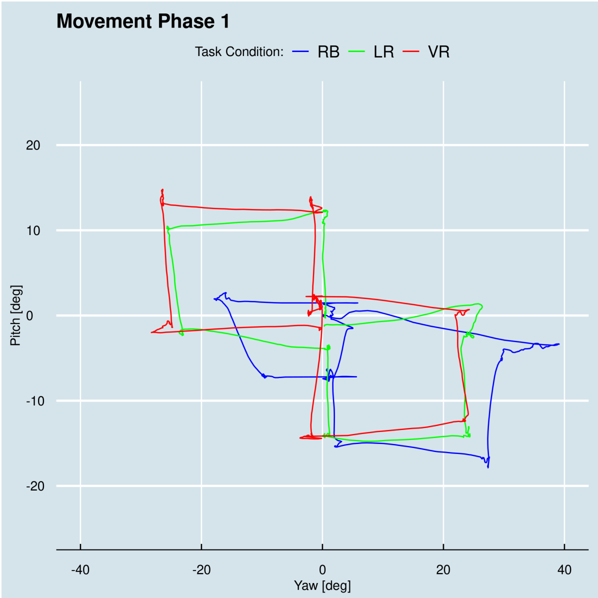


Figure A.35: Head trajectories of user 18

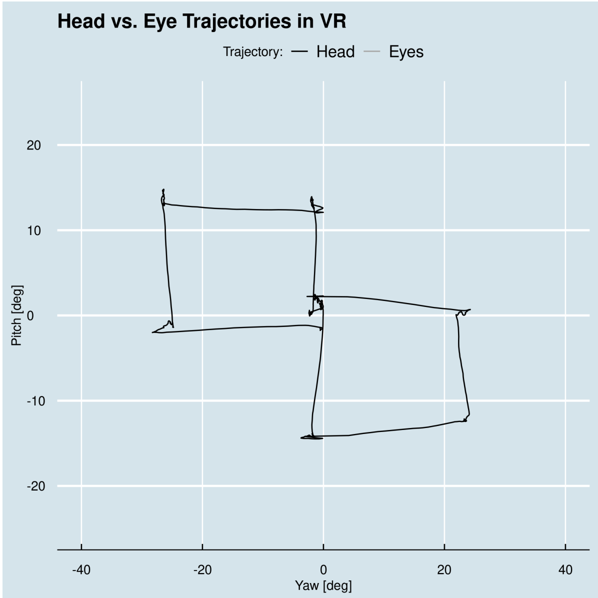


Figure A.36: Eye and head trajectories in VR of user 18

The eye trajectories for the VR test condition were unfortunately scrambled to such an extent that they could not be reconstructed.

User 19:

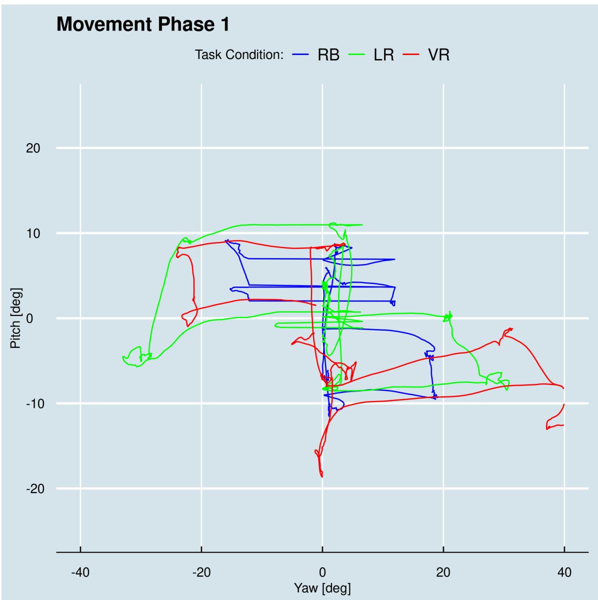


Figure A.37: Head trajectories of user 19

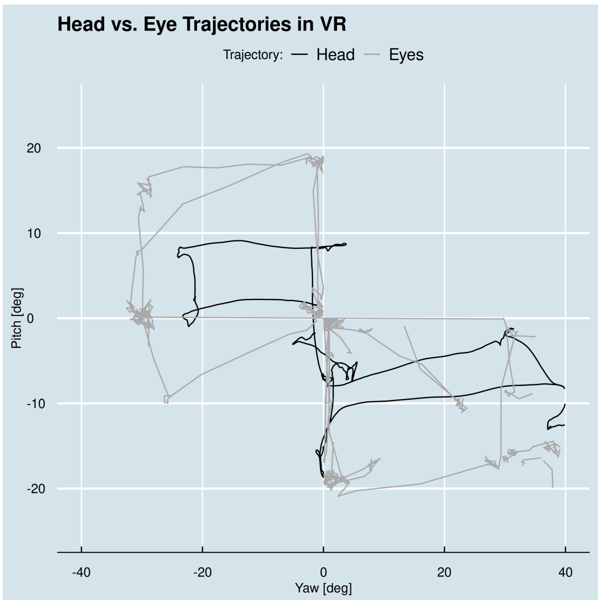
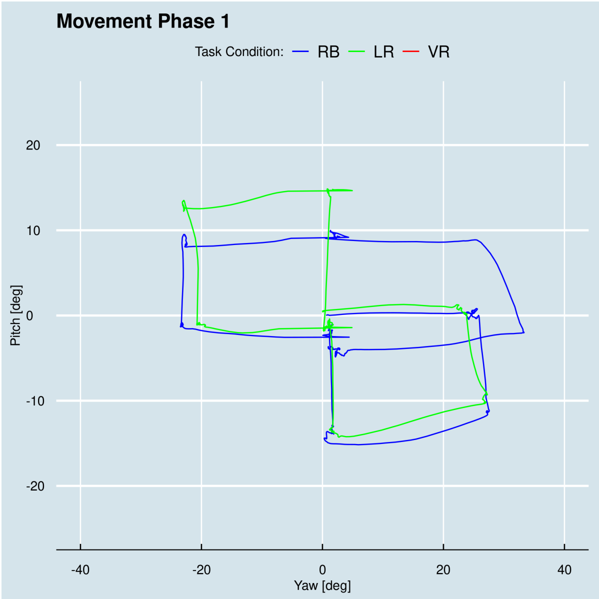


Figure A.38: Eye and head trajectories in VR of user 19

User 20:



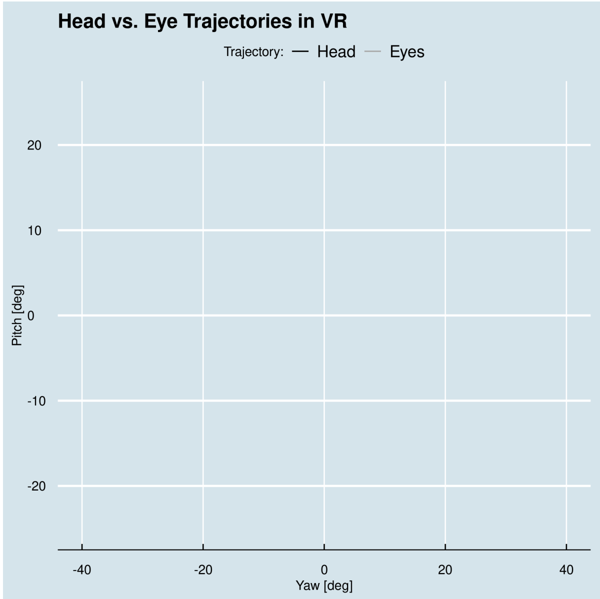
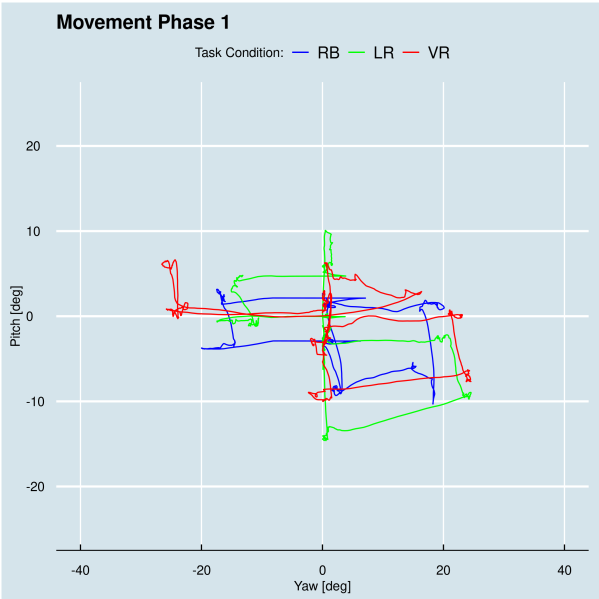


Figure A.39: *Head trajectories of user 20*

Figure A.40: *Eye and head trajectories in VR of user 20*

The head and eye trajectories for the VR test condition were unfortunately scrambled to such an extent that they could not be reconstructed.

User 21:



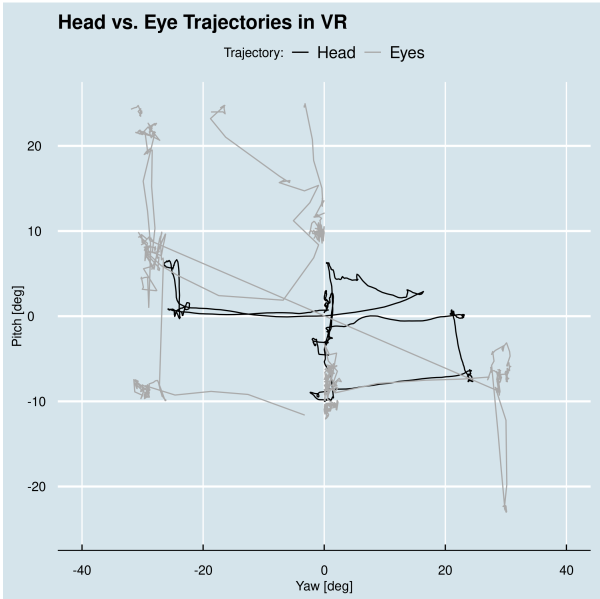


Figure A.41: *Head trajectories of user 21*

Figure A.42: *Eye and head trajectories in VR of user 21*

User 22:

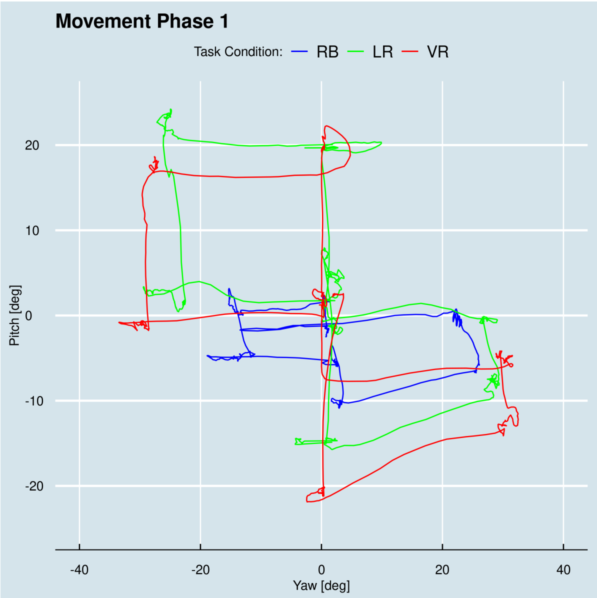


Figure A.43: *Head trajectories of user 22*

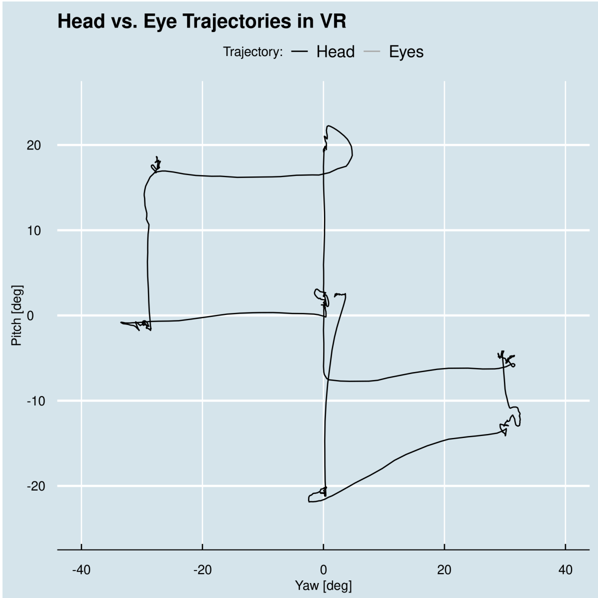


Figure A.44: *Eye and head trajectories in VR of user 22*

The eye trajectories for the VR test condition were unfortunately scrambled to such an extent that they could not be reconstructed.

User 23:

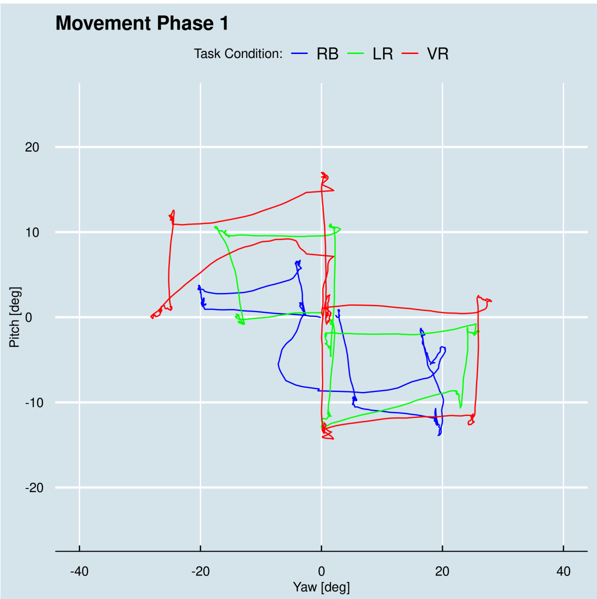


Figure A.45: *Head trajectories of user 23*

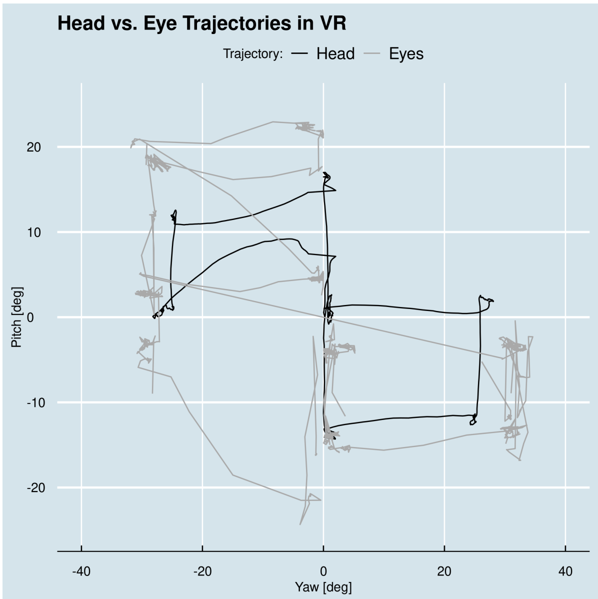


Figure A.46: *Eye and head trajectories in VR of user 23*

User 24:

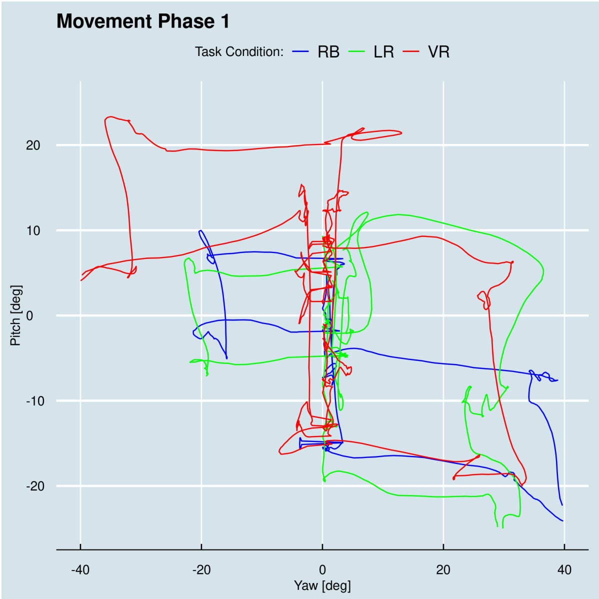


Figure A.47: Head trajectories of user 24

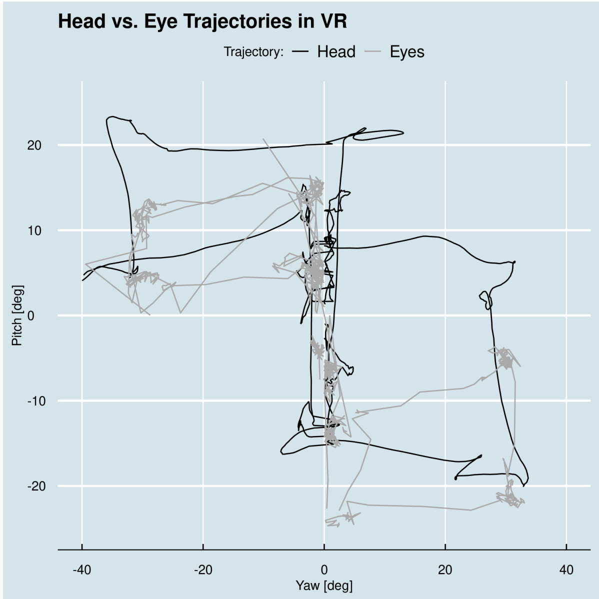


Figure A.48: Eye and head trajectories in VR of user 24

User 25:

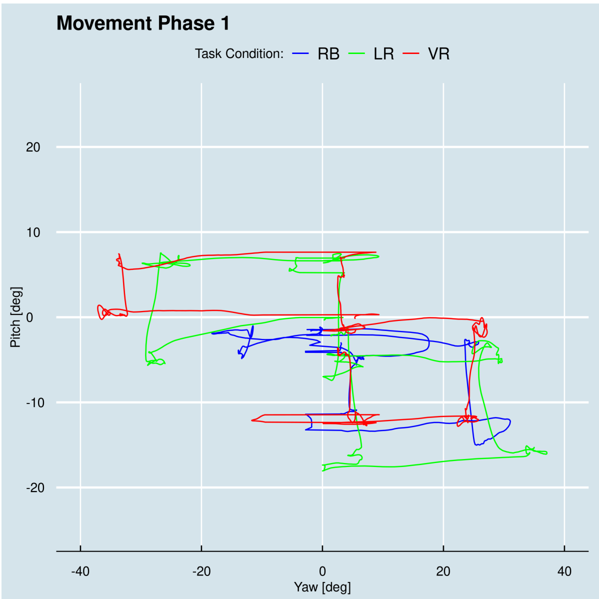


Figure A.49: Head trajectories of user 25

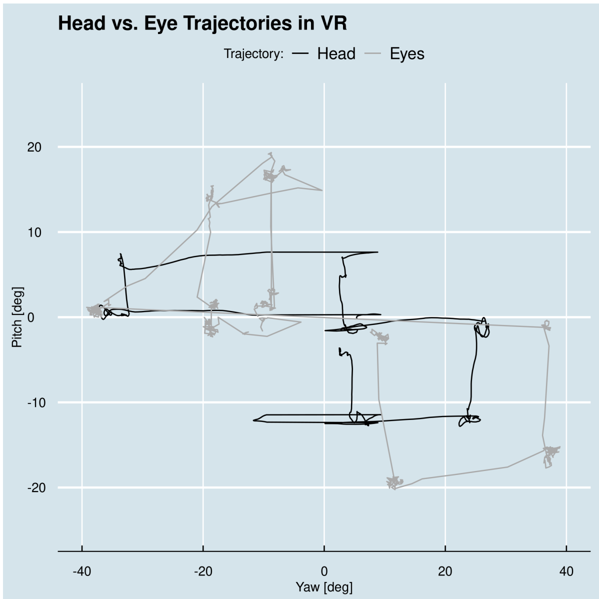


Figure A.50: Eye and head trajectories in VR of user 25

User 26:

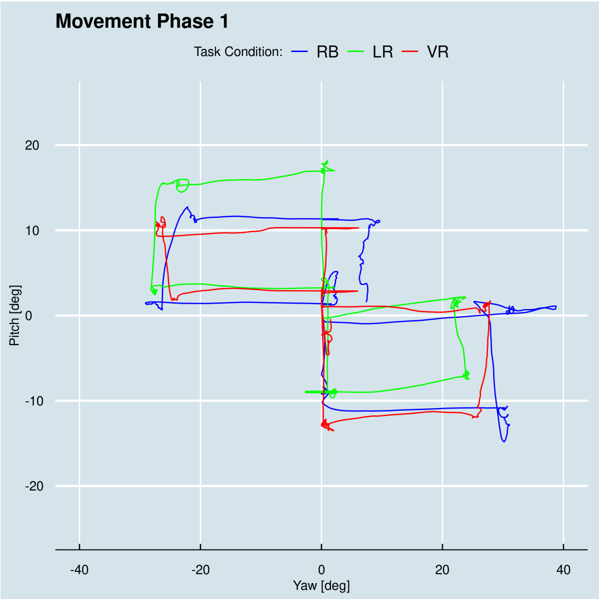


Figure A.51: *Head trajectories of user 26*

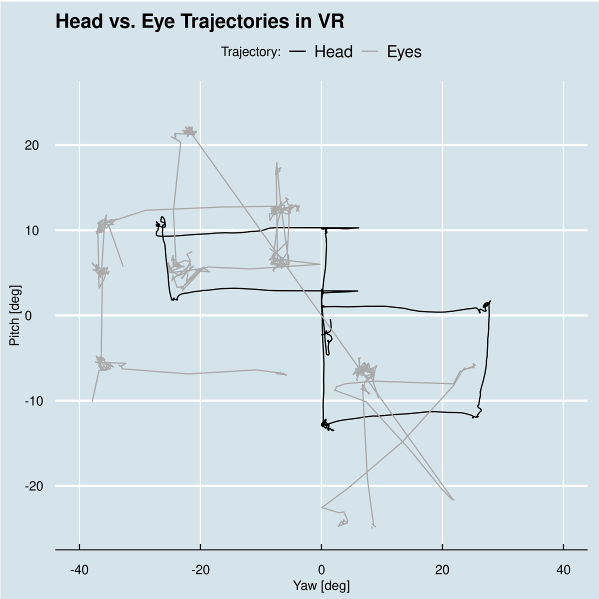


Figure A.52: *Eye and head trajectories in VR of user 26*

User 27:

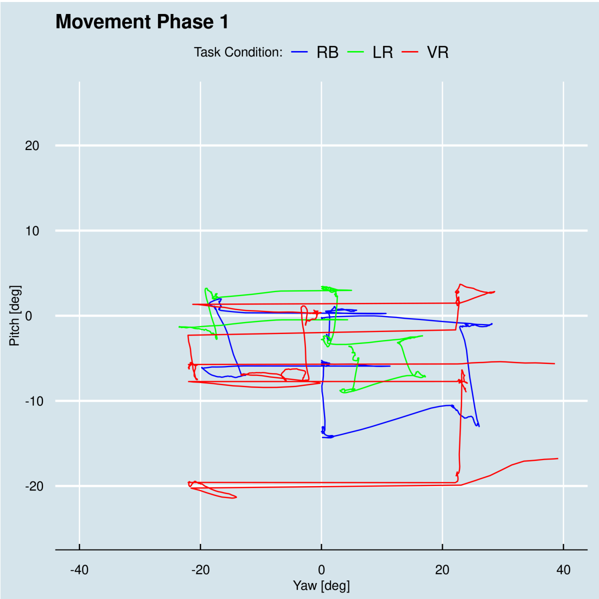


Figure A.53: *Head trajectories of user 27*

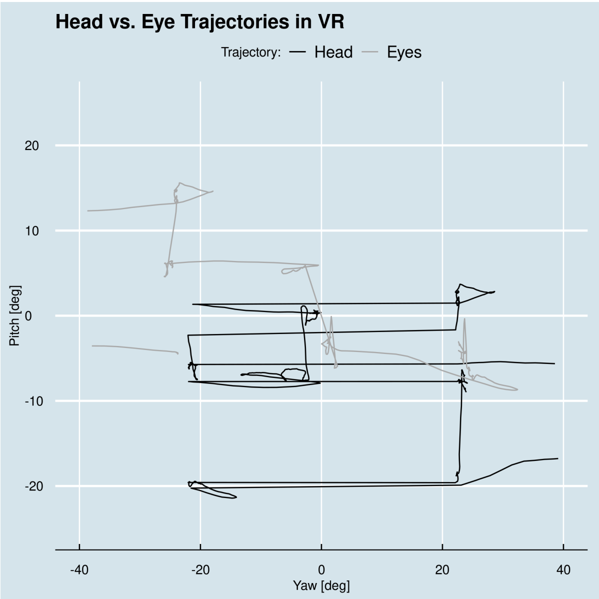


Figure A.54: *Eye and head trajectories in VR of user 27*

User 28:

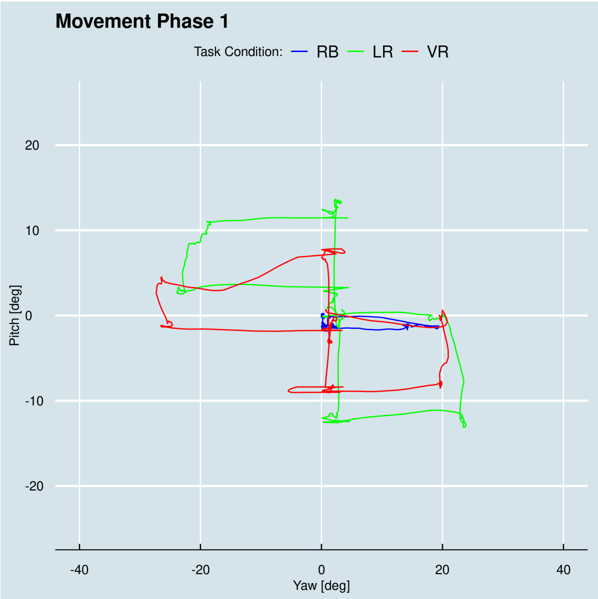


Figure A.55: *Head trajectories of user 28*

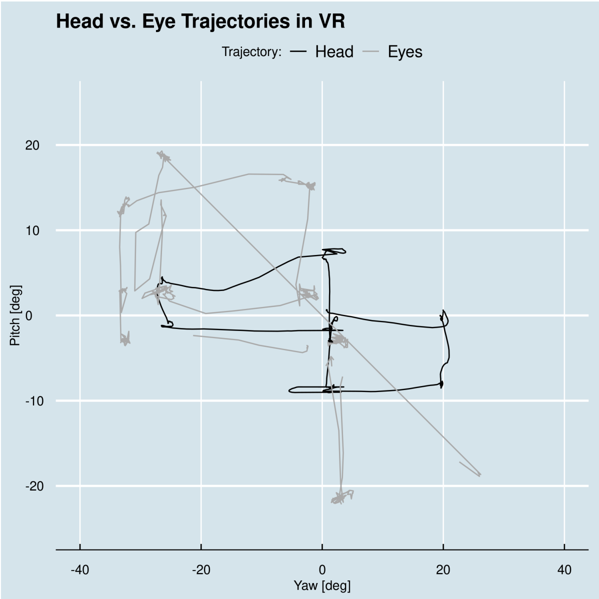


Figure A.56: *Eye and head trajectories in VR of user 28*

User 29:

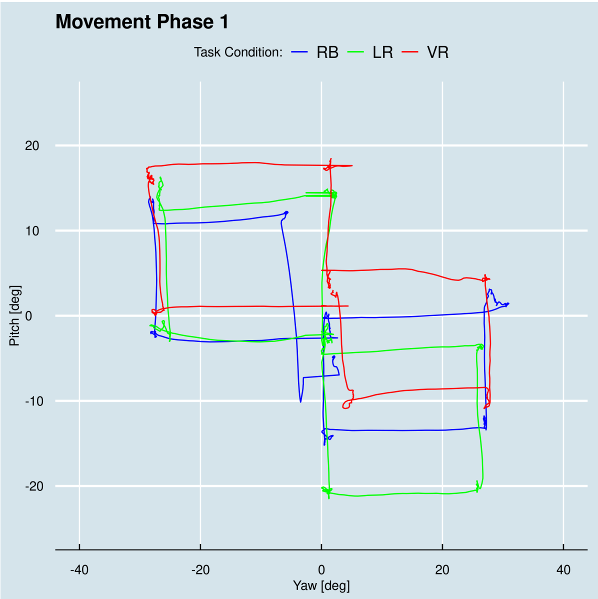


Figure A.57: *Head trajectories of user 29*

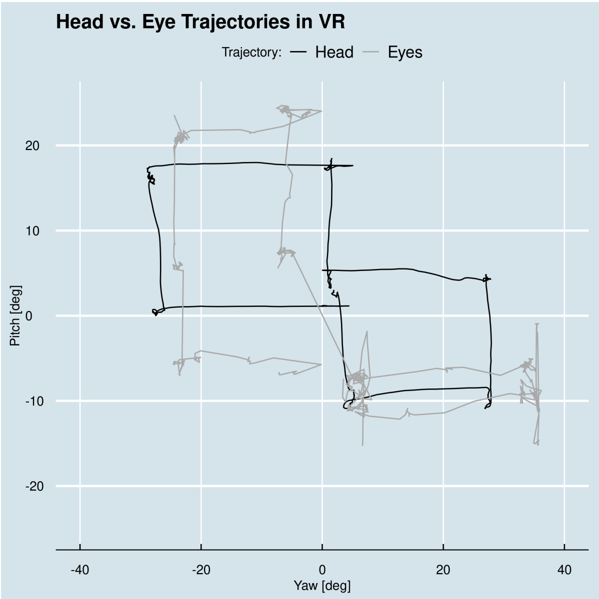


Figure A.58: *Eye and head trajectories in VR of user 29*

User 30:

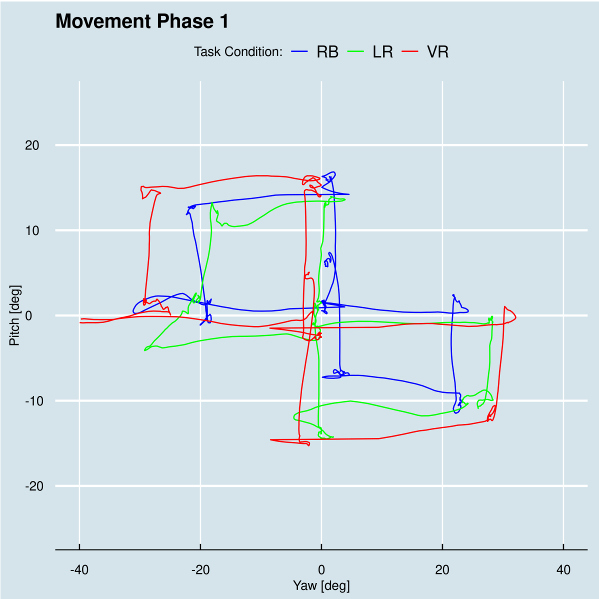


Figure A.59: *Head trajectories of user 30*

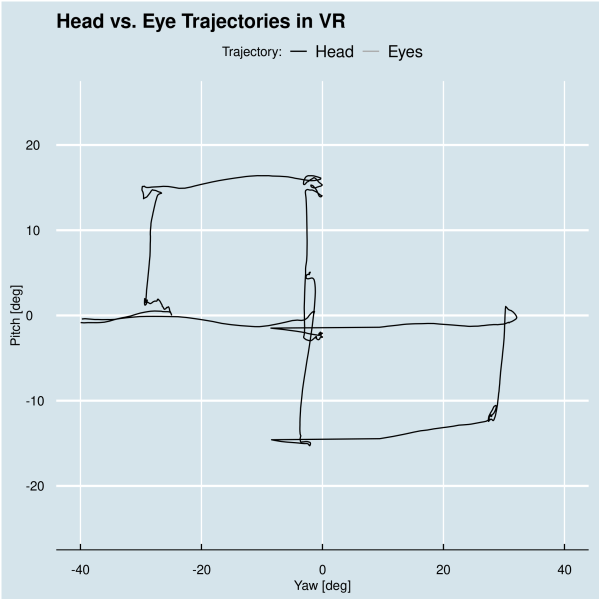


Figure A.60: *Eye and head trajectories in VR of user 30*

The eye trajectories for the VR test condition were unfortunately scrambled to such an extent that they could not be reconstructed.

User 31:

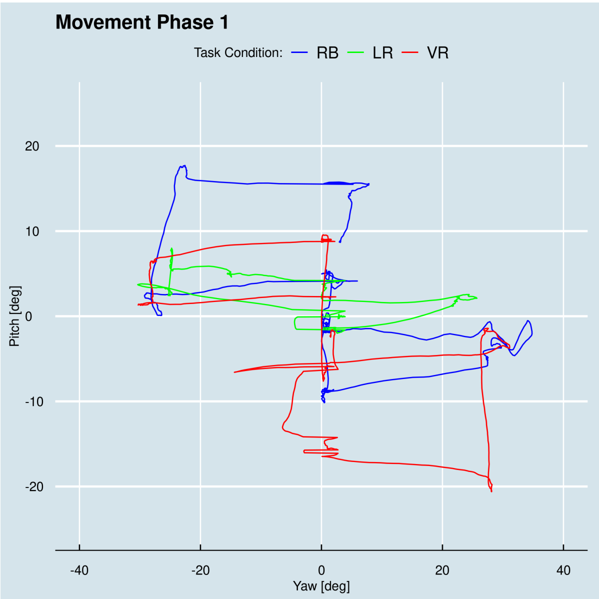


Figure A.61: *Head trajectories of user 31*

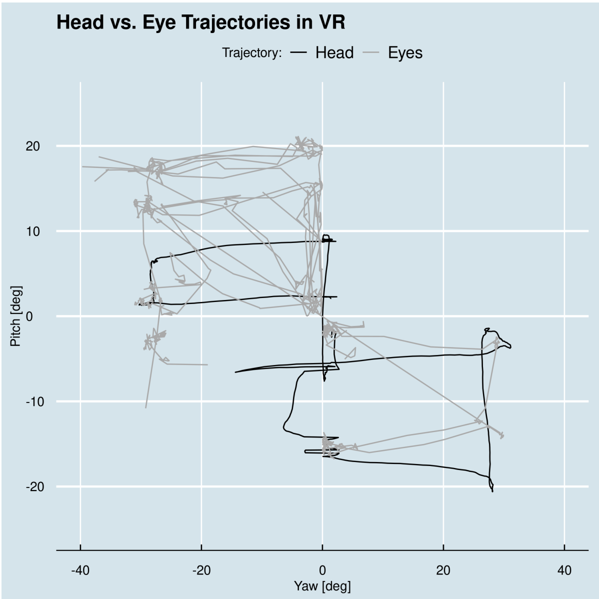


Figure A.62: *Eye and head trajectories in VR of user 31*

A.2 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 public GitHub repository:

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

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Bibliography

[1] N. Kishishita, K. Kiyokawa, J. Orlosky, T. Mashita, H. Takemura, and E. Kruijff, "Analysing the effects of a wide field of view augmented reality display on search performance in divided attention tasks," in *2014 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, Sep. 2014, pp. 177–186.

[2] I. Staretu, "From using virtual reality in the training process to virtual engineering," *Global Journal of Computer Sciences*, Jan. 2014. [Online]. Available: https://www.academia.edu/42661071/From_using_virtual_reality_in_the_training_process_to_virtual_engineering (Accessed 2023-01-22).

[3] F. A. Felipe, F. O. de Carvalho, E. R. Silva, N. G. L. Santos, P. A. Fontes, A. S. de Almeida, D. C. Garçao, P. S. Nunes, and A. A. de Souza Araújo, "Evaluation instruments for physical therapy using virtual reality in stroke patients: a systematic review," *Physiotherapy*, vol. 106, pp. 194–210, Mar. 2020. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0031940619300744 (Accessed 2023-01-21).

[4] M. Huri, *Occupational Therapy: Occupation Focused Holistic Practice in Rehabilitation*. BoD – Books on Demand, Jul. 2017, google-Books-ID: J22PDwAAQBAJ.

[5] M. Zyda, "From visual simulation to virtual reality to games," *Computer*, vol. 38, no. 9, pp. 25–32, Sep. 2005.

[6] K. Wolf, M. Funk, R. Khalil, and P. Knierim, "Using virtual reality for prototyping interactive architecture," in *Proceedings of the 16th International Conference on Mobile and Ubiquitous Multimedia*, ser. MUM '17. New York, NY, USA: Association for Computing Machinery, Nov. 2017, pp. 457–464. [Online]. Available: https://doi.org/10.1145/3152832.3156625 (Accessed 2023-01-22).

[7] D. Wang, Y. Guo, S. Liu, Y. Zhang, W. Xu, and J. Xiao, "Haptic display for virtual reality: Progress and challenges," *Virtual Reality & Intelligent Hardware*, vol. 1, no. 2, pp. 136–162, Apr. 2019, https://www.sciencedirect.com/science/article/pii/S2096579619300130.

[8] M. Lee, S. A. Lee, M. Jeong, and H. Oh, “Quality of virtual reality and its impacts on behavioral intention,” *International Journal of Hospitality Management*, vol. 90, p. 102595, Sep. 2020. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S027843192030147X (Accessed 2023-01-22).

[9] D. J. Harris, G. Buckingham, M. R. Wilson, J. Brookes, F. Mushtaq, M. Mon-Williams, and S. J. Vine, “The effect of a virtual reality environment on gaze behaviour and motor skill learning,” *Psychology of Sport and Exercise*, vol. 50, p. 101721, Sep. 2020. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1469029220300947 (Accessed 2023-01-22).

[10] M. Minderer, C. D. Harvey, F. Donato, and E. I. Moser, “Virtual reality explored,” *Nature*, vol. 533, no. 7603, pp. 324–325, May 2016, number: 7603 Publisher: Nature Publishing Group. [Online]. Available: https://www.nature.com/articles/nature17899 (Accessed 2023-01-22).

[11] S. Riches, S. Elghany, P. Garety, M. Rus-Calafell, and L. Valmaggia, “Factors Affecting Sense of Presence in a Virtual Reality Social Environment: A Qualitative Study,” *Cyberpsychology, Behavior and Social Networking*, vol. 22, no. 4, pp. 288–292, Apr. 2019.

[12] D. A. Bowman and R. P. McMahan, “Virtual Reality: How Much Immersion Is Enough?” *Computer*, vol. 40, no. 7, pp. 36–43, Jul. 2007.

[13] T. Rose, C. S. Nam, and K. B. Chen, “Immersion of virtual reality for rehabilitation - Review,” *Applied Ergonomics*, vol. 69, pp. 153–161, May 2018. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0003687018300176 (Accessed 2023-01-22).

[14] M. van Gisbergen, M. Kovacs, F. Campos, M. van der Heeft, and V. Vugts, “What We Don’t Know. The Effect of Realism in Virtual Reality on Experience and Behaviour,” in *Augmented Reality and Virtual Reality: The Power of AR and VR for Business*, ser. Progress in IS, M. C. tom Dieck and T. Jung, Eds. Cham: Springer International Publishing, 2019, pp. 45–57. [Online]. Available: https://doi.org/10.1007/978-3-030-06246-0_4 (Accessed 2023-01-22).

[15] S. H. Nguyen, Q. Sun, and D. Williams, “How do we make the virtual world a better place? Social discrimination in online gaming, sense of community, and well-being,” *Telematics and Informatics*, vol. 66, p. 101747, Jan. 2022. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0736585321001866 (Accessed 2023-01-22).

[16] H. M. Traquair, *An Introduction to Clinical Perimetry*. Henry Kimpton, 1938, google-Books-ID: TTRKAAAAMAAJ.

[17] “VRcompare.” [Online]. Available: https://vr-compare.com/compare?h1=mLbW9G7f4&h2=gc__iL-JZfK (Accessed 2023-01-21).

[18] A. Toet, S. E. M. Jansen, and N. J. Delleman, “Effects of field-of-view restrictions on speed and accuracy of manoeuvring,” *Perceptual and Motor Skills*, vol. 105, no. 3 Pt 2, pp. 1245–1256, Dec. 2007.

[19] S. E. M. Jansen, A. Toet, and P. J. Werkhoven, “Human locomotion through a multiple obstacle environment: strategy changes as a result of visual field limitation,” *Experimental Brain Research*, vol. 212, no. 3, pp. 449–456, Jul. 2011.

[20] A. Toet, M. Kahrimanović, and N. J. Delleman, “Locomotion through a complex environment with limited field-of-view,” *Perceptual and Motor Skills*, vol. 107, no. 3, pp. 811–826, Dec. 2008.

[21] A. Toet, S. E. M. Jansen, and N. J. Delleman, “Effects of field-of-view restriction on manoeuvring in a 3-D environment,” *Ergonomics*, vol. 51, no. 3, pp. 385–394, Mar. 2008.

[22] S. E. M. Jansen, A. Toet, and P. J. Werkhoven, “Obstacle crossing with lower visual field restriction: shifts in strategy,” *Journal of Motor Behavior*, vol. 43, no. 1, pp. 55–62, 2011.

[23] E. D. Ragan, D. A. Bowman, R. Kopper, C. Stinson, S. Scerbo, and R. P. McMahan, “Effects of Field of View and Visual Complexity on Virtual Reality Training Effectiveness for a Visual Scanning Task,” *IEEE transactions on visualization and computer graphics*, vol. 21, no. 7, pp. 794–807, Jul. 2015.

[24] K. Grinyer and R. J. Teather, “Effects of Field of View on Dynamic Out-of-View Target Search in Virtual Reality,” in *2022 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, Mar. 2022, pp. 139–148, iSSN: 2642-5254.

[25] N. F. Polys, S. Kim, and D. A. Bowman, “Effects of information layout, screen size, and field of view on user performance in information-rich virtual environments,” *Computer Animation and Virtual Worlds*, vol. 18, no. 1, pp. 19–38, 2007, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/cav.159. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/cav.159 (Accessed 2022-11-01).

[26] F. van den Oever, V. Gorobets, B. Sætrevik, M. Fjeld, and A. Kunz, “Comparing Visual Search between Physical Environments and VR,” 2022.

[27] I. B. Adhanom, N. Navarro Griffin, P. MacNeilage, and E. Folmer, “The Effect of a Foveated Field-of-view Restrictor on VR Sickness,” in *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, Mar. 2020, pp. 645–652, iSSN: 2642-5254.

[28] A. Viau, A. G. Feldman, B. J. McFadyen, and M. F. Levin, “Reaching in reality and virtual reality: a comparison of movement kinematics in healthy subjects and in adults with hemiparesis,” *Journal of NeuroEngineering and Rehabilitation*, vol. 1, no. 1, p. 11, Dec. 2004. [Online]. Available: https://doi.org/10.1186/1743-0003-1-11 (Accessed 2022-11-20).

[29] G. Cirio, A.-H. Olivier, M. Marchal, and J. Pettré, “Kinematic evaluation of virtual walking trajectories,” *IEEE transactions on visualization and computer graphics*, vol. 19, no. 4, pp. 671–680, Apr. 2013.

[30] S. Arlati, N. Keijsers, G. Paolini, G. Ferrigno, and M. Sacco, “Kinematics of aimed movements in ecological immersive virtual reality: a comparative study with real world,” *Virtual Reality*, vol. 26, no. 3, pp. 885–901, Sep. 2022. [Online]. Available: https://doi.org/10.1007/s10055-021-00603-5 (Accessed 2022-11-20).

[31] “Steamvr base Stations,” https://www.valvesoftware.com/en/index/base-stations, (Accessed 2023-02-25).

[32] “SteamVR Base Station 2.0,” https://www.vive.com/us/support/vive-pro/category_howto/about-the-base-stations.html, (Accessed 2023-02-25).

[33] “SteamVR - Valve Corporation.” [Online]. Available: https://www.steamvr.com/en/ (Accessed 2023-01-22).

[34] “Tobii Vive Pro Eye.” [Online]. Available: https://www.tobii.com/products/integration/xr-headsets/device-integrations/htc-vive-pro-eye (Accessed 2023-01-22).

[35] “HTC VIVE Pro Eye.” [Online]. Available: https://www.vive.com/us/product/vive-pro-eye/specs/ (Accessed 2023-01-22).

[36] “HTC VIVE Tracker.” [Online]. Available: https://www.vive.com/us/support/wireless-tracker/

category_howto/tracker.html (Accessed 2023-01-22).

[37] U. Technologies, “The world’s leading platform for real-time content creation | Unity Pro.” [Online]. Available: https://store.unity.com/products/unity-pro (Accessed 2023-01-22).

[38] B. Foundation, “Blender.” [Online]. Available: https://www.blender.org/about/ (Accessed 2023-01-22).

[39] “Posit.” [Online]. Available: https://www.posit.co/ (Accessed 2023-01-22).

[40] “GitHub.” [Online]. Available: https://github.com (Accessed 2023-01-22).

[41] “NX for Manufacturing | Siemens Software.” [Online]. Available: https://www.plm.automation.siemens.com/global/en/products/nx/nx-for-manufacturing.html (Accessed 2023-02-21).

[42] R. S. Kennedy, N. E. Lane, K. S. Berbaum, and M. G. Lilienthal, “Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness,” *The International Journal of Aviation Psychology*, vol. 3, no. 3, pp. 203–220, Jul. 1993, publisher: Taylor & Francis _eprint: https://doi.org/10.1207/s15327108ijap0303_3. [Online]. Available: https://doi.org/10.1207/s15327108ijap0303_3 (Accessed 2023-01-28).

[43] D. Harris, M. Wilson, and S. Vine, “Development and validation of a simulation workload measure: the simulation task load index (SIM-TLX),” *Virtual Reality*, vol. 24, no. 4, pp. 557–566, Dec. 2020. [Online]. Available: https://doi.org/10.1007/s10055-019-00422-9 (Accessed 2023-01-28).

[44] “HTC Vive Tracker switches orientation,” https://forum.htc.com/topic/7785-htc-vive-tracker-switches-orientation/, Mar. 2020, (Accessed 2023-02-25).

[45] W. Einhäuser, F. Schumann, S. Bardins, K. Bartl, G. Böning, E. Schneider, and P. König, “Human eye-head co-ordination in natural exploration,” *Network: Computation in Neural Systems*, vol. 18, no. 3, pp. 267–297, Jan. 2007, https://doi.org/10.1080/09548980701671094.