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Curriculum

Innovative Technologies in Diagnostic and Therapy

A Virtual Reality-Based Platform for Powered Wheelchair Training for Individuals with Neuromotor Disabilities

Graduation Thesis in

Neurorobotics and Neurorehabilitation

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List of Abbreviations

- VR — Virtual Reality
- PMP — Powered Mobility Program
- CP — Cerebral Palsy
- WSP — Wheelchair skill program
- PWC — Powered wheelchair.
- W/c — Wheelchair
- PPWST — Pediatric powered wheelchair screening test
- 3PM — Progression of pediatric powered mobility
- FGM — Focus Group Meeting
- UI — User Interface
- AR — Augmented Reality
- VR — Virtual Reality
- CGI — Computer Generated Imagery
- API — Application Programming Interfaces
- CAVE — Cave automatic virtual environment
- XR — Extended Reality
- FOV — Field of View
- HMD — Head Mounted Display
- IPD — Interpupillary Distance
- ILD — Inter-lens distance
- POV — Point of view
- CAT — Centro Regionale Ausili
- NASA-TLX — Nasa Task Load Index
- MSAQ — Motion Sickness assessment questionnaire
- GDQ — Game development questionnaire
- MWL — Mental Workload
- IPQ — iGroup presence questionnaire
- RMSE — Root mean square error.

Abstract

Powered wheelchairs are essential to increase the mobility and independence of individuals with neuromotor disabilities and enable them to live more independently, but unfortunately powered wheelchair training for individuals with neuromotor disabilities has often been limited to their physical presence in a rehabilitation center for extended periods of time to ensure safe driving conditions which may not be possible for everyone due to logistic reasons, availability of these centers everywhere and the excessive cost for the national health system. With the advancements in virtual reality (VR) technology and its widespread availability, it now offers a feasible alternative to traditional training methods. VR technology will ensure that individuals can receive powered wheelchair training from the comfort of their homes in a familiar environment with the help of their caregiver which will cut the amount of time they need to spend at rehabilitation centers drastically. One of the standards used to measure the driving skills of individuals Is the powered mobility program (PMP) which consists of 34 tasks 20 of which are indoor tasks, these tasks are designed to test the proficiency level of individuals when it comes to driving a powered wheelchair. In this project, the focus was on the 20 indoor tasks that were recreated in a virtual environment, named Virtual Reality for Powered Mobility Program (VR-PMP) with the same challenges that wheelchair users face in real life. A preliminary testing phase was conducted with able-bodied participants and young adults with cerebral palsy to evaluate the usability of the system. Performance metrics were collected during the training and used to evaluate individuals' performance to track their progress. Our findings showed that powered wheelchairs are essential for individuals with disabilities to lead an independent life and VR offers more individuals access to new training methods.

***Keywords*-** Virtual Reality, wheelchair training, cerebral palsy, 3D Game applications, Head-Mounted Display.

Chapter 1. Introduction

1.1. Motivation

Cerebral palsy (CP) is the most common neuromotor disability in childhood [1], Recent population-based studies from around the world report prevalence estimates of CP ranging from one to 4 per 1,000 live births or per 1,000 children [2]. Moreover, about 1 in 345 children (3 per 1,000 8-year-old children) in the United States have been identified with CP, according to 2010 estimates from the Center for Disease Control and Prevention (CDC) and Autism and Developmental Disabilities Monitoring Network (ADDM) [3]. In 2010, 58.9% of children with CP could walk independently, 7.8% walked using a hand-held mobility device, and 33.3% had limited or no walking ability [3]. Examining these statistics and keeping in mind that children with CP suffer deficits in their motor, sensory, and cognitive abilities, as well as in their visuospatial competencies. Moreover, behavioral problems are common in children with cerebral palsy, including social skill problems, anger issues, and behavior issues in school, some children with cerebral may experience cognitive impairments, including low attention span, poor concentration skills, problem-solving deficiencies, and learning and language issues. Powered wheelchairs offer an opportunity to children who suffer from CP to lead a more fulfilling life and engage with their surroundings in ways that would not have been possible otherwise. Before using powered wheelchairs there must be an extensive period of training and users must pass a test that is supervised by a clinician to ensure their safety and other people's safety. There are many evaluation protocols and assessment techniques used by clinicians, for example: Wheelchair Skills Program (WSP) [4], Pediatric Powered Wheelchair Screening Test (PPWST), Powered Mobility Program (PMP) [5], Progression of Pediatric Powered Mobility (3PM) [6]. In my thesis project, I focused on PMP because it is the driving skill assessment used at the Institute of Neurological Sciences of Bologna (ISNB), AUSL Bologna where I conducted my internship for this thesis project. Up until recently the only accessible training method was to have powered wheelchairs users physically be present at a physical rehabilitation center and work with clinicians to train on how to operate a powered wheelchair which poses a lot of problems including financial ones and

logistical ones, as these centers have high operating costs and are not available everywhere. Also, in some countries, users may have to travel a long distance to reach their rehabilitation center which causes more problems instead of alleviating these problems. During the COVID pandemic when some of these centers had to shut down which disrupted the training schedule of their patients, it became clear that there is a need for an alternative training method that does not require the patients to be physically present at the rehabilitation centers. VR offers an affordable and practical alternative to the usual training methods.

1.2. Project Overview

The overall goal of this project was to develop a 3D software application able to simulate the PMP protocols and allow wheelchair users to improve their driving skills but at the same time support clinicians in understanding the user's ability to use the wheelchair in a safe manner. As such, this project was conducted within a multidisciplinary team and the software architecture was designed with the help of clinicians, engineers, and stakeholders. We decided to design and develop a 3D game application that could interact with a head-mounted display to simulate the virtual environment. The basic architecture of the software includes three modes which are cybersickness mode, PMP mode, and fun mode. The game application also includes a user interface for navigating these modes and a login menu to have user profiles. Performance metrics are collected after every use of the system and stored locally on the laptop. The system can have multiple input methods which include the oculus controllers, computer keyboard and mouse, and alternative switch access devices used at "Centro Ausili Tecnologici" (CAT), AUSL Bologna where I specifically carried out my internship and had the opportunity to incorporate the input systems, they have into the software application and control the system also using these input methods. In future versions of the simulator, the next planned step will be to interact with the software using a Brain-Computer Interface (BCI).

Embarking on this project I had set for myself some research goals which are:

- Develop a VR application that is compatible with windows OS or Android or Linux and this application will have the following features:
    - ❖ A user-friendly interface
    - ❖ Continuous Data collection

- ❖ Local Database for security concerns
- ❖ Carefully designed scenarios such as “Fun Mode,” “Cybersickness Mode,” and “PMP Mode” these scenarios will help train users on the use of powered wheelchairs.
- ❖ Performance metrics are used to track users’ progress.
- ❖ Various kinds of input controllers to fit the needs of differently abled users.

- Design a study protocol for data collection and data analysis.
- Run focus group meetings (FGMs) with clinicians and stakeholders (i.e., wheelchair users or individuals with cerebral palsy) to get feedback during the process of developing VR-PMP.
- Analyze all the collected data to get useful information that can be used to better understand how to help individuals with neuromotor disabilities.

The first version of the system, which is called VR-PMP (Virtual Reality for Powered Mobility Program), was assessed in the first focus group meeting (FGM) with two groups of clinicians and four participants. These groups of clinicians included clinicians who work exclusively with children and adolescents and the other group works with all age demographics. This first version included seven tasks (each task had 3 difficulty levels) that were taken from the powered mobility program (PMP) and a circuit that resembled the training circuit present at CAT in Bologna. The feedback obtained from the first FGM was used to develop the second version of VR-PMP that included the same 7 PMP tasks but with the addition of a scoring system that is based on the performance metrics collected. The second version also included 2 free roaming scenarios (i.e., the user is free to explore and navigate the scenario) and a cybersickness scenario. The second version was tested in a second FGM, the participants in this FGM were all able-bodied individuals and no experts in VR but they were all engineers. The feedback from the second FGM was analyzed and helped in the development of the third version of VR-PMP which included 20 PMP tasks with the scoring system and an innovative design for the training circuit of CAT center. The last FGM was a follow-up with the same group of clinicians as the first FGM to get feedback about the final version of VR-PMP.

1.3. Thesis Roadmap

This thesis is divided into 6 chapters. Chapter 1 of the thesis introduces the motivation, research questions and objectives, and the thesis outline. Chapter 2 presents the background which includes the software used, an in-depth look at VR, cybersickness and how to overcome it. In Chapter 3, there is a detailed description of the application VR-PMP and a walkthrough of the user interface. Chapter 4 presents the methodology that was applied to develop the study protocol, the questionnaires used, and the technology used. Chapter 5 shows the results of the four focus group meetings that led to the development of VR-PMP. Chapter 6 is a discussion about the results and future development of VR-PMP.

Chapter 2. Background

2.1. Cerebral Palsy

Cerebral palsy (CP) is a group of neuromuscular disorders that affect motor, posture, and manual abilities. CP is the most common motor disability in childhood. CP is caused by abnormal brain development or damage to the developing brain that affects a person's ability to control his or her muscles [7]. The symptoms of CP vary from person to person. A person with severe CP might need to use special equipment to be able to walk or might not be able to walk at all and might need lifelong care. A person with mild CP, on the other hand, might walk a little awkwardly, but might not need any special help. CP does not get worse over time, though the exact symptoms can change over a person's lifetime. All people with CP have problems with movement and posture. Many also have related conditions such as intellectual disability, seizures, problems with vision, hearing, or speech, changes in the spine (such as scoliosis), or joint problems (such as contractures).

Signs and symptoms of CP can vary greatly from person to person. CP can affect the whole body, or it might be limited primarily to one or two limbs, or one side of the body. Generally, signs and symptoms include problems with movement and coordination, speech and eating, development, and other problems.

Some of the symptoms [8] that affect movement and coordination control are:

- Stiff muscles and exaggerated reflexes (spasticity), the most common movement disorder:
- Variations in muscle tone, such as being either too stiff or too floppy.
- Stiff muscles with normal reflexes (rigidity).
- Lack of balance and muscle coordination (ataxia).
- Tremors or jerky involuntary movements.
- Slow, writhing movements.
- Favoring one side of the body, such as only reaching with one hand or dragging a leg while crawling.
- Difficulty walking, such as walking on toes, a crouched gait, a scissors-like gait with knees crossing, a wide gait or an asymmetrical gait.

- Difficulty with fine motor skills, such as buttoning clothes or picking up utensils.

There is no cure for CP [9], but a child's quality of life can improve with:

- treatment that may involve medicine or surgery.
- therapy, including physical therapy, occupational therapy, and speech therapy.
- special equipment to help kids get around and communicate with others.

Depending on the severity of the condition, people with cerebral palsy may require a wheelchair or a powered wheelchair to move around. In particular, according to a report by the CDC, approximately 1 in 323 children in the United States have CP and of those, around 28% use a wheelchair, with 7% using a powered wheelchair [10]. Instead, the European Cerebral Palsy Register (EU-CPR), a database that collects data on children and adults with CP from multiple European countries, reports that the prevalence of CP in Europe is estimated to be around 2.11 cases per 1000 live births and approximately 31% of children and adults with CP in Europe use a powered wheelchair for mobility [11].

It is important to note that the specific needs of each child with CP can vary, and the decision to use a wheelchair or powered wheelchair is always made in consultation with a healthcare professional.

2.2. Powered Mobility Proficiency Assessments

There are several methods for powered wheelchair assessment for people with CP, and the specific methods used may vary depending on the individual's needs and the expertise of the healthcare team. Some common methods include:

- Clinical assessment: This involves evaluating the individual's physical abilities, cognitive function, and other factors that may impact their ability to use a powered wheelchair.
- Standardized assessments: There are several standardized assessments that can be used to evaluate an individual's powered wheelchair skills and abilities, such as the Power Mobility Clinical Driving Assessment (PMCDA) [12] and the Functional Mobility Assessment (FMA) [13].
- Instrumented assessments: These assessments use specialized equipment, such as sensors or motion capture systems, to measure the individual's performance and identify areas for improvement.

- Goal-oriented assessments: These assessments focus on specific goals that the individual wishes to achieve with their powered wheelchair, such as navigating a particular environment or performing a specific activity.

There are several programs designed to help children with CP learn to use powered mobility devices. Some of the most used are:

- Wheelchair Skills Test for Power Wheelchair Users: This assessment evaluates a person's ability to maneuver a powered wheelchair through a series of indoor and outdoor obstacles, including ramps, curbs, and tight spaces [14].
- Powered Mobility Program for Children with Cerebral Palsy: This program is designed to help children with CP learn to use powered mobility devices such as powered wheelchairs and mobility scooters. The program focuses on teaching children and their families about powered mobility devices and providing individualized training to help children achieve their mobility goals [15,16].
- Powered Mobility Program: The program includes a variety of training activities aimed at improving the child's driving skills and safety while using the power wheelchair [5].
- Pediatric Powered Mobility Program (PPMP): This program is designed to help children with mobility impairments, including CP, learn to use powered mobility devices. The program includes assessments, individualized training, and ongoing support to help children achieve their mobility goals [17].

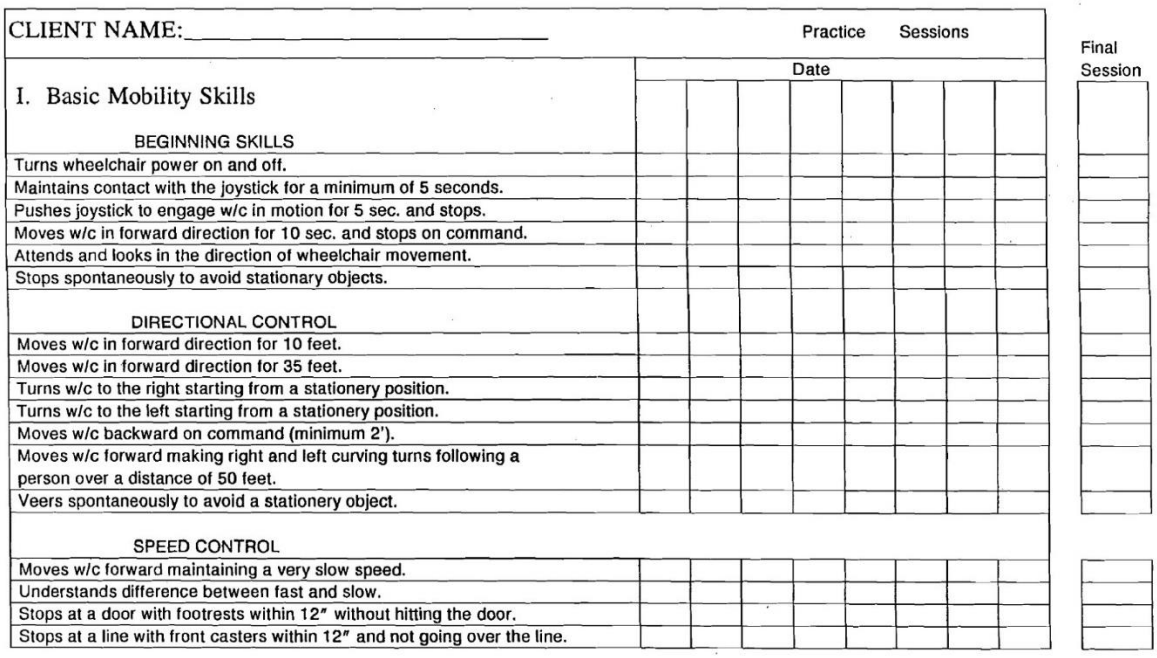
2.2.1. Powered Mobility Program

The first study related to the Powered Mobility Program (PMP) was proposed by Jan Furumasu et al. in 1996 [5]. In their paper, authors proposed for the first time a new way to evaluate the powered wheelchair driving skills of children with CP using a six-point scoring system from 0 to 5 where 0 signifies that the user did not finish the task while 5 is the highest score that the user can achieve. Figures 1 and 2 show the PMP tasks. The PMP was specifically designed for children with physical disabilities, including CP, who use power wheelchairs as their primary mode of mobility.

Several studies evaluated the effectiveness of the PMP in improving the driving skills and safety of children with physical disabilities, including CP, such as the PPMP [17].

The scoring of the PMP is based on an estimation of the percentage of assistance needed by the therapist and the type of assistance. The score relates to the amount of verbal and physical assistance that the driver needs and if they can perform the skill, which are subjective measures that are hard to quantify.

The PMP consists of five stages, each of which focuses on a different aspect of powered wheelchair use, including basic operation, indoor and outdoor maneuvering, obstacle avoidance, and advanced driving skills. The program uses a variety of training techniques, including video feedback, verbal feedback, and practice exercises, to help children improve their driving skills and confidence.



CLIENT NAME:_____	Practice Sessions								Final Session
	Date								
I. Basic Mobility Skills									
BEGINNING SKILLS									
Turns wheelchair power on and off.									
Maintains contact with the joystick for a minimum of 5 seconds.									
Pushes joystick to engage w/c in motion for 5 sec. and stops.									
Moves w/c in forward direction for 10 sec. and stops on command.									
Attends and looks in the direction of wheelchair movement.									
Stops spontaneously to avoid stationary objects.									
DIRECTIONAL CONTROL									
Moves w/c in forward direction for 10 feet.									
Moves w/c in forward direction for 35 feet.									
Turns w/c to the right starting from a stationery position.									
Turns w/c to the left starting from a stationery position.									
Moves w/c backward on command (minimum 2').									
Moves w/c forward making right and left curving turns following a person over a distance of 50 feet.									
Veers spontaneously to avoid a stationery object.									
SPEED CONTROL									
Moves w/c forward maintaining a very slow speed.									
Understands difference between fast and slow.									
Stops at a door with footrests within 12″ without hitting the door.									
Stops at a line with front casters within 12″ and not going over the line.									

Figure 1. First seventeen tasks of PMP. Picture taken from [5]

									Session
Maneuvers w/c through a doorway without hitting the door frame.									
Moving along a hallway, self correcting movement to avoid the wall for a minimum of 50 feet.									
Maneuvers w/c along a curving pathway with two turns.									
NEGOTIATING A RAMP									
Moves w/c up a ramp, staying in between the rails and turns a corner.									
Backs up far enough to negotiate a turn between the rails of a ramp.									
Turns w/c within a 5' by 5' space.									
Moves w/c down a ramp staying in between the rails.									
Stops w/c when driving down a ramp.									
Slows speed down when moving w/c down a ramp.									
NEGOTIATING A SIDEWALK									
Moves w/c along a narrow 28" wide sidewalk, w/o curb for a distance of 35' without veering off the sidewalk with supervision within 5'.									
Moves w/c along a 36" wide sidewalk with an unmarked 6" curb for a distance of 35" without veering off the sidewalk with supervision within 5'.									
III. Integration of Basic Skills for Functional Mobility – Unstructured Environment									
COMMUNITY MOBILITY									
Follows "rules of the road", e.g. stays on one side of a hallway, avoiding people and objects, looking at intersections of hallways.									
Moves w/c in an open, busy area maneuvering around multiple objects and moving people.									
Moves w/c along a sidewalk and down a ramp and stops before entering a parking lot.									
Recognizes difference between curb and curb cut.									
Moves w/c in and out of small rooms.									

Figure 2. Remaining seventeen PMP tasks. Figure taken from [5].

Specifically, the PMP includes thirty-four tasks in total divided into indoor and outdoor tasks which are as follows:

A. Basic mobility skills

Beginning skills

1. Turns wheelchair power on and off.
2. Maintains contact with the joystick for a minimum of 5 seconds.
3. Pushes joystick to engage wheelchair (*wlc)* in motion for 5 sec. and stops.
4. Moves *wlc* in forward direction for 10 sec. and stops on command.
5. Attends and looks in the direction of wheelchair movement.
6. Stops spontaneously to avoid stationary objects.

Directional control

7. Moves *wlc* in forward direction for ten feet.

8. Moves *wlc* in forward direction for thirty-five feet.
9. Turns *wlc* to the right starting from a stationary position.
10. Turns *wlc* to the left starting from a stationary position.
11. Moves *wlc* backward on command (minimum 2').
12. Moves *w/c* forward making right and left curving turns following a person over fifty feet.
13. Veers spontaneously to avoid a stationary object.

Speed control

14. Moves *wlc* forward maintaining a slow speed.
15. Understands the difference between fast and slow.
16. Stops at a door with footrests within 12" without hitting the door.
17. Stops at a line with front casters within 12" and not going over the line.

B. Integration of basic skills for functional mobility-structured environment

18. Maneuvers w/c through a doorway without hitting the door frame.
19. Moving along a hallway, self-correcting movement to avoid the wall for a minimum of fifty feet.
20. Maneuvers w/c along a curving pathway with two turns.

Negotiating a ramp

21. Moves w/c up a ramp, while staying in between the rails and turns a corner.
22. Backs up far enough to negotiate a turn between the rails of a ramp.
23. Turns w/c within a 5' by 5' space.
24. Moves w/c down a ramp staying In between the rails.
25. Stops w/c when driving down a ramp.

26. Slows speed down when moving w/c down a ramp.

Negotiating a sidewalk

27. Moves w/c along a narrow 28" wide sidewalk, w/o curb for 35’ without veering off the sidewalk with supervision within 5'.
28. Moves w/c along a 36" wide sidewalk with an unmarked 6" curb for 35” without veering off the sidewalk with supervision within 5'.

C. Integration of basic skills for functional mobility - unstructured environment.

29. Follows "rules of the road", e.g., staying on one side of a hallway, avoiding people and objects, and looking at the intersections of hallways.
30. Moves w/c in an open, busy area maneuvering around multiple objects and moving people.
31. Moves w/c along a sidewalk and down a ramp and stops before entering a parking lot.
32. Recognizes the difference between curb and curb cut.
33. Moves w/c in and out of small rooms.
34. Avoids potholes/hazards.

These thirty-four tasks can be subdivided into two main groups: outdoor and indoor tasks.

In VR-PMP, twenty indoor tasks were implemented with plans to design the remaining tasks in the future.

The tasks are again divided into three subgroups which are as follows.

- **Basic Mobility Skills**: these tasks can be further divided into
  - ❖ Beginning skills
  - ❖ Directional Control
  - ❖ Speed Control
- **Integration of basic skills for functional mobility-structured environment**: these tasks can be further divided into
  - ❖ Negotiating a ramp

- ❖ Negotiating a Sidewalk

- **Integration of basic skills for functional mobility -unstructured environment.**

At the end of this test, which usually takes place at a rehabilitation facility and under the supervision of a physiotherapist, the user is given a score that reflects how much help they needed to complete the tasks.

VR-PMP was designed to facilitate this process and to allow individuals to practice their PMP tasks from the comfort of their own homes.

2.2.2. Progression of Pediatric Powered Mobility

Another adapted version of the PMP was proposed by Naomi Gefen et al. [6] named 3PM showed in Figures 3, 4, 5, and 6.

3PM is considered an improvement upon the PMP. The name of the assessment, Progression of Pediatric Powered Mobility, was selected to focus on this purpose. There is no "pass" or "fail" scoring, the 3PM assessment aims to monitor the children's evolving progress in powered mobility and how it reflects their development and response to therapy and practice.

They adopted a Three points system (0-1-2). Based on input from the focus group and interviews, a simple and easy-to-use 3-point rating scale was chosen: each skill was scored on an ordinal scale where "0" =no (skill not present), "1" =emerging (skill not fully integrated) and "2" =yes (skill performed consistently).

3PM includes 14 items pertaining to demographics and previous powered mobility experience, 10 skills related to the exploratory stage, 17 skills related to the operational stage and 14 skills related to the functional stage.

During the exploratory stage, children learn through motivating activities that encourage self-initiated mobility in a protected and familiar environment; this requires constant assistance as well as close supervision.

During the operational stage, children learn basic powered mobility skills through ongoing, adapted play in one or two environments; they need assistance at times as well as close adult supervision.

During the functional stage, children learn to integrate powered mobility safely in a variety of activities and environments once they have mastered basic control and require only moderate supervision [18].

3PM - Progression in Pediatric Powered Mobility
Dr. Naomi Gefen and Dr. Lori Rosenberg, ALYN Hospital, Hebrew University, Ilanot School

Date
Name
Date of Birth
Diagnosis
GMFCS
Mode of Communication – verbal, AAC, gestures, no communication
Home Environment (accessibility)
School (accessibility)

Access mode e.g joystick, switches … (for switches – how many)
Access Site tried for this assessment
For switches- list all access sites
Present method of Mobility
Description of sitting posture
Description of powered wheelchair and seating system used in evaluation.
Description of initial free driving in an encouraging environment (open question)
Description of assessment environment (open question)

Legend:
No- Child does not perform skill. Including hand over hand assistance
Emerging- Child performs the skill some of the time but not consistently
Yes- Child performs the skill consistently.
Level of assistance:
Physical Cue (PC)- for example: Therapist touches hand or other part to remind child to stop
Direct Verbal Cue (DV)- for example: Giving direct instructions
Indirect Verbal Cue (IV)- for example: Calling attention to the situation without saying what to do (exclamations)
Spontaneous- (S)- for example: Child lifts hand to joystick without prompting

Demographics
Notes:

Figure 3. Demographic data collection in 3PM taken from [6]

Exploratory level:
* **If skill is not evaluated , mark NA;**

		0	1	2
1	Awareness of motion	No	Emerging	Yes
2	Cause and Effect	No	Emerging	Yes
3	Initiates wheelchair motion	No	Emerging	Yes
4	Emotional response (shows affect) to wheelchair motion	No	Emerging	Yes
5	Emotional response to crashing (shows affect)	No	Emerging	Yes
6	Self-generated goal directed motion towards significant toy or person	No	Emerging	Yes
7	Distance moved continuously	Less than 1 meter, un-continuous	Less than 1 meter, continuous	1 meter or more, continuous
8	Spontaneous Stopping (e.g doesn't continue driving when hitting wall)	No	Emerging	Yes
9	Spatial awareness (e.g aware of the spatial requirements of chair)	No	Emerging	Yes
10	Aware of danger	No	Emerging	Yes

Level of Assistance: PC /DV / IV / S
Specific items that required assistance:_____

Figure 4. Exploratory level tasks taken from [6]

Operational Level

*** If skill is not evaluated , mark NA;**

		0	1	2	Comments
1	Drives purposefully	up to 10 seconds	11-30 seconds	more than 30 seconds	
2	Attempts to turn towards object/person	No	Emerging	Yes	
3	Drives forward towards a person /object	Less than 1 meter	1-3 meters	More than 3 meters	
4	Turns right from stationary position towards significant item/ person on the right	No	Emerging	Yes	
5	Turns left from stationary position towards significant item/ person on the left	No	Emerging	Yes	
6	Reverse	No	Emerging	Yes	
7	Uses a variety of directions to drive	No	Emerging	Yes	
8	Drives 10 meters along a hallway	No	Following a person	Yes	
9	Drives through a doorway that does not require turning (straight entrance)	No	Emerging	Yes	
10	Stops upon demand	No	Emerging	Yes	
11	Stops **before** an obstacle	No	Emerging	Yes	
12	Drives around a stationary obstacle	No	Emerging	Yes	
13	Drives around a moving obstacle	No	Emerging	Yes	
14	Drives into a spacious room without obstacles approx.. 3*4 or more meters , turns around and exits	No	Attempts	Yes	
15	Can drive for 5 minutes without need of intervention and without collision in quiet environment	No	Emerging	Yes	
16	When makes a mistake / gets stuck is able to solve the problem	No	Emerging	Yes	
17	Can shift attention from driving to stimuli and return to drive	No	Emerging	Yes	

Figure 5. Operational level tasks taken from [6]

Functional Level

*** If skill is not evaluated , mark NA;**

		0	1	2	Comments
Indoor skills					
1	Drives efficiently including adjusting speed according to situation (smooth and precise)	No	Emerging	Yes	
2	Engages with others while in wheelchair	No	Emerging	Yes	
3	Drives into small room (2 meter turning radius) turns around and exits	No	Emerging	Yes	
4	Drives into an elevator (or simulated elevator)	No	Emerging	Yes	
5	Drives in a crowded environment	No	Emerging	Yes	
Outdoor skills					
6	Drives up slope	No	Emerging	Yes	
7	Drives down slope	No	Emerging	Yes	
8	Drives on sidewalk	No	Emerging	Yes	
9	Drives down curb cutout	No	Emerging	Yes	
10	Avoids potholes or dangers	No	Emerging	Yes	
11	Able to cross a street at crosswalk (age appropriate)	No	Emerging	Yes	
12	Drives in multi stimuli environment (noise, movement, crowd, weather)	No	Emerging	Yes	
13	Problem solving relating to driving (e.g power turns off, route is blocked)	No	Emerging	Yes	
14	Automatic intuitive driver	No	Emerging	Yes	

Level of Assistance: PC /DV / IV / S

Specific items that required assistance: _____

_____

_____

_____

_____

Figure 6. Functional level tasks taken from [6]

2.3. Powered Wheelchair Training Simulators

There are a few wheelchair training simulators for powered wheelchair training that help people improve their driving skills based on game applications or virtual reality experiences. For example, there is the Power Mobility Simulator, a computer-based simulator that allows users to practice driving a powered wheelchair in a virtual environment. The simulator provides users with feedback on their driving skills and helps them improve their ability to navigate over various obstacles and terrains [19]. Another tool is the DriveLab, a virtual reality-based simulator that includes a variety of driving scenarios and challenges, such as navigating through crowded spaces or over rough terrain [20].

The last simulator available is the McGill Immersive Wheelchair Simulator (MiWe), a 3D simulator for powered wheelchair training developed by researchers at McGill University in Canada [21,22]. The MiWe provides a realistic and immersive training environment for individuals who use powered wheelchairs. The MiWe simulator uses virtual reality technology to simulate various real-world environments and obstacles, such as city streets, parks, and buildings. Users can practice a range of skills and maneuvers, such as driving over curbs and ramps, navigating through tight spaces, and interacting with other pedestrians and vehicles. One of the unique features of the MiWe simulator is its ability to customize the simulation to match the user's specific abilities and needs. For example, the simulator can adjust the speed and sensitivity of the wheelchair controls to match the user's level of physical ability, and it can simulate different types of powered wheelchair controls to help users learn how to use different devices.

The MiWe simulator is still in development and has not yet been widely released for public use. So far you cannot access MiWe with a VR head-mounted display (HMD) using a desktop monitor. MiWe was developed in Unity to compare real power mobility movement to that of the simulator, as a clinical assessment and practice tool to examine upper extremity reaching during powered mobility. The MiWe runs on a Windows computer, with an operating system of at least Windows 7, with a graphics card of at least 1 GB of video memory and able to run DirectX 11. The user operates a joystick to interact with a series of six simulated environments (navigating an elevator or car ramp, driving in a supermarket or mall, entering a narrow room or crossing a street) via a first person, non-stereoscopic viewpoint. Pausing at a defined spot for several seconds (dwelling)

activates an elevator button or used cashier services. Joystick actions, the simulated wheelchair trajectory, collisions, and task duration are recorded. Each environment has three levels differing in the number of tasks, obstacles and the time allotted per task. The tasks incorporated elements from the Wheelchair Skills Test [4]

I personally tested the MiWe applications, and I identified the following limitations:

1. Outdated Icons
2. Clunky (for lack of a better word) user interface.
3. Button hover and button click do not match.
4. Sense of presence is very limited.
5. No head movement tracking.
6. No user profiles.
7. No instructions. It would be useful to have in-game hints on what to do instead of just at the beginning.
8. No real-time feedback about either time spent or number of collisions.
9. No clear method to reset progress and start over.
10. Not compatible with Oculus or other HMD.
11. No clear controls tutorial.
12. No speed controls.

MiWe was not specifically developed considering children and young adults as end-users and it did not implement the PMP tasks. Also, the metrics that have been implemented are difficult to identify and use to estimate a total score to be compared to the clinical assessment of a protocol such as the PMP. Also considering the limitations of the MiWe, further software solutions are necessary to improve powered mobility training supporting therapists and stakeholders.

2.4. Unity Game Engine

In this section, I highlight why I chose Unity to develop VR-PMP and what sets it apart from other game engines available.

2.4.1. Unity Game Engine: a Brief Introduction

The following guide to unity is a summary extracted from the work of [23].

Unity is a 2D & 3D game engine that was developed in 2005. Developed by Unity Technologies, it was made to provide more developers access to game development tools, which in those days was a novel venture. Over the course of its long life, the engine has changed and expanded dramatically, managing to keep up with the latest practices and technologies. Even today, the game engine's focus is to both provide the most robust set of tools possible for game development beginners as well as professionals. They have also expanded their reach into other industries as well with a huge focus on real-time 3D development and virtual reality, making it one of the most powerful game engines available.

Figure 7 Unity logo

2.4.2. Unity Game Engine: Key Features

3D and 2D Graphics Support

Unity provides support for both 3D and 2D graphics – allowing you the freedom to choose the art style you want for your projects. Each graphic type comes with its own specialized set of tools (such as sprite sheet cutting for 2D graphics) and even has its own script APIs (Application Program Interfaces) to call upon for different physics options that are suited for each style.

3D graphics also offer an extremely robust set of tools as well with the ability to create custom materials, build shaders with the Shader Graph, customize lighting, utilize post-processing effects,

and more. You can even generate 3D terrain or create 2D tile maps right in the engine, so there is a well-rounded set of tools to use for whatever graphics you are using.

Easy-to-Understand Architecture

Unity offers a very transparent method for composing your game architecture. Each "level" in a Unity game project is divided into a Scene, and each scene contains all the game objects needed for the player to use the level – whether that is the background, player character, enemy, bullet, or something else.

Unity also offers the ability to have a parent-child relationship between objects in the Hierarchy, making it extremely easy to add multiple objects (like an outfit, gun, or collider for collision detection) to one parent player character object. Beyond this, Unity also features the Inspector tool which gives you quick access to all your object's properties, meaning you can change things on the fly quickly without needing to dive into the code all the time.

Unity Scripting API

Unity comes with a powerful scripting API that offers you quick access to the most needed features. This includes both general game features, as well as specific API calls that allow you to access specific features and nuances for the engine.

For example, while you can adjust user interface (UI) elements from the engine itself, such as text color, the Scripting API also exposes those elements so you can adjust them via code as well. This goes for everything that can be accessed from the Unity Inspector, including position, rotation, materials, audio playback, and more beyond the name. Plus, there is a lot of documentation to help you out.

Cross-platform Build Support

Unity games support building an immense number of platforms. If the developer downloads the appropriate kit, you can export games for Android, iOS, Windows, MacOS, Linux, PS4, Xbox One, and more. You can even export HTML5 games if you want to put your game on the web.

The engine also makes it, so you must make as few changes as possible for the various builds, limiting the need to have multiple versions of your project for each platform.

Virtual Reality & Augmented Reality Capabilities

When it comes to VR and AR, which are newer technologies, Unity is one of the key supporters for developing with them. For VR, there are numerous packages available that support all VR headsets available, and they are constantly updated and kept flexible with this changing technology. You can even test your VR games in the engine.

AR is not to be left behind though, with numerous packages for ARCore and ARKit. Unity also offers AR Foundation, which Unity built to allow Unity developers to create AR apps for Android and iOS at the same time, eliminating the need for separate projects.

To boot, Unity also now has the XR Interaction Toolkit to make developing VR and AR games even easier. So, suffice it to say, Unity is one of the biggest supporters of XR technologies.

Large Asset Store

Whether you need graphical assets, specific game genre templates, audio, particle effects, or something else, Unity has got you covered. Its immensely large asset store comes with a variety of paid and free assets you can use for any game project. While Unity does develop some of these, many of them are also made by the community, meaning you have a wide variety to choose from. Plus, Unity makes it quite easy to add assets to your collection and install them into your project with the package manager, meaning no fussing with files manually.

2.4.3. Why Unity?

For most beginning developers, it is free.

Unity is free to use. Applications developed using the free version of unity can even be sold. It is only when sales of the application reach the $100K threshold that you must start worrying about expensive licenses.

It is beginner friendly.

While there is a slight learning curve in understanding the Unity UI, past that using Unity is a breeze. The architecture of Unity is quite easy to understand, and adding objects is as simple as right-clicking in the correct spot. Plus, with the Unity Inspector, most properties are readily exposed and can be adjusted from the engine itself – no coding from scratch is needed if you do not want to. In addition, Unity does offer kits and frameworks to take out even more of the grunt work if you are not ready to learn C#, so being beginner-friendly is a specialty of the engine.

It is simultaneously powerful and versatile.

There is no question that Unity is capable of anything. With its high-quality pipelines, you can render even the most intense of graphical projects. At the same time, though, Unity offers one of the most robust sets of games that supports any kind of game or project you want to make. As such, if you only have a vague idea of what you will be doing with your project, Unity can suit about anything.

Because of its popularity, there is a huge community.

Unity is one of the most popular engines. As such, there are numerous discussion areas about Unity where you can discuss with other developers. With a larger community, means you have more opportunities to network and get help with any kind of coding problems you might experience while developing.

Many programs consider export or development for Unity.

Given that Unity is so popular, a lot of programs consider how their own assets might be imported into Unity. This might include something as simple as making sure the file formats used are applicable in Unity. However, some companies partner with Unity to certain degrees and develop tools specifically for integration with Unity. Even further, other companies develop SDKs specifically for Unity so that developers have easy access to the technologies they create. As such, just in terms of compatibility with other programs, Unity is one of the best game engines for that purpose.

The asset store is a huge help.

Having such a huge asset store available makes developing applications easier for beginners and users who are not proficient in 3D design. It allows you to get assets quickly and implement them into your project with just a few clicks. This means you can focus on what matters to you.

2.5. Simulators and Games

Games and simulations are interactive multimedia having dynamic elements that are user controlled. For the public, games and simulations have no differences. A game is what one can play in a computer game whereas a simulation combines strategy and skills along with the game. Simulations and games are hugely different in their purposes. While a simulation is designed for evaluative or computational purposes, a game is designed for entertainment and educational

purposes. While accuracy is the upshot of simulations, clarity is the upshot of games. While a simulation is a considerable effort to precisely represent a real phenomenon in another, a game is an artistic representation of some phenomenon. The creators of simulations do not simplify designs in a deliberate manner and only as a concession to intellectual and material limitations. On the contrary, the creators of games use designs elaborately and in a deliberate manner. When games are stylized, simulations are incredibly detailed. Games are known to suppress details whereas simulations elaborate on all the details. The characters or happenings in a game do not go beyond a writer's imagination. The games come with many rules which allow you to do some things and restrict you from doing other things. There is also a lot of competition in games.

The difference between computer simulations and computer games is subtle but important. At the core, the distinction is that simulations are about things (or systems) and how they behave, and games are about a fun user experience [24,25]

2.6. VR Games

2.6.1. Virtual Reality

Virtual reality (VR) is an immersive media experience that replicates either a real or imagined environment and allows users to interact with this world in ways that feel as if they are there. To create a virtual reality experience, two primary components are necessary. First, one must be able to produce a virtual world. This can either be through video capture—recording a real-world scene—or by building the environment in Computer Generated Imagery (CGI). Second, one needs a device with which users can immerse themselves in this virtual environment. These take the form of dedicated rooms or head-mounted displays.

Cumbersome, lab-based technologies for VR have been in use for decades and theorized about for even longer. But recent technological advances in 360-degree, 3D-video capture, computational capacity; and display technology have led to a new generation of consumer-based virtual reality production. Over the past three years, an ecosystem of companies and experimentation has emerged on both the content and dissemination sides of VR. This renaissance can be traced to the development of the Oculus Rift headset. Palmer Luckey, who was frustrated with the state of headset technology launched Oculus which was a wildly popular Kickstarter campaign in 2012.

Less than two years later, Facebook bought the company for $2 billion. While devices have been evolving rapidly, so has the content for them. While the video game industry has driven most of the content development, new camera technology also enables virtual reality experiences based on video-capturing real events. These new cameras are being placed at sporting events, music concerts, and even on helicopters and drones. Virtual Reality Technology has the capacity to improve a lot of fields, but we are interested in how to use this technology to create a system to train powered wheelchair users in a safe and controlled environment.

2.6.2. VR Environments

VR simulation has come a long way in the past decade and has now reached a point where it has been demonstrated to effectively improve learning outcomes in clinical settings. Virtual reality developers are no longer only concerned with games, over the past decade the application of VR technology has expanded from the entertainment industry to clinical medicine. Researchers and doctors have explored the effects of VR simulation on physical rehabilitation, pain management, surgical training, anatomical education, and treatment of psychiatric disorders. Compared with traditional methods, VR technology is regarded as a cost-effective and efficient tool in the aforementioned areas therefore many industries have adopted VR and related technologies, and nowhere are the benefits of VR greater than in healthcare.

Training is easier if the experience is pleasant or enjoyable, which means a higher level of engagement and understanding. Training is necessary to ensure that individuals can learn a skill like driving a powered wheelchair.

2.6.3. VR Workload Evaluation

Recently there has been increasing interest in the use of VR technologies for simulation training, as VR affords innovative training methods that can be applied to otherwise dangerous or impractical environments. VR allows the user to interact with a simulation of some real environment, in real time, using their own senses and motor skills [26]. A number of studies have shown the beneficial effects of VR on rehabilitation [27]. Currently, however, there is limited understanding of how VR environments impact the cognitive processes of the user. For instance, it is unclear whether the cognitive demands imposed by a virtual task are equivalent to that of the real world.

Workload is a multifaceted construct, which results from the interaction of the intrinsic demands of the task and the conditions under which the task is performed, as well as the behavior, skill, and perceptions of the performer [28]. Cognitive load theory [29] describes mental workload because of the number of informational units that must be held in working memory.

The most widely used self-report measure of workload in human factors research is the NASA-task load index [30]. The NASA-TLX assesses workload along six dimensions: mental demand; physical demand; temporal demand; own performance; effort; and frustration. The NASA-TLX was designed to provide better diagnosticity (i.e., to discriminate between different types of workload) by assessing multiple sources of load, rather than a unidimensional construct.

Participants are asked to rate each subscale on a scale from 1 to 21, with 1 indicating "no workload" and 21 indicating "maximum workload". The scores are then transformed on a scale from 0 to 100, by subtracting 1 and multiplying by 5. For example, a score of 17 will become 80 as such (17-1) x 5. The scores are averaged across the subscales to obtain an overall workload rating.

2.7. VR over the Years

VR research started as early as 1968 by Ivan Sutherland and his student Bob Sproull, but most types of equipment were too expensive for consumer use, and their use for games was limited. In the late 1980s, Jaron Lanier and Thomas G. Zimmerman began developing hardware under the name VPL Research, with Lanier coining the term "virtual reality" for their products [31]. One of VPL's products was the VPL DataGlove, a glove that sensed the user's finger movement and translated it into computer input. The idea inspired engineers at Abrams/Gentile Entertainment (AGE) to work with Mattel and Nintendo to build a low-cost version of the DataGlove to work with the Nintendo Entertainment System (NES), omitting much of the technical sophistication and movement sensitivity of the DataGlove as to achieve a reasonable consumer cost [32]. Interest in VR grew in the 1990s. Reflection Technology, Inc. (RTI) had been developing a head-mounted, stereoscopic head-tracking system using light-emitting diode (LED) displays.

VR systems without head-mounted hardware were also developed in the 1990s, including the Cave automatic virtual environment (CAVE) [33]. CAVE systems included multiple flat screens displays, typically at least three walls to surround the human player, and incorporated some type of tracking sensor system to match the images on the walls to what direction the player was

looking. Early applications of CAVE system were game-based demonstrations, but the cost remained prohibitive for commercial deployment even through the 2010s.

Strong interest from academics remained to explore what VR, along with augmented reality and other mixed reality systems, could bring to video games, through the 2000s, but these games were mostly prepared for research proofs-of-concept to demonstrate the interaction of VR hardware, software, and human motion rather than for commercial release since hardware costs were still high [34].

After decades of attempts from its introduction, low-cost, consumer-grade VR hardware began to appear in the 2010s [35]. The Oculus Rift is considered the first consumer-ready VR headset and was first released in 2016. Oculus was first announced in 2013 as an inexpensive VR option for video games. Despite the availability of low-cost hardware for VR, the technology had still not taken off for video games by 2018 as had been expected when the Oculus Rift was announced.

2.8. Cybersickness

In this section, I discuss what cybersickness is and what are the protocols in place to reduce it.

2.8.1. Cybersickness Definition

VR experiences often elicit a negative effect, cybersickness, which results in nausea, disorientation, and visual discomfort [36].

Cybersickness is a form of motion sickness that occurs because of exposure to immersive Extended Reality (XR) environments, such as virtual reality (VR) and augmented reality (AR) applications. Depending on the immersive content, 20%-95% of users typically experience some form of cybersickness, ranging from a slight headache to an emetic response [37]. The most common symptoms include general discomfort, headache, eyestrain, stomach awareness, nausea, sweating, sopite syndrome (a.k.a. drowsiness), and disorientation; on exceedingly rare occasions (~1%) an emetic response is experienced [38]. Symptoms can last from minutes to days post exposure, with aftereffects manifesting as postural ataxia, visual displacements, and altered hand-eye coordination, among other ailments. Cybersickness has been referred to as the “elephant in the room,” due to its potential to drastically limit the proliferation of XR technology.

One current challenge in the area is the fact that cybersickness varies based on the type of immersion, with VR exposure typically having more disorientation (D) than nausea (N) and lastly, oculomotor disturbance (O) symptoms (i.e., a D>N>O profile), whereas AR exposure typically results in an O>D>N profile. As VR tends to lead to overt manifestations of motion sickness, such as stomach awareness and nausea, this technology is oftentimes self-limiting as users will curtail exposure when they feel compromised. AR, on the other hand, is associated with everyday ailments such as headaches and eyestrain, which are less overtly noxious and thus could be ignored by users and lead to protracted AR exposure, the safety of which has yet to be established. Research is needed to understand the nuances of cybersickness in VR versus AR environments, specifically: how XR dose (i.e., stimulus intensity) varies with VR versus AR system factors, how the capacity of the individual exposed (e.g., susceptibility) varies with VR versus AR, content design strategies that could minimize cybersickness in VR versus AR, how usage protocols should vary for VR versus AR exposure, among other concerns.

2.8.2. Cybersickness Contributing Factors

These factors are a summary of a guide made by NVIDIA [39] for VR creators and users.

There are three types of contributing factors to Cybersickness In VR, there are over fifty factors that can contribute to these physiological disagreements for your users. They are broken down into three categories of factors as follows:

1. System factors: introduced by the hardware and operating system.

2. Application and User Interaction factors: caused by the design of the Software (e.g., game), the user experience, and how the user chooses to interact.

3. Individual and various perceptual factors: specific to a user based on their health and wellbeing

A: System factors

There are several system factors from both VR hardware systems and operating systems that can cause or increase cybersickness symptoms as identified in the table. The main factors are:

• **Head Tracking:** it is critical that the rendered viewport and any updates due to movement correspond to the position and movements of the head. Any sensory mismatches such as drift or inaccuracy can cause shifts in the position of objects leading to cybersickness symptoms.

• **Rendering:** motion-to-photon latency, especially when it varies during the experience, is another leading cause of the discrepancy between what is seen and felt by the user. Constant latency allows the experience to be much more predictable and thus less sickness-inducing.

• **Field of View (FOV):** a wider FOV can increase cybersickness symptoms from increased scene motion and flicker perceived by the user's peripheral vision.

• **Optics**: a head-mounted display's (HMD) optical subsystem can include displays, lenses, mirrors, filters, Interpupillary Distance (IPD)5 adjustments, and focus adjustment lenses may introduce distortion which changes how images are projected and perceived, while displays can contribute to chromatic aberration and dispersion.

System factors contributing to Cybersickness.

• Head Tracking (accuracy, drift, precision, degrees of freedom, calibration)

• Rendering (latency, frame rate, binocular image onset)

• Display (refresh rate, response time, persistence, flicker, dirty screen)

• Field of View

• Lenses (distortion, chromatic aberration, inter-lens distance)

• Vergence/Accommodation Conflict

• HMD & Fit (ergonomics, open to periphery, weight, and center of mass, excessive heat, poor eye alignment with lenses, uneven or excessive pressure, hygiene)

• Temperature

B: Application and User Interaction factors

It is not just the hardware—the VR application itself and the way the user interacts with it can also cause cybersickness symptoms or exacerbate those introduced by system factors. The following are the top four application and user interaction factors:

• **Lack of Control:** the ability for the user to control their position and orientation (e.g., navigation, viewpoint) in a VR app helps the user anticipate upcoming visual motion. As in other situations where users cannot anticipate or control visual motion (e.g., on airplanes or roller coasters), users may experience an increase in symptoms.

• **Duration:** longer VR experiences tend to increase the intensity of symptoms. However, studies show that steadily increasing exposure and duration over several days can sometimes help users adapt and reduce their symptoms.

• **Head Motion:** the frequency and intensity of head movement, especially yaw7, tends to increase symptoms. As a result, users may try to limit their head movements to reduce cybersickness.

Application and User Interaction factors contributing to Cybersickness.

• Visual Acceleration and Vection
• Virtual Rotation
• Scene Motion and Complexity
• Rest Frames
• Height Above Ground
• Graphic Realism
• Conflicting Depth Cues
• Excessive Binocular Disparity
• Luminance
• Control
• Duration
• Head Motion
• Position (standing/sitting)
• Eye Motion

C: Individual factors

Finally, in addition to system and application factors, individual users can be predisposed to cybersickness at varying levels due to their physical and mental state and health. Here are a few key factors to understand for your users:

• **Motion Sickness History:** susceptibility to motion sickness varies by individual, with some having a stronger disposition and history of symptoms than others.

• **Lack of VR/Game Experience:** inexperienced users tend to be more susceptible than experienced users because symptoms can often decrease after repeated exposure over time as the user learns to adapt to the environment.

• **Interpupillary Distance (IPD):** a mismatch between the user's IPD and a device's

inter-lens distance (ILD) can lead to headaches, eye strain, and discomfort. Females may be more susceptible because they tend to have smaller IPDs (Interpupillary Distance) than males, and HMDs tend to be optimized for the average IPD of males.

• **Illness and Health:** illnesses such as the flu or cold can affect how visual motion is perceived by the brain, as can overall health and lifestyle choices such as sleep,
medication, etc.

Individual factors contributing to Cybersickness.

• Motion Sickness History
• VR/Game Experience
• Real-world Task Experience
• Gender, Age, Ethnicity
• Illness
• Sleep Deprivation
• Medication
• Migraine History
• IPD
• Head Size for HMD Fit
• Balance Control
• 3D (3-Dimensional) Motion Sensitivity
• Flicker/Fusion Frequency Threshold
• Anxiety, Emotional Stress
• Expectations

Developer approaches when designing VR experiences.

As we have seen, there are many factors that may cause your VR experience to induce cybersickness in the users. Here are a few approaches to consider that may reduce or prevent it when developing and designing your VR experience:

1. Viewpoint Control

• Users should have active control of the viewpoint and be responsible for initiating movement. The resulting scene movement should be predictable, and users should be able to anticipate upcoming visual motion.

• Similarly, all movement of the viewpoint by the camera should be as predictable as possible.

• Reduce or eliminate any non-user-initiated movement (i.e., any movement not related to the user's own navigation around space). Artificially moving the user increases the risk of nausea, especially for sensitive individuals.

2. Visual Acceleration

• Avoid or limit linear or angular accelerations without corresponding vestibular stimulation.

• Maintaining constant velocity is preferred since it does not affect the vestibular system for most users.

• In general, developers should think about the distinct types of allowable camera-initiated movements in their experience as a spectrum of tolerance, where the latter movements listed are more likely to cause symptoms: user locomotion (natural) > linear visual movement > visual acceleration > visual rotation > visual acceleration + rotation.

3. Visual Leading Indicators

Display visual indicators or motion trajectories (e.g., arrows indicating the upcoming travel direction) so that users can anticipate upcoming visual movements.

4. Rest-Frame Cues

Display visual cues that remain stable as the user moves. This provides users with fixed points that can help them judge motion. There are two general types of cues you can display:

• Foreground Cues: cues that remain locked in the viewport as the user moves (e.g., cockpit, car dash, helmet, etc.).

• Background Cues: cues that are locked to the user's inertial frame of reference (e.g., clouds, mountains, horizon, etc.).

5. Reduce or Modify the FOV:

• Dynamically scale down the FOV based on the linear or angular velocity of the virtual environment, to reduce the amount of scene motion perceived by the user's peripheral vision.

• Perform dynamic blurring of unimportant/ non-salient areas.

2.8.3. Cybersickness Assessment

The Motion Sickness Assessment Questionnaire (MSAQ) is a tool used to assess the severity of motion sickness symptoms experienced by individuals in virtual environments [40]. The MSAQ consists of 16 items that measure four different dimensions of motion sickness symptoms: nausea, oculomotor symptoms, disorientation, and general discomfort.

Each item on the MSAQ is rated on a scale of 0 to 10, with 0 indicating no symptoms and 10 indicating the most severe symptoms. The questionnaire can be administered before, during, and after exposure to a virtual environment to track changes in symptoms over time.

The MSAQ has been validated in several studies and has been found to be a reliable and valid tool for assessing motion sickness in virtual environments. For example, a study by Kennedy et al. (2003) [41] used the MSAQ to assess motion sickness in a virtual reality driving simulator and found that the questionnaire was able to accurately discriminate between participants who experienced motion sickness and those who did not.

Overall, the MSAQ is a useful tool for researchers and clinicians who are interested in assessing motion sickness symptoms in virtual environments and monitoring changes in symptoms over time.

2.9. Sense of Presence

The sense of presence in VR has been defined as "the subjective feeling of being present in a virtual environment" [42]. This feeling is often described as a sense of "being there" in the virtual environment, and it is a crucial factor in creating a truly immersive experience [43] Research has shown that the sense of presence in VR is influenced by several factors, including the quality of the VR hardware, the realism of the virtual environment, and the user's level of engagement and interaction with the virtual world [44]. For example, a study by Steuer (1992) [45] found that the sense of presence in VR was greater when users had more control over their virtual environment. More recent research has also explored the neural basis of the sense of presence in VR. A study by Mucci et al. (2019) used functional magnetic resonance imaging (fMRI) to investigate brain

activity during a VR experience and found that the sense of presence was associated with increased activity in regions of the brain involved in spatial perception and sensory integration.
Overall, the sense of presence in VR is a complex and multifaceted phenomenon that is influenced by a variety of factors and is of great interest to researchers studying the psychology and neuroscience of virtual reality.

2.9.1. Sense of Presence Assessment

The IPQ (Immersion and Presence Questionnaire) is a tool used to measure the sense of immersion and presence experienced by users in virtual reality (VR) environments [46]. The IPQ consists of 14 items that are designed to measure three dimensions of VR experience: spatial presence, involvement, and realness.
Spatial presence refers to the subjective feeling of being located within the virtual environment, involvement refers to the user's cognitive and emotional engagement with the virtual world, and realness refers to the degree to which the virtual environment is perceived as realistic.
Each item on the IPQ is rated on a scale of 1 to 7, with higher scores indicating a greater sense of immersion and presence in the virtual environment. The IPQ has been used in a wide range of VR research studies to assess the effectiveness of different VR systems, as well as to evaluate the impact of various factors on the user's sense of presence and immersion. Overall, the IPQ is a useful tool for researchers and developers who are interested in understanding the psychological and perceptual aspects of VR experiences.

2.10. VR Legs

2.10.1. What is “VR legs”

VR legs is a term used in the field of VR to characterize the user’s habituation to the virtual environment. The Urban Dictionary describes it as “the metaphorical representation of being accustomed to immersion in a virtual reality environment, particularly in regard to virtual locomotion.” VR legs are therefore related to simulator sickness, and since the release to the public

of new VR devices, users and developers have been dealing with this problem and trying to find ways to overcome it [47].

VR legs refers to resistance to motion sickness when playing VR. When playing VR, your vision is restricted entirely from the outside world and you only see the game, of course. This is tricky for your inner ear, which determines your sense of balance. So, if a game is "high motion," or if things push your character around, it can cause your inner ear to become confused and cause motion sickness, dizziness, and possibly cause you to fall over.

2.10.2. How to Increase "VR legs"

There is not a specific protocol to follow but there are tried and tested methods posted on the internet by VR users who suffered from cybersickness and overcame it. These are some of the tips found online [48]:

- Make sure to go at your own pace. Some people might be able to do all these steps in a week, others might take a few months. Pushing yourself too hard can have a negative effect. If you really struggle with smooth locomotion, I recommend spending more time in games like VRChat using teleportation.
- Getting VR legs is not a black or white thing: at first, you might only be able to spend 2 minutes in smooth locomotion, but that number will gradually increase to 5 minutes, 10 minutes, 30 minutes, 1 hour, then until you rarely or never experience VR motion sickness.
- Be persistent. Use VR daily. If you take long breaks in between each session, it will take much longer for you to get your VR legs.
- Having a higher refresh rate can decrease motion sickness (although do not use the 120 Hz option if you cannot maintain a stable refresh rate).
- Games that contain realistic pictures can cause more motion sickness. Avoid these when starting out.

Chapter 3. VR-PMP Architecture

3.1. Architecture and Workflow of VR-PMP

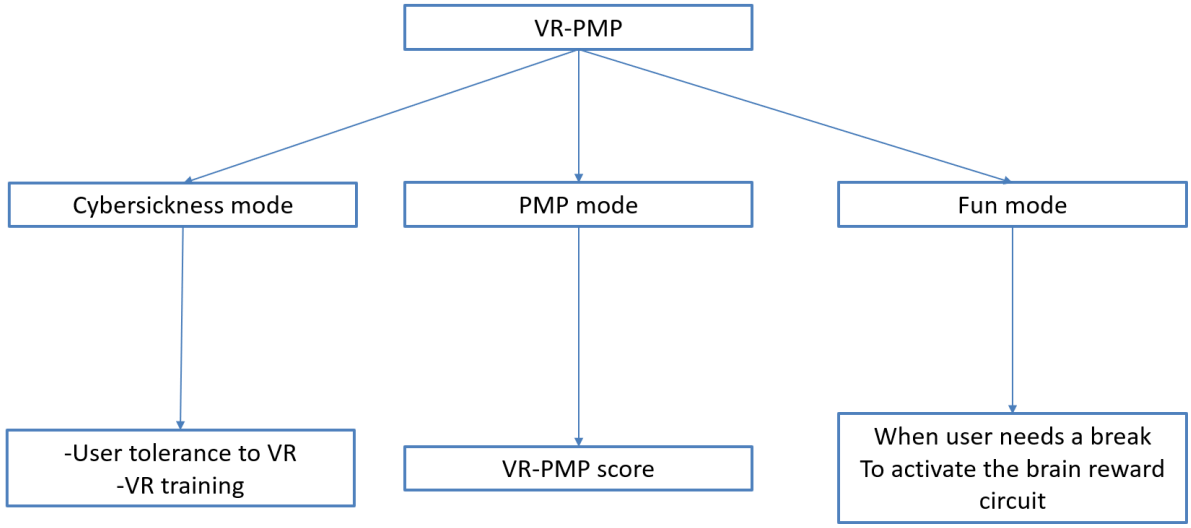


Figure 8. VR-PMP architecture

In this chapter, the VR-PMP simulator for wheelchair driving skills training is presented. The VR-PMP is a 3D game application developed in Unity using C#. The overall goal of the VR-PMP is to allow the users to have fun during practice with the VR tasks and provide therapists with some outcome metrics that allow defining a total score comparable to the PMP scores.

Figure 7 shows the overall architecture of VR-PMP. As we can see, there are 3 main modes for the user to choose from:

- Cybersickness mode
  - ❖ This mode is for testing the user's tolerance and how long inside the virtual environment they can tolerate before feeling discomfort.
  - ❖ This mode is composed of 2 scenarios: the city scenario and the basketball scenarios.
    1. City scenario: this environment is designed to be the user's introduction to VR-PMP, so the function controls are kept simple and the only objective in

this mode is to explore the city while relaxing music is played in the background.

2. Basketball scenario: in this scenario, I introduced more controls to slightly increase the complexity of the control scheme, the objective in this scenario is to get the ball in the hoop and score a point which is accompanied by white flares to provide feedback to the user.

- PMP mode
  - ❖ This mode is composed of 20 PMP tasks that the user must complete in order to get a score at the end. The score is calculated using the performance metrics that are constantly being collected using C# scripts.
- Fun mode
  - ❖ This mode is the reward for completing the PMP mode or if the user needs a break. In this mode, the user is in an outdoor circuit with a ramp and a bridge and the user is instructed to collect coins and each time they collect a coin there is an audio cue to provide feedback to the user.

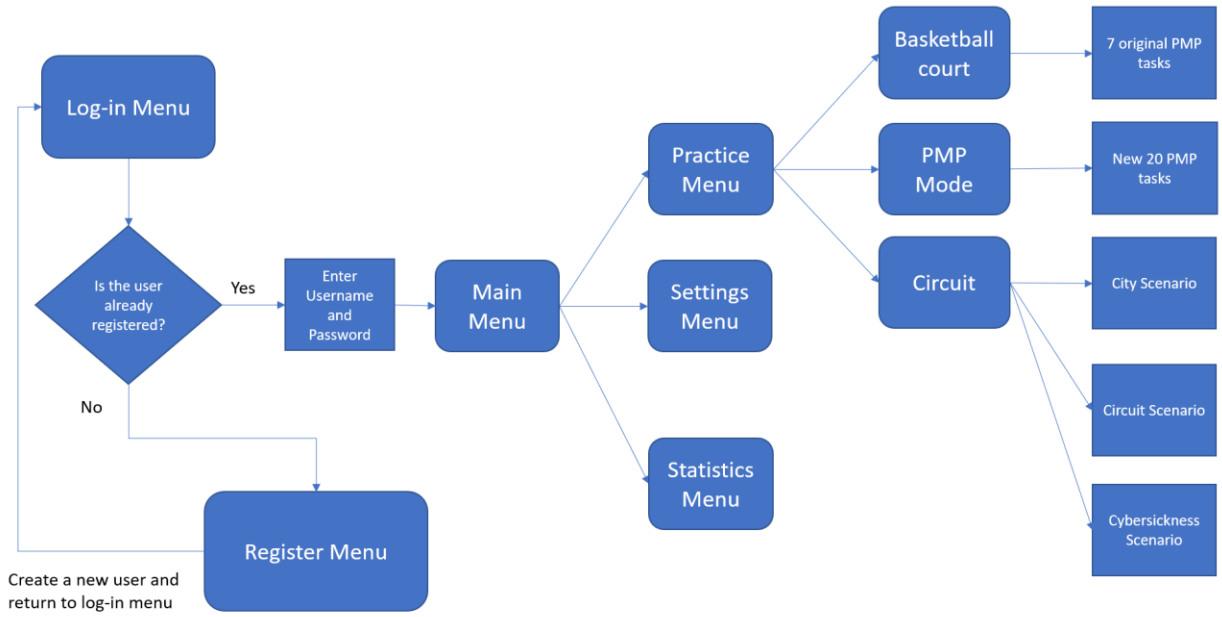


Figure 9. Flowchart illustrating the workflow of VR-PMP

Figure 8 describes the menu architecture of the VR-PMP. VR-PMP simulates a wheelchair avatar that can be controlled like a real wheelchair. The user's first interaction with VR-PMP is the log-in menu, the user is prompted to log-in using their credentials or register if they are first time users.

Then the user is redirected to the Main menu which has 3 options:

1) Practice menu: this menu is divided into 3 modes which are basketball court, Circuit, PMP mode. This menu is used to access the scenarios.
2) Settings menu: this menu is part of the future development and will be used to select different input systems other than the standard oculus controllers.
3) Statistics menu: this menu is used to display basic performance metrics like total duration, average velocity, and score (which is calculated as a ratio of passed tasks to total tasks done).

The VR-PMP can be played with HMD and desktop screens. It can be controlled with the HMD controllers or the laptop keyboards. It is compatible with some switch access technologies shown in Section 3.3.2.

3.2. User Interface

In this section, I will highlight the user interface and a walkthrough of the design of the menus of the VR-PMP.

3.2.1. Log-in Menu

The log-in menu (Figure 10) is the first phase of interaction that the user will face, the user is prompted to either sign in with credentials or create a new user.

In the back end of this menu, there is a script that is contacting the local database. This script is responsible for user authentication and returns either a "login successful" message or "login failed."

- The new user button will direct the user to the register menu.
- The login button will direct the user to the main menu.

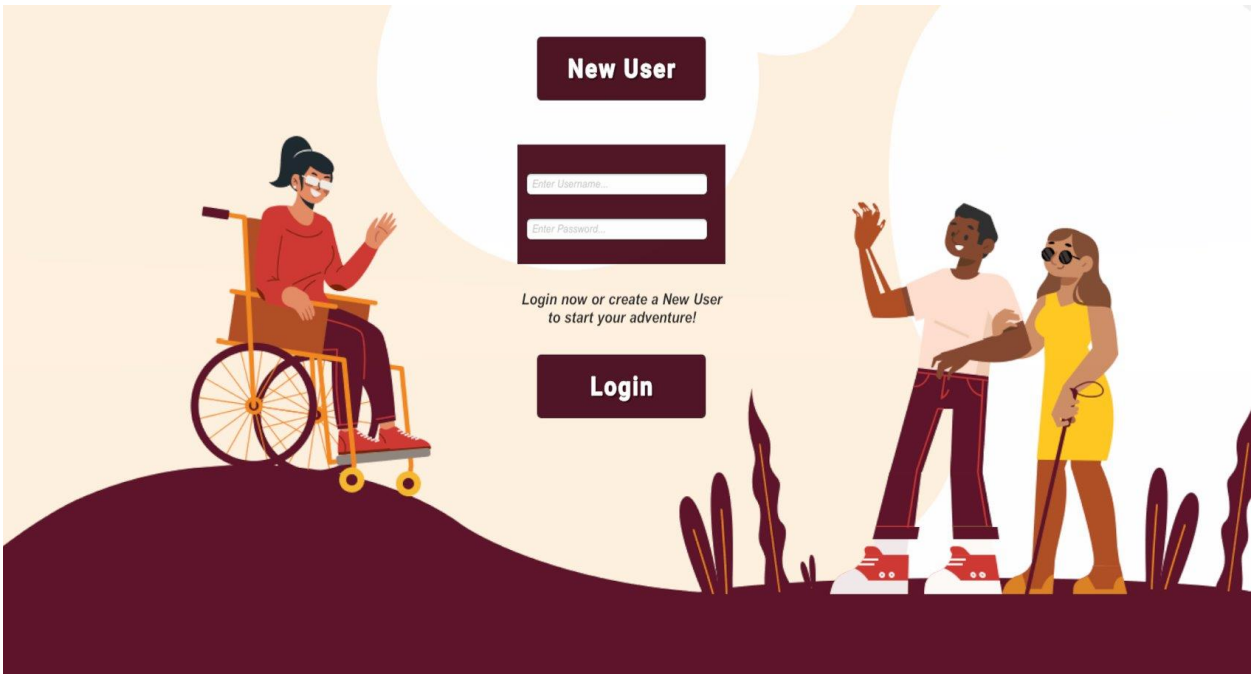


Figure 10. Log-in Menu of VR-PMP

The log-in menu (Figure 9) is the first phase of interaction that the user will face, the user is prompted to either sign in with credentials or create a new user.

In the back end of this menu, there is a script that is contacting the local database. This script is responsible for user authentication and returns either a “login successful” message or “login failed.”

- The new user button will direct the user to the register menu.
- The login button will direct the user to the main menu.

3.2.2. Register Menu

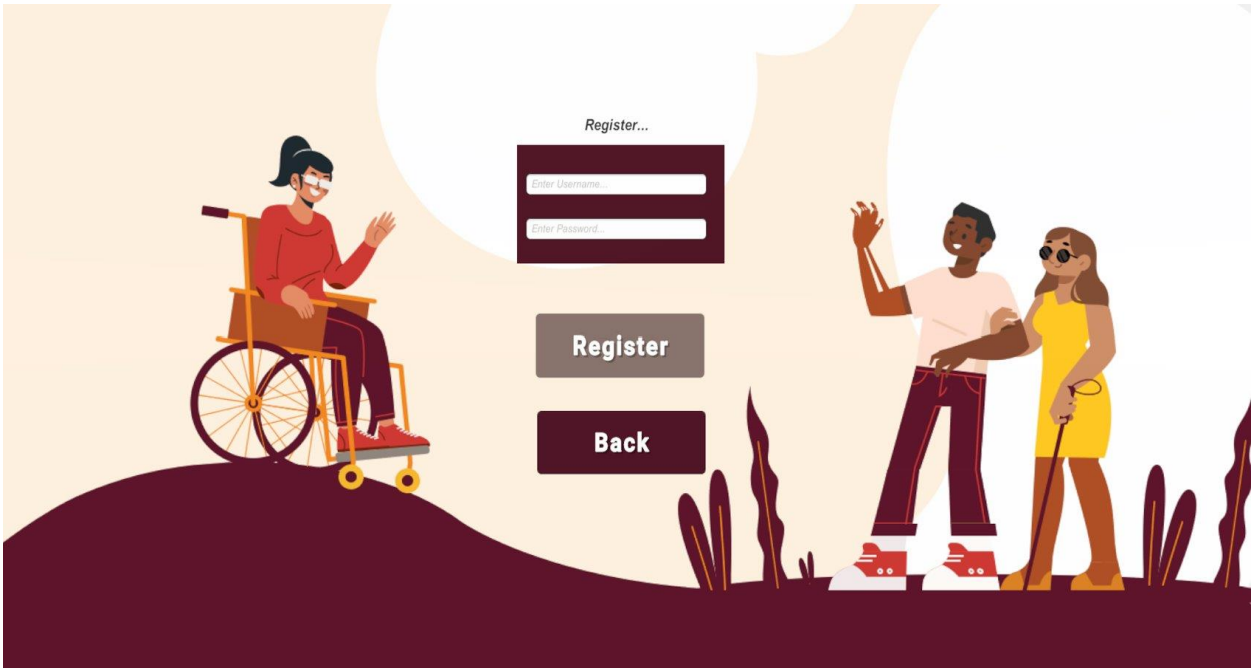


Figure 11. Register Menu of VR-PMP

In case this is the first time a user is interacting with VR-PMP they are prompted to create a new user in the register menu (Figure 11).

In the back end of this menu, there is a script that is contacting the local database, this script is responsible for creating a new user and adding them to the database.

- The back button will direct the user to the login menu to login after creating a new user.

3.2.3. Main Menu

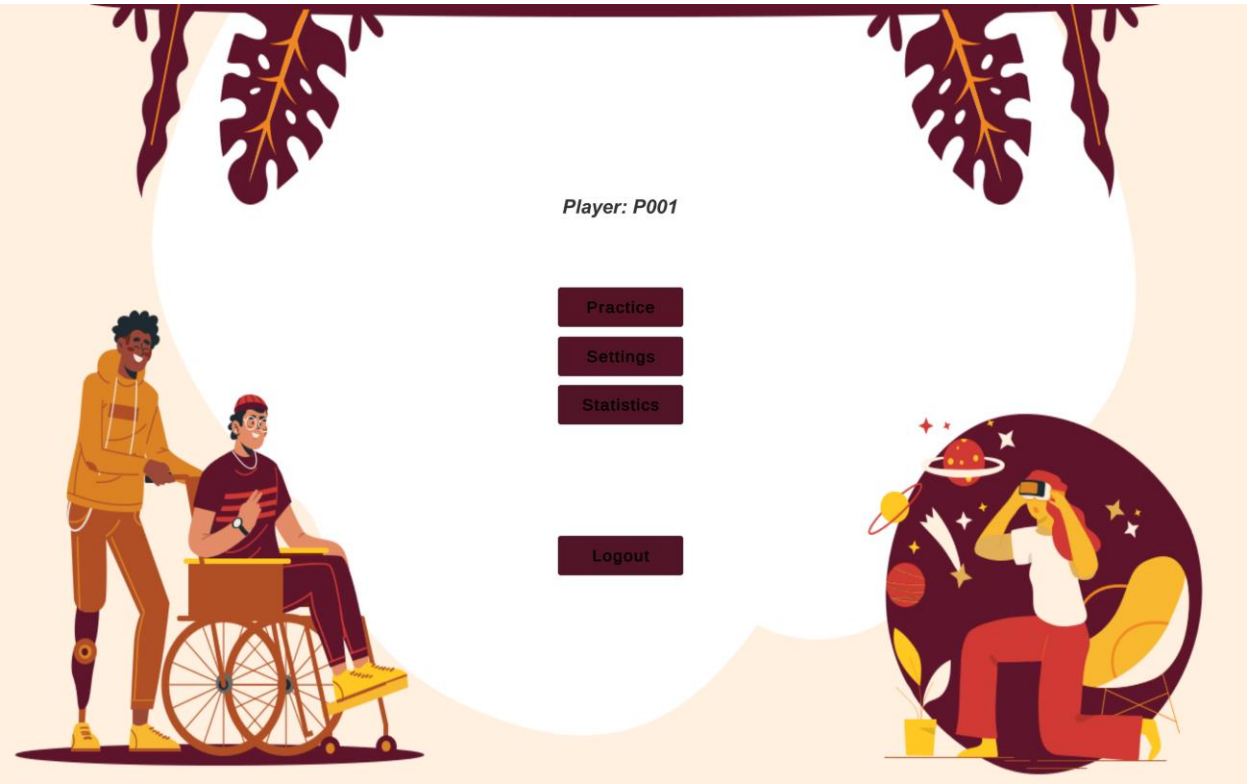


Figure 12 Main Menu of VR-PMP

Figure 12 shows the main interface of VR-PMP where a user can choose which scenario to play or change the settings or access the statistics of this user.

- The practice button will direct the user to the practice menu.
- The settings button will direct the user to the settings menu.
- The statistics button will direct the user to the statistics menu to check the performance of the user.

3.2.4. Practice Menu

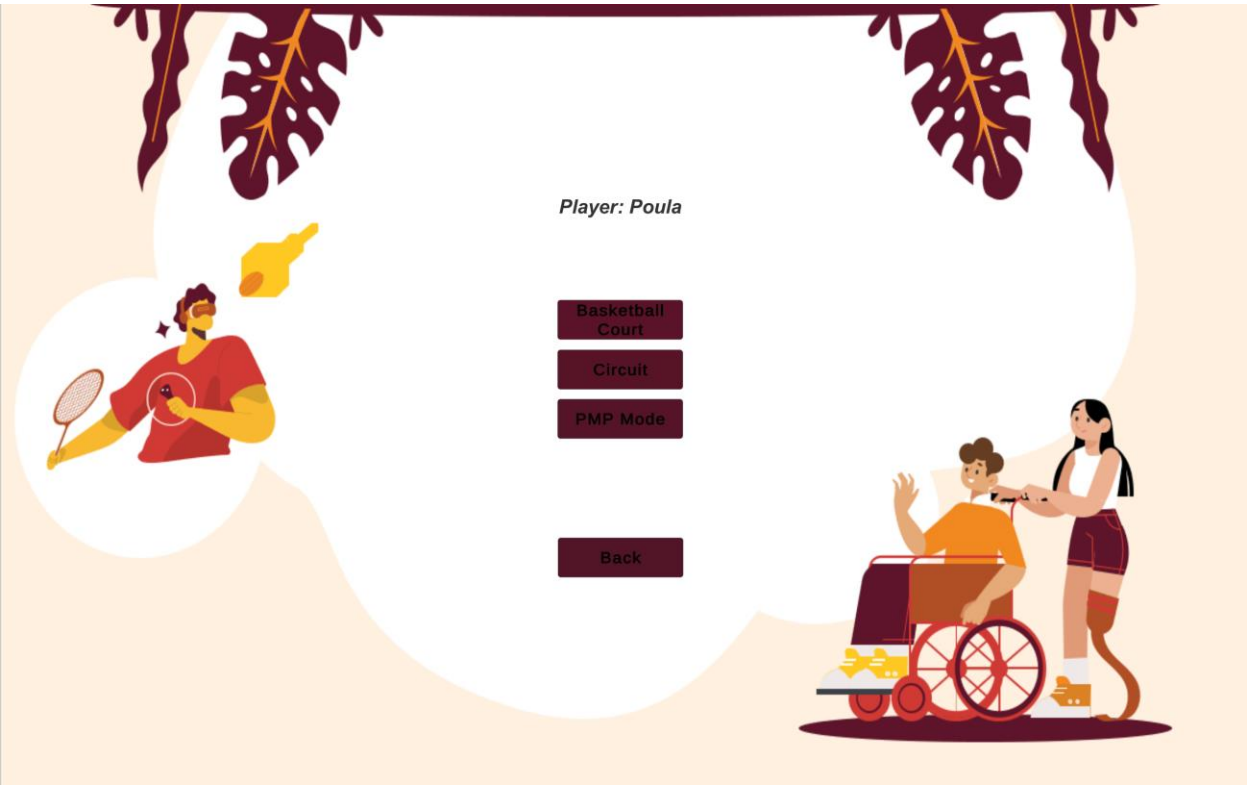


Figure 13. Practice Menu of VR-PMP

Figure 13 shows the menu used to access the different scenarios of VR-PMP where a user can choose from the following.

- Basketball Court: contains 7 PMP tasks and a preliminary version of the circuit scenario.
- Circuit: contains the city scenario, the circuit scenario and the cybersickness mode.
- PMP Mode: launches the new 20 PMP tasks.

The Back button will direct the user to the Main menu.

3.2.4. Basketball Court Menu

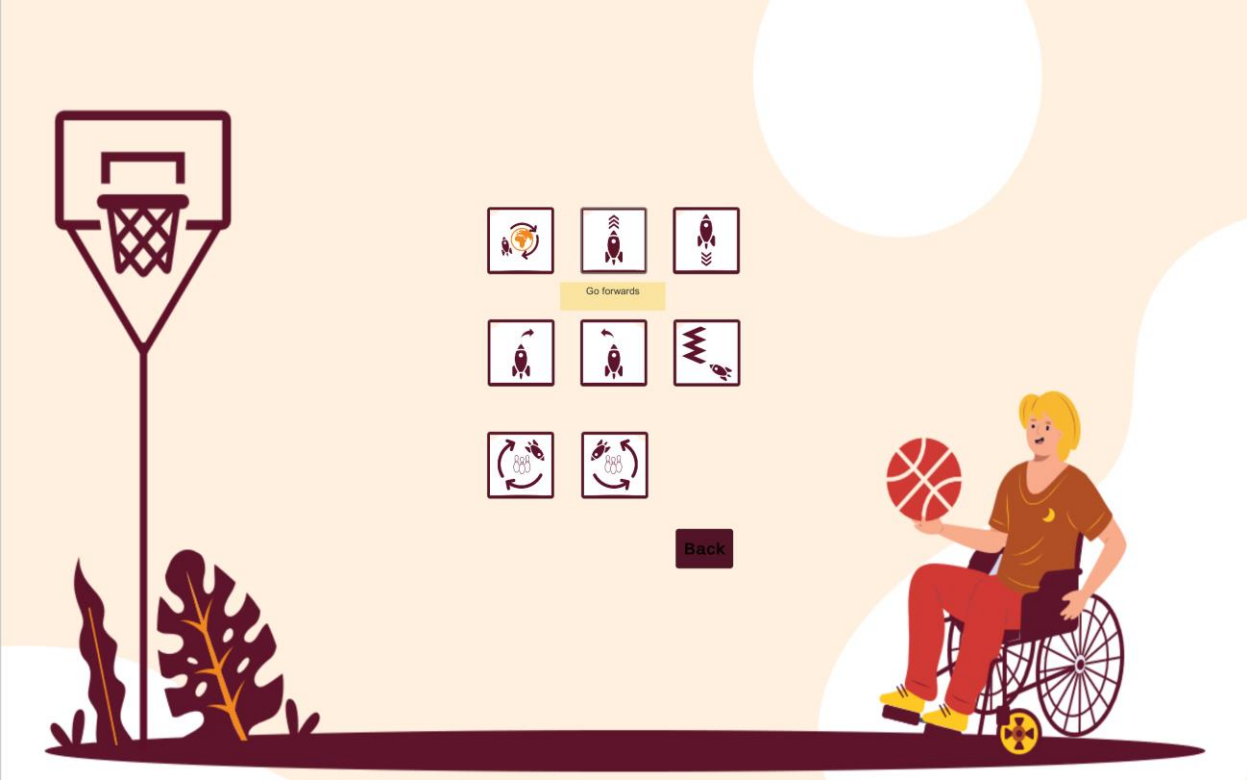


Figure 14. Basketball Court Menu of VR-PMP

The menu showed in Figure 14 is used to access the seven original PMP tasks and the old circuit scenario where a user can choose from the following:

1) Go forward.
2) Go backward.
3) Turn Right.
4) Turn left.
5) Zigzag
6) Rotate clockwise around an object.
7) Rotate counterclockwise around an object.
8) Preliminary circuit scenario

The back button will direct the user to the Practice menu.

3.2.5. Difficulty Selection Menu

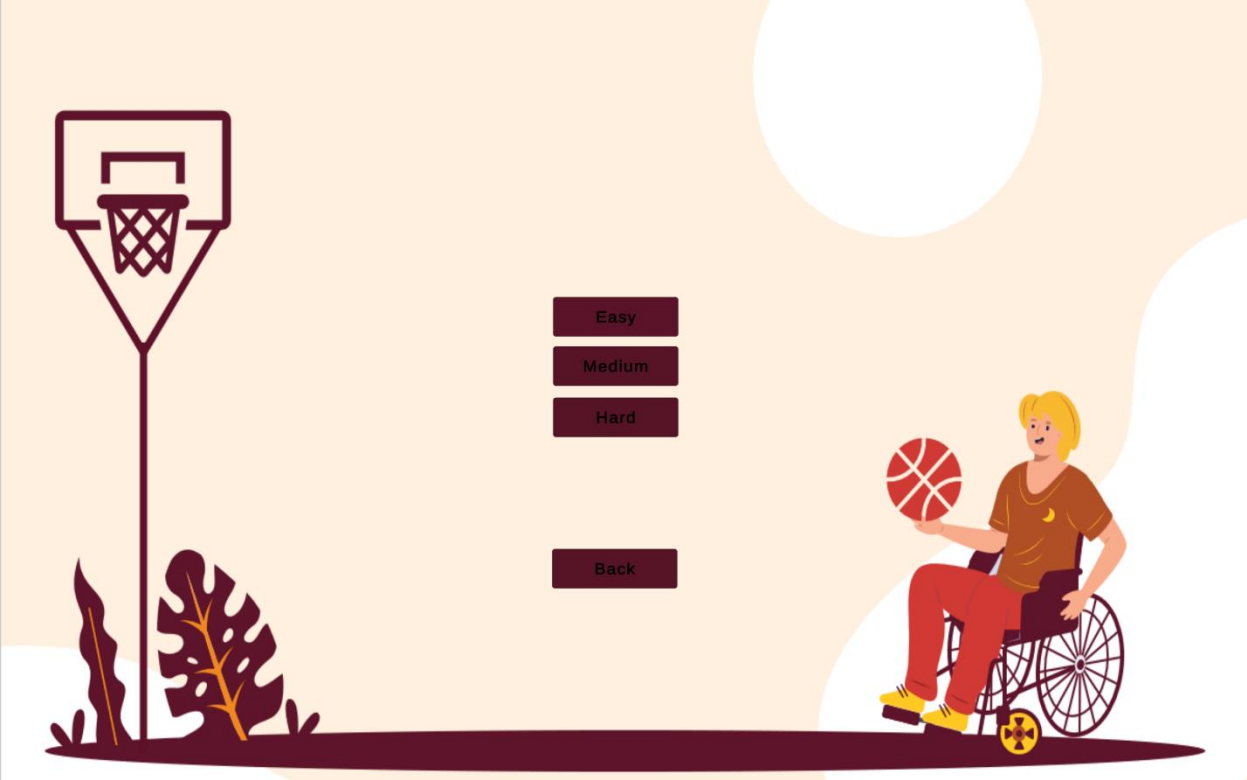


Figure 15. Difficulty selection menu of VR-PMP

The menu shown in Figure 15 is loaded when a user chooses a PMP task from the basketball court menu.

Each of the 7 PMP tasks has three difficulty levels ranging from easy to hard, these scenarios were designed to increase the proficiency of the users as they practice.

When the user becomes proficient in a certain task, they can move on to the next difficulty level.

3.2.6. Court Menu

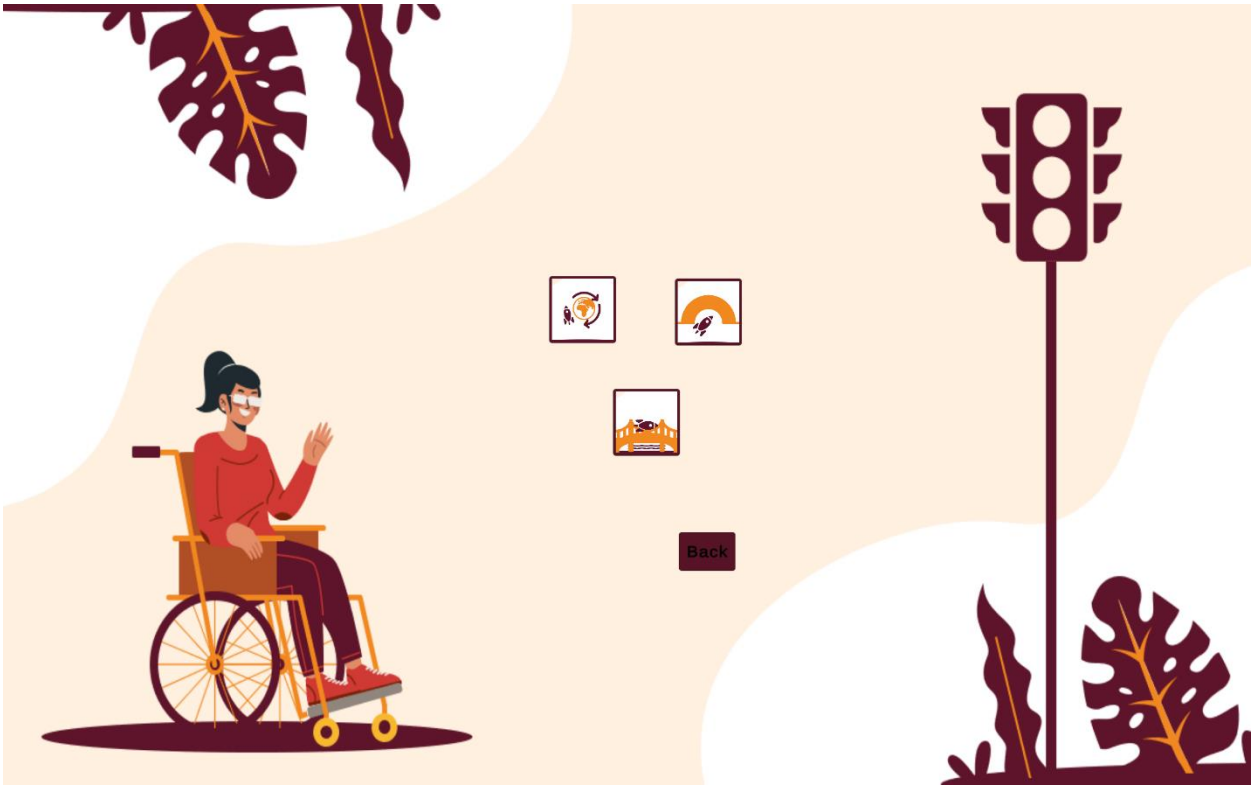


Figure 16. Court menu of VR-PMP

The Court menu (Figure 16) is used to select one of the following scenarios.

- Cybersickness Mode
- City Scenario
- Circuit Scenario

And the back button will direct the user to the practice menu.

3.3. VR-PMP Scenarios

In this section, I highlighted the different scenarios available in VR-PMP and the function of each. I will also describe the protocol that we developed during our brainstorming meetings with the clinicians.

3.3.1. Cybersickness Scenario

The Cybersickness scenario (Figure 17) is designed to test whether the user is ready to work with VR or they would have to use a desktop version of VR-PMP.

In this scenario, the user is asked to play basketball using the oculus controllers and after one minute the researcher asks them if they are feeling okay, if the answer is yes, they keep going for another two minutes and then the researcher repeats the question.

At the end, the user should be able to spend 5 minutes in this scenario without feeling too much discomfort to be able to go on to the next mode.

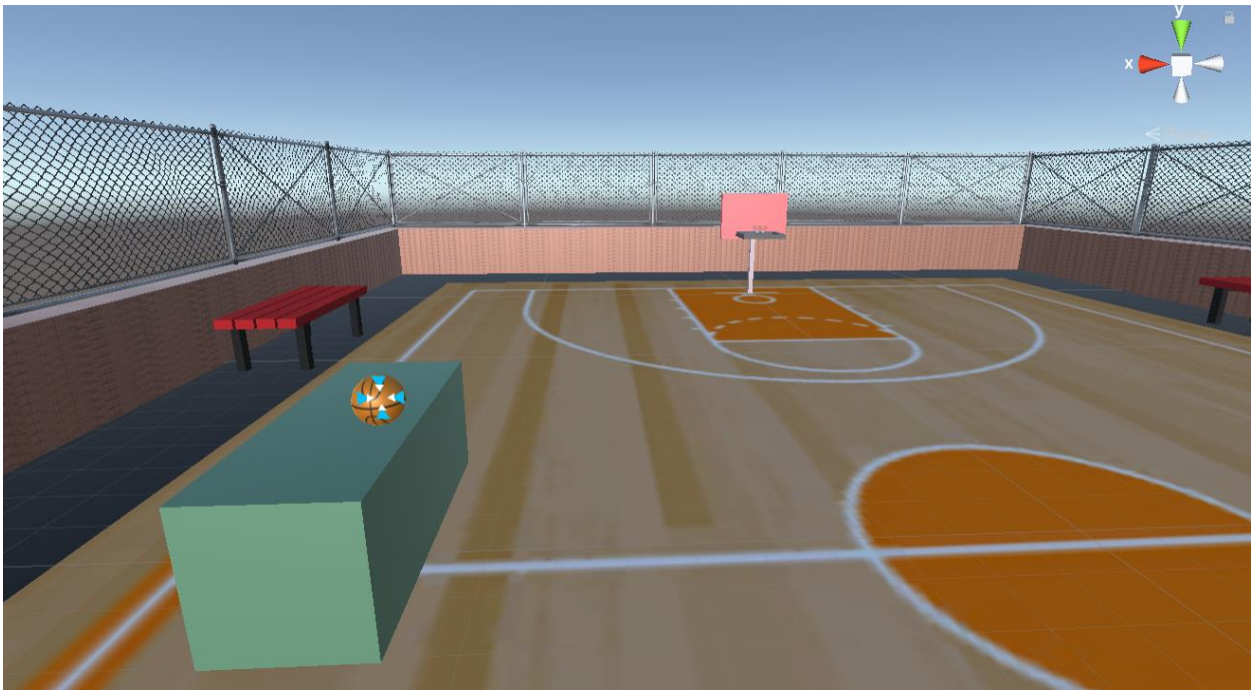


Figure 17. Cybersickness scenario of VR-PMP

3.3.3. City Scenario

The City scenario (Figure 18), the same as cybersickness scenario, is designed to test whether the user is ready to work with VR or they would have to use a desktop version of VR-PMP.

The user is asked to explore the city while calming music is played in the background.

The researcher is responsible for asking the participant every minute if they feel cybersickness or not, if the response is positive the user continues to explore until 5 minutes have elapsed and the participant moves on to another task.

Figure 18. City Scenario of the VR-PMP

3.3.2. Fun Mode Scenario

The Fun Mode scenario (Figure 19) was designed to be used as a reward after completing the PMP tasks and it is designed to resemble the “Corte Roncati” at CAT in Bologna and it also incorporates a ramp and a bridge to get the user more familiar with outdoor environments while at the same time providing entertainment.

The circuit also contains coins that the user is asked to collect while exploring the environment, audible feedback is provided every time a coin is collected to give the user feedback based on knowledge of performance.

Figure 19. Fun Mode of the VR-PMP

3.3.4. VR-PMP Mode Scenario

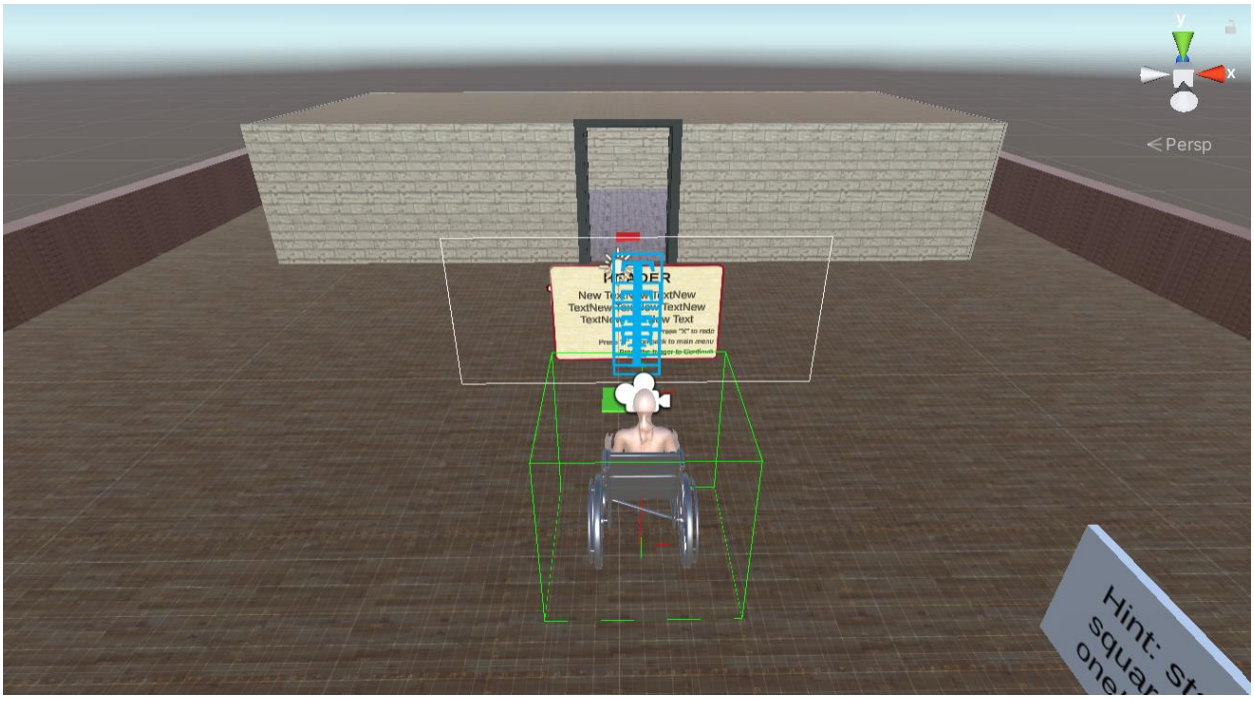


Figure 20. A scenario where the user is asked to walk through a doorway.

Figure 20 shows one of the 20 VR-PMP mode scenarios. The VR-PMP task mode is accessed through the practice menu, and it is designed to emulate a full PMP test in which the participant performs all the tasks in a row. After the first task is complete the user is asked to press the trigger button to continue or “X” to redo or “Y” to go back to main menu

The following PMP tasks have been implemented:

- Turns wheelchair power on and off.
- Maintains contact with the joystick for a minimum of 5 seconds.
- Pushes joystick to engage *wlc* in motion for 5 sec. and stops.
- Moves *wlc* in forward direction for 10 sec. and stops on command.
- Stops spontaneously to avoid stationary objects.
- Moves *wlc* in forward direction for ten feet.
- Moves *wlc* in forward direction for thirty-five feet.
- Turns *wlc* to the right starting from a stationary position.
- Turns *wlc* to the left starting from a stationary position.
- Moves *wlc* backward on command (minimum 2').
- Moves *w/c* forward making right and left curving turns following a person over 50 feet.
- Veers spontaneously to avoid a stationary object.
- Moves *wlc* forward maintaining a slow speed.
- Understands the difference between fast and slow.
- Stops at a door with footrests within 12" without hitting the door.
- Stops at a line with front casters within 12" and not going over the line.
- Maneuvers w/c through a doorway without hitting the door frame.

- Moving along a hallway, self-correcting movement to avoid the wall for a minimum of fifty feet.
- Maneuvers w/c along a curving pathway with two turns.

3.4. Input Systems

VR-PMP can have more than one input system to allow different users who may have different neuromotor disabilities and therefore will need to use different input methods that will be suitable for their needs.

3.3.1. Oculus Controllers

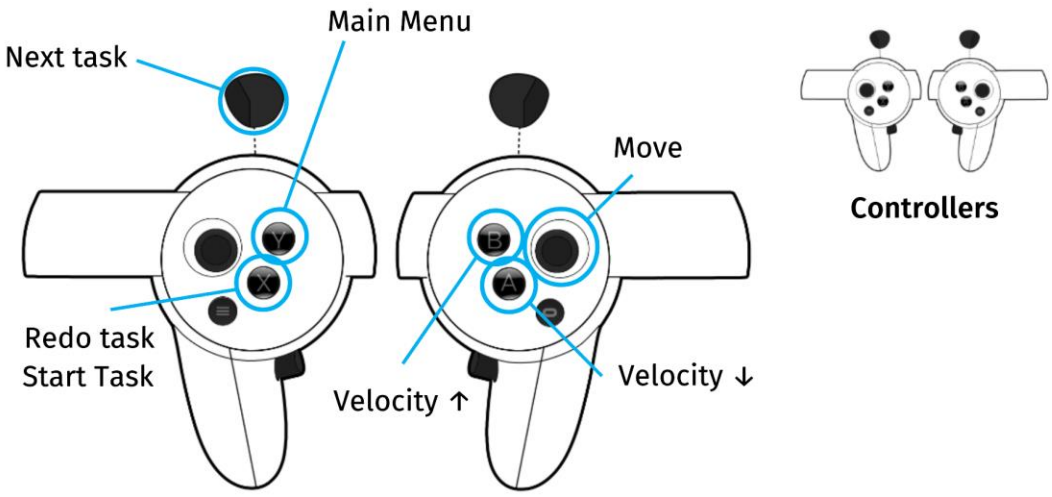


Figure 21. Oculus controllers with the button configuration

The standard input method while working with Oculus Quest 2 and Unity is to use the oculus controllers (Figure 21). This input method allows the user to take advantage of all the functionalities within VR-PMP such as the option to increase and decrease the speed, the option to redo the task, and the option to go to the next task.

3.3.2. Switch Access Devices at Centro Regionale Ausili (CAT)

During my internship, I had the opportunity to visit CAT and work with the input methods that they are currently using to interact with powered wheelchairs. This center helps individuals with neuromotor disabilities and their families with identifying and using the appropriate input methods that will help the individuals to interact with their environment whether at home or at school.

At CAT I was able to control the VR-PMP with input methods that can interface with a computer so I can map the method's output to input to VR-PMP.

This was needed because not all users have the fine motor skills that are needed to use the oculus controllers.

In the following sections, I will highlight some of the input methods that have been implemented into VR-PMP.

3.3.2.1. N-abler Joystick

Figure 22. N-abler joystick pro controller taken from [49]

N-Abler Joystick Pro is a large Joystick characterized by extreme precision and reliability. It is equipped with Left Click, Right Click, Double Click, Locked Drag and Speed Regulator functions. The function keys are hollowed out in such a way as to facilitate those who have problems with fine hand control. There are two inputs for sensors to emulate the Left Click and the Right Click of the Mouse if needed.

VR-PMP was altered to allow individuals with neuromotor disabilities to use N-abler joystick pro to control the avatar of the wheelchair in VR using an input method that they are more accustomed to than oculus controllers.

3.3.2.2. Optima Joystick

Figure 23. OPTIMA joystick controller taken from [50]

Optima Joystick and Trackball are compact, desktop mouse alternatives that do not require fine motor skills and are suitable for a wide spectrum of computer users. They are specifically designed to respond to the lightest touch to give accurate cursor navigation and precise targeting of objects on the computer screen while occupying the minimum amount of desk space. Optima also features a low profile, providing a natural hand rest for comfortable operation, and will work with USB and on computers of all types. There are four speed settings, and the center button gives the user access to a ‘drag’ feature, allowing the left click to be engaged for an extended period, for example when moving an icon on the screen.

As with the N-abler controller, VR-PMP is altered to work with OPTIMA joystick as well.

3.3.2.3. Optima Trackball

Figure 24. OPTIMA trackball controller, taken from [51]

Optima is an extremely robust trackball, designed for those with motor problems that prevent fine hand movement and consequently the use of conventional mice. Equipped with optical technology, it has no moving mechanical parts inside to ensure reliability, precision, and safety. The function keys for the left click (red key) and the right click (yellow key) and the locked dragging key (blue) are available for direct access on the instrument. The keys are slightly hollow with respect to the support surface of the instrument to facilitate typing in case of motor difficulties in the fine use of the fingers.

As with previously discussed alternative input methods, VR-PMP can be altered to work with Optima trackball as well.

3.3.2.4. Helpibox 16 Interface

Figure 25. Helpibox 16 interface, taken from [52]

Helpibox 16 is a simple interface for sensors(buttons) that does not need any driver to be installed; it is automatically recognized by the Operating System and connects to the PC via the

USB port. This device allows you to emulate the following function keys through the standard buttons on the market.

This device is used to map the computer keyboard and the mouse with some external buttons that are easier to press by people with motor disabilities.

Then we can use the input from these buttons to control the avatar of the wheelchair in VR-PMP.

Chapter 4. Materials and Methods

4.1 Study Design

To evaluate the design, functionality, and usability of the VR-PMP, we organized 4 Focus Group Meetings (FGMs) that helped with the development of the simulator. Each FGM had a similar structure. During the first 30 minutes, a team member described the main characteristics of the VR-PMP and the controllers with a DEMO of the VR-PMP performed by one of the researchers. After the simulation, clinicians, stakeholders, or engineers individually tested the VR-PMP with the help of one of the team members. Based on the aims of each FGM, some questionnaires might have been filled out. In this section, I will discuss the study protocol of the 4 FGMs.

4.1.1. First Focus Group Meeting

FGM 1 was performed using the first version of VR-PMP (Section 1.3.).

4.1.1.1. Participants and VR-PMP Tasks

In this meeting the participants were as follows:

- 7 clinicians that work with children with motor disabilities.
    - 7 Females
    - Age group (30-50 years)
- 6 clinicians that work with adults with motor disabilities.
    - 3 Females
    - 3 Males
    - Age group (30-50 years)
- 4 End user participants but not currently wheelchair users.
    - 2 Males with cerebral palsy (age 17)
    - 2 Females with cerebral palsy (age 20)

The first FGM was carried out using the first version of VR-PMP which included the following features:

- 7 PMP tasks that included.
    - ❖ Move Forward
    - ❖ Move Backward
    - ❖ Move in a zigzag manner to avoid obstacles
    - ❖ Turn to the right
    - ❖ Turn to the left
    - ❖ Move clockwise around an obstacle
    - ❖ Move counterclockwise around an obstacle
- The first version of Corte Roncati circuit that was completely changed in the updated version of the VR-PMP.

In FGM 1, the performance metrics collected were extremely basic and they included total time, average velocity, and success rate.

4.1.1.2. Study Protocol and Questionnaires

The Study protocol for this meeting was as follows:

1. The researcher will set-up the PC
    1. Launch Oculus application.
    2. Launch MAMP database software.
    3. Launch VR-PMP
2. The researcher will set up the Oculus quest 2.
    1. Connect the oculus to the PC.
    2. Sign in using a Facebook account.
    3. Launch Oculus Link from the settings menu.
3. The researcher will measure the IPD (Interpupillary Distance) using any means available five times. The researcher will average the 5 measures to get an estimated IPD.
4. Adjust the IPD on the HMD (Head-Mounted Display) until the image is clear according to this table provided by Oculus manufacturers.

IPD Range	Lens Spacing Setting
61 mm or smaller (<61 mm)	1 (narrowest, 58 mm)
61 mm to 66 mm	2 (middle, 63 mm)
66 mm or larger (>66 mm)	3 (widest, 68 mm)

Table 1. IPD Measurement

5. The researcher explains the button layout and the control scheme (i.e., controllers, buttons, speed controls) the researcher will explain that the user has the possibility to increase or decrease velocity when they want.
6. Explain the user interface (Points, timer, speed)
7. Participants will be asked to fill in a custom questionnaire related to motion sickness and game design.

4.1.2. Second Focus Group Meeting

The feedback from the first FGM went into developing the second version of VR-PMP (Section 1.3.). The second version was tested during FGM 2.

4.1.2.1 Participant and VR-PMP Tasks

In this meeting the participants were as follows:

- 4 engineers with no VR experience:
  - ❖ 1 female and 3 males
  - ❖ Age group (24-35 years)
- 2 end user participants:
  - ❖ 1 Male wheelchair user (age 37)
  - ❖ 1 female (age 16)

This FGM was carried out using the second version of VR-PMP which included the following features:

- 7 PMP tasks that included.

- ❖ Move Forward
- ❖ Move Backward
- ❖ Move in a zigzag manner to avoid obstacles
- ❖ Turn to the right
- ❖ Turn to the left
- ❖ Move clockwise around an obstacle
- ❖ Move counterclockwise around an obstacle

- An updated version of Corte Roncati.
- Cybersickness mode
- Fun mode

In FGM 2, the performance metrics collected were more advanced and they included total time, average velocity, success rate, and trajectory data.

4.1.2.2. Study Protocol

The Study protocol for this meeting was as follows:

1. The researcher will set-up the PC
    - Launch Oculus application.
    - Launch MAMP database software.
    - Launch VR-PMP
2. The researcher will set up the Oculus quest 2.
    - Connect the oculus to the PC.
    - Sign in using a Facebook account.
    - Launch Oculus Link from the settings menu.
3. The researcher will measure the IPD (Interpupillary Distance) using any means available five times. The researcher will average the 5 measures to get an estimated IPD.
4. The researcher Adjusts the IPD according to Table 1 on the HMD (Head- Mounted Display) until the image is clear.

5. The researcher will explain the button layout and the control scheme (i.e., controllers, buttons, speed controls) the researcher will explain that the user has the possibility to increase or decrease velocity whenever they need.
6. Explain the user interface (Points, timer, speed)
7. The researcher will launch the cybersickness mode and start a Timer.
    a. The participant plays for 1 minute while the researcher checks the timer.
    b. If everything works fine, the participant plays for an additional 2 minutes.
    c. If everything works fine, the participant plays for an additional 2 minutes.
8. The participant will start with the PMP tasks at the easiest difficulty.
9. The researcher will ask the participant if the difficulty needs to be adjusted or if the current setting is sufficient.
10. The researcher will adjust the difficulty level if needed.
11. The participant will play the fun mode to collect 25 coins.
12. The researcher stops the timer and makes a note of the time taken to complete everything.
13. Participants will be asked to fill in the following questionnaires.
    - NASA-TLX: NASA task load index; It is used to measure the change in mental and physical load before and after the test.
    - MSAQ: Motion sickness assessment questionnaire; it is used to measure motion sickness level after the test.
    - IPQ: igroup presence questionnaire; it is used to measure the sense of presence.
    - GDQ: game developing questionnaire; it is used to assess the quality of the design of a game.

4.1.3. Third Focus Group Meeting

The feedback from the previous FGMs went into developing the third and last version of VR-PMP. The final version of the VR-PMP was tested during two FGMs: FGM 3 and FGM 4.

4.1.3.1 Participant and VR-PMP Tasks

In FGM 3 the participants were as follows:

- 5 engineers with no VR experience

- ❖ 2 females and 3 males
- ❖ Age group (25-42 years).

FGM 3 was carried out using the third version of VR-PMP which included the following features:

- 7 PMP tasks that includes.
  - ❖ Move Forward
  - ❖ Move Backward
  - ❖ Move in a zigzag manner to avoid obstacles
  - ❖ Turn to the right
  - ❖ Turn to the left
  - ❖ Move clockwise around an obstacle
  - ❖ Move counterclockwise around an obstacle
- 20 new PMP tasks that includes.
  - ❖ Turns wheelchair power on and off.
  - ❖ Maintains contact with the joystick for a minimum of 5 seconds.
  - ❖ Pushes joystick to engage *wlc* in motion for 5 sec. and stops.
  - ❖ Moves *wlc* in forward direction for 10 sec. and stops on command.
  - ❖ Stops spontaneously to avoid stationary objects.
  - ❖ Moves *wlc* in forward direction for ten feet.
  - ❖ Moves *wlc* in forward direction for thirty-five feet.
  - ❖ Turns *wlc* to the right starting from a stationary position.
  - ❖ Turns *wlc* to the left starting from a stationary position.
  - ❖ Moves *wlc* backward on command (minimum 2').
  - ❖ Moves *w/c* forward making right and left curving turns following a person over 50 feet.
  - ❖ Veers spontaneously to avoid a stationary object.
  - ❖ Moves *wlc* forward maintaining a slow speed.
  - ❖ Understands the difference between fast and slow.
  - ❖ Stops at a door with footrests within 12" without hitting the door.
  - ❖ Stops at a line with front casters within 12" and not going over the line.
  - ❖ Maneuvers w/c through a doorway without hitting the door frame.

- ❖ Moving along a hallway, self-correcting movement to avoid the wall for a minimum of fifty feet.
- ❖ Maneuvers w/c along a curving pathway with two turns.

- An updated version of Corte Roncati
- Cybersickness mode
- City scenario
- Fun mode

In FGM 3, the performance metrics collected were more advanced and they included total time, average velocity, success rate, and trajectory data.

4.1.3.2. Study Protocol

The Study protocol for this meeting was as follows:

1. The researcher will set-up the PC
    1. Launch Oculus application.
    2. Launch MAMP database software.
    3. Launch VR-PMP
2. The researcher will set up the Oculus quest 2.
    1. Connect the oculus to the PC.
    2. Sign in using a Facebook account.
    3. Launch Oculus Link from the settings menu.
3. The researcher will measure the IPD (Interpupillary Distance) using any means available five times. The researcher will average the 5 measures to get an estimated IPD.
4. Adjust the IPD according to Table 1 on the HMD (Head Mounted Display) until the image is clear.
5. The participant is asked to fill in the following questionnaires.
    1. Preliminary questionnaire
    2. NASA-TLX (pre- session)

6. The researcher Explains the button layout and the control scheme (i.e., controllers, buttons, speed controls, trigger, grip) the researcher will explain that the user has the possibility to increase or decrease velocity whenever they need.
7. Explain the user interface (Points, timer, speed)
8. The researcher will explain that the user has the possibility to increase or decrease velocity when they want.
9. Explain the user interface (Points, timer, speed)
10. The research will launch the cybersickness mode and start a Timer.
11. Run cybersickness mode (City scenario) for 5 minutes.
    a. The participant plays for 1 minute while the researcher checks the timer.
    b. If everything works fine, the participant plays for an additional 2 minutes.
    c. If everything works fine, the participant plays for an additional 2 minutes.
12. The researcher will launch the second scenario for cybersickness mode.
13. Run cybersickness mode (Basketball court scenario) for 5 minutes.
14. If the participant is willing to continue, the researcher will launch the PMP (Powered Mobility Program) mode, the participant will play 10 PMP tasks.
15. The researcher will start the first PMP task and the participant will continue to play the other PMP tasks.
16. At task #10 the researcher will ask the participant if they need a break (after TURN LEFT)
17. The participant will continue playing the remaining tasks.
18. The participant will play the fun mode (i.e., park scenario) to collect 25 coins.
19. The researcher will stop the timer. If the participants stop to use the VR take the time and make a note
20. The participant will be asked to fill in the following questionnaires:
    a. NASA-TLX (post- session)
    b. MSAQ
    c. IPQ
    d. GDQ

4.1.4. Fourth Focus Group Meeting

The fourth FGM (FGM 4) is a follow-up to the FGM 1, some participants of the FGM 1 were asked to evaluate the final version of VR-PMP. All participants were pediatric clinicians. This FGM allowed testing the final version and validating the performance metrics of the VR-PMP.

4.1.4.1 Participant and VR-PMP Tasks

In this meeting the participants were as follows:

- 4 pediatric clinicians
  - ❖ 4 females
  - ❖ Age group (24-56 years).

The version of the VR-PMP that was used is the same version of the FGM 3 with a few tweaks to the sound effects of the circuit scenario and a few additions to the city scenario to make it safer as adding barriers to the edges of the city to prevent users from going off the map that was designed.

4.1.4.2. Study Protocol

The study protocol that was used in FGM 4 is the same as the one used in FGM 3 with one addition that was implemented based on feedback from the FGM 3 which was swapping the order of the cybersickness mode and the city mode. Participants felt that starting with the city scenario would be more convenient as the control scheme is easier in the city scenario which would be a better introduction to VR. The city scenario allows participants to get familiar with VR with fewer buttons than cybersickness mode.

4.2. Questionnaires

In this section, I will highlight the questionnaires that were used during the FGMs.

4.2.1. Questionnaire for FGM 1

	Type of question	Question	Score
1	Virtual environment & gaming experience	I like the colors used in the video game	
2	Virtual environment & gaming experience	The video game menu design is visually pleasing	
3	Virtual environment & gaming experience	I understand all the windows/writings in the scene	
4	Virtual environment & gaming experience	The instructions are clear enough	
5	Virtual environment & gaming experience	This gaming experience was fun	
6	Virtual environment & gaming experience	Did you feel immersed in the virtual environment, or did you feel like you were in the real room with us? Did you hear sounds, other people…	
	Virtual environment & gaming experience	Total	
7	usability - satisfaction - work load	The game was easy to use	
8	usability - satisfaction - work load	I think that I do not need to learn a lot of things before to use it	
9	usability - satisfaction - work load	I found the headset and controller comfortable	
10	usability - satisfaction - work load	The experience was not mentally demanding	
11	usability - satisfaction - work load	The experience was not physically demanding	
	workload	Total	
12	motion sickness	I Felt sweaty	
13	motion sickness	I felt queasy	
14	motion sickness	I felt orientated	
15	motion sickness	I felt tired	
16	motion sickness	I felt dizzy	
17	motion sickness	it was easy	
18	motion sickness	I felt safe	
	motion sickness	Total	

Table 2. Questionnaire used in the first FGM.

For FGM 1, we developed a preliminary custom questionnaire as shown in Table 2.

The users were asked to give a score from 1 to 5 for each question.

The questionnaire can be divided into three main groups of questions which are:

- Virtual environment and gaming experience: this part of the questionnaire is concerned with collecting feedback about the overall design of the game and the gaming experience.
- Usability/satisfaction/workload: this part is concerned with collecting feedback about the whole experience from a usability point of view so questions about the workload and satisfaction were asked during this part of the questionnaire.
- Motion sickness: this part is concerned with collecting feedback about the cybersickness that the users feel during and after their experience with VR.

4.2.2. NASA-TLX (task load index)

Question	Score
1. Mental workload How mentally demanding the task/ or how much you have done so far	
2. Physical workload How physically demanding has the task/or how much has been done so far?	
3. Time workload How hasty or hasty was the pace of the task/ or how much has been done so far?	
4. Performance workload	

How successful have you been in accomplishing what you have been asked to do?	
5. Effort How hard did you have to work to reach your level of performance?	
6. Frustration How insecure, discouraged, irritated, stressed, and annoyed were you?	

Table 3. NASA TLX questionnaire taken from [53,54]

As anticipated in Chapter 2, the NASA task load index (NASA TLX) described in Table 3, is a tool for measuring and conducting a subjective mental workload (MWL) assessment. It allows you to determine the MWL of a participant while they are performing a task. It rates performance across six dimensions to determine an overall workload rating. The six dimensions are as follows:

1. Mental demand: how much thinking, deciding, or calculating was required to perform the task.
2. Physical demand: the amount and intensity of physical activity required to complete the task.
3. Temporal demand: the amount of time pressure involved in completing the task.
4. Effort: how hard does the participant have to work to maintain their level of performance?
5. Performance: the level of success in completing the task.
6. Frustration level: how insecure, discouraged, or secure or content the participant felt during the task.

Each subscale is presented to the participants either during or after the experimental trial. They are asked to rate their score on an interval scale ranging from low (1) to high (21).

NASA-TLX is used to evaluate the mental workload demand on an individual performing a specific task.

Advantages

- Provides a quick and simple estimate of the operator's mental workload.

- Generic subscales allow the technique to be used across multiple domains.

Disadvantages

- May be intrusive to the task when administered during the trial.
- Participants may be prone to correlate their task performance with their workload ratings.
- When administered post-task, the participants may forget details of the task.

4.2.3. IPQ (igroup presence questionnaire)

Question	Score
1. In the world generated by the game application I had the feeling of "being there".	
2. Somehow, the virtual world surrounded me.	
3. I felt like I was just perceiving images.	
4. I didn't feel present in the virtual space.	
5. I had the feeling of acting inside the virtual space and not outside	
6. I felt present in the virtual space.	
7. How aware were you of the real world around you as you navigated the virtual world? (e.g., sounds, room temperature, other people, etc.)?	
8. I was not aware of the environment in which I really was.	
9. I continued to pay attention to the real environment.	
10. I was completely fascinated by the virtual world.	
11. How real did the virtual world seem to you?	

12. How similar did your experience in the virtual environment seem to you to your experience in the real world?	
13. How real did the virtual world seem to you?	
14. The virtual world seemed more realistic than the real world.	

Table 4. IPQ questionnaire [46]

The Igroup Presence Questionnaire (IPQ), as anticipated in Chapter 2, is a scale for measuring the sense of presence experienced in a virtual environment (VE). It has been constructed using a large pool of items and two survey waves with approximately 500 participants. It was originally constructed in German but is now also available in English and Dutch.

The following instructions are provided to the participants:

“Using the scale from 0 to 6, consider how accurately the following statements describe your experience. Each statement can be assigned a score from 0 (not at all agree) to 6 (extremely agree).”

The IPQ questions are described in Table 4. The current version of the IPQ has three subscales and one additional general item not belonging to a subscale. The three subscales emerged from principal component analyses and can be regarded as independent factors. They are:

1. Spatial Presence - the sense of being physically present in the VE.
2. Involvement - measuring the attention devoted to the VE and the involvement experienced.
3. Experienced Realism - measuring the subjective experience of realism in the VE.

The additional general item assesses the general "sense of being there", and has high loadings on all three factors, with an especially strong loading on Spatial Presence.

We understand the sense of presence as the subjective sense of being in a virtual environment. Importantly, the sense of presence can be separated from the ability of technology to immerse a user. While this immersion is a variable of the technology and can be described objectively, presence is a variable of a user's experience. Therefore, we obtain measures of the sense of

presence from subjective rating scales.The Igroup Presence Questionnaire (IPQ) is a scale for measuring the sense of presence experienced in a virtual environment (VE). It has been constructed using a large pool of items and two survey waves with approximately 500 participants. It was originally constructed in German but is now also available in English and Dutch.

The current version of the IPQ has three subscales and one additional general item not belonging to a subscale. The three subscales emerged from principal component analyses and can be regarded as independent factors. They are:

4. Spatial Presence - the sense of being physically present in the VE.
5. Involvement - measuring the attention devoted to the VE and the involvement experienced.
6. Experienced Realism - measuring the subjective experience of realism in the VE.

The additional general item assesses the general "sense of being there", and has high loadings on all three factors, with an especially strong loading on Spatial Presence.

4.2.4. GDQ (game development questionnaire)

Question	Score
1. I liked the game colors	
2. The colors of the game are tiring	
3. I liked the design (type of objects and avatars used in the game)	
4. I understood all the written instructions in the game that are clear	
5. The game is fun	
6. I felt immersed in the virtual environment (I felt inside the game, and I did not perceive that I was in the room)	
7. I was not bothered by noises or other people around me	

8. The rewards provided by the game (lives, points collected, sounds and animations) allowed me not to get bored	
9. I feel better	
10. The game application is easy to use	
11. I think I must learn a lot before I can use this game to improve wheelchair driving	
12. The equipment (viewer, joystick) is comfortable	
13. Playing this game is tiring	

Table 5. GDQ Questionnaire taken from [55]

The GDQ is a custom questionnaire developed *ad hoc* for the project to evaluate the game design and gamification (Table 5).

Participants were asked to fill in the questionnaire with the following instructions: "Using the scale from 1 to 9, rate how accurately the following statements describe your experience. Each statement can be scored from 1 (strongly disagree) to 9 (strongly agree).

This questionnaire is used to get feedback on the overall design, usability, and user experience of VR-PMP.

4.2.5. MSAQ (motion sickness assessment questionnaire)

Question	Score
1. I felt stomachache (G)	
2. I felt faint (C)	
3. I felt annoyed/irritated (S)	
4. I felt sweaty (P)	
5. I felt unwell (indisposed) (G)	
6. I felt dizzy (C)	

7. I felt sleepy (S)	
8. I felt sweaty/sweating cold (P)	
9. I felt disoriented (C)	
10. I felt tired/fatigued (S)	
11. I felt nauseous (G)	
12. I felt hot (P)	
13. I got dizzy (C)	
14. I felt like my head was spinning (C)	
15. I felt like I could vomit (G)	
16. I was anxious (S)	
Note: G: Gastrointestinal, C: Central, P: Peripheral, S: Sopite-related.	

Table 6. MSAQ questionnaire taken from [40].

The MSAQ as described in Chapter 2 is a standardized questionnaire to evaluate motion sickness during VR tasks and it is reported in detail in Table 6.

Participants were asked to fill in the questionnaire with the following instructions: "Using the scale from 1 to 9, rate how accurately the following statements describe your experience. Each statement can be scored from 1 (strongly disagree) to 9 (strongly agree).

The overall motion sickness score is obtained by calculating the percentage of total points scored: (sum of points from all items/144) × 100. Subscale scores are obtained by calculating the percentage of points scored within each factor: (sum of gastrointestinal items/36) × 100; (sum of central items/45) × 100; (sum of peripheral items/27) × 100; (sum of sopite-related items/36) × 100.

Exploratory and confirmatory factor analyses were used to differentiate motion sickness symptoms along four dimensions: gastrointestinal, central, peripheral, and sopite-related. A questionnaire was subsequently developed to assess these four dimensions of motion sickness. Total scores from the developed questionnaire correlated strongly with scores from other questionnaires, indicating that it is a valid instrument for the overall assessment of motion sickness. Thus, the MSAQ may

be used to assess both the overall experience of motion sickness (using total scores) and the four distinct dimensions of motion sickness identified (using subscale scores).

4.2.6. Preliminary Questionnaire

Question	Score
1. Do you know how to read?	
2. Have you ever played video games?	
3. Do you have a favorite genre of video games?	
3. Do you have a favorite genre of video games?	
5. If yes, have you ever tried virtual reality?	
6. If yes, have you ever tried virtual reality headsets/helmets	
7. Do you suffer from motion sickness (e.g., motion sickness)?	
8. Did you ever suffer from motion sickness when you were younger?	
9. Have you ever controlled a technology or a computer with electrodes attached to the head? (only for those who will use the BCI)	
After trying the HMD	
10. After trying the VR headset, did you feel pain?	
After trying VR (only if the participant has decided to continue the test with the headset	
11. After playing the game in VR, did you feel annoyed?	
12. The patient finished the test in VR after: (indicate the number of minutes)	

Table 7. Preliminary questionnaire

We developed a custom questionnaire (Table 7) to collect information about participants related to their previous experience with VR and cybersickness. This preliminary questionnaire is

administered before the VR-PMP evaluation except for the last 3 questions that are asked by the researcher after the VR-PMP test.

4.3. Equipment

In this section, I will discuss what kind of technologies were required to implement and run VR-PMP.

4.3.1. VR headset

To run VR-PMP we need a head-mounted display (HMD), in this section, I will highlight which HMD I used and briefly compare it to other options available.

4.3.1.1. Types of VR headsets

1. Tethered headset
    - These are headsets that are physically connected to a powerful PC.
    - Currently, they can provide the best experience on the market with full 360 tracking.
2. Smartphone
    - These are headsets that utilize your phone's processor and screen to provide VR.
    - They offer a limited experience compared to a headset that uses a PC and can only do limited tracking.
    - Often cost effective as it uses an existing mobile phone.
3. Console
    - These headsets connect and utilize the power of your console.
    - These offer a better than average experience compared to mobile headsets but are not currently on par with PC connected headsets.
    - They can only do limited tracking.

- It can be cost-effective if the owner currently owns a compatible console.

4. Stand-Alone
    - A stand-alone VR headset requires no external connections and works on its own.
    - They are currently comparable to the quality and experience of smartphone headsets but are improving constantly.
    - It can only do limited tracking.
    - It is convenient as it works straight out of the box.
5. Wireless PC
    - These are headsets that connect to a powerful PC without the use of wires.
    - They are new to the market and currently only available as an add-on to existing headsets.
    - Future headsets may choose to embed this technology.
    - It is much more useful for room scale experiences.

The Oculus Quest 2 combines the specifications of more than one type because it can be used as a wireless headset or a tethered headset or a standalone headset.

In case it is connected to the PC via the oculus link, it is tethered. On the other hand, if it is connected to the PC via air link, it acts as a wireless system. VR-PMP can be built as an android application, and it can be uploaded to the Oculus quest 2 then it can run as a standalone device without any need for a connection to a PC.

4.3.1.2. Oculus Quest 2 specifications

The following section is a summary of [56].

Hardware Specifications:

- Oculus Quest 2 (Figure 26) uses the Qualcomm Snapdragon XR2 SoC (System on Chip), a derivative of the Snapdragon 865 designed for VR and augmented reality devices. It includes 6 GB of LPDDR4X RAM
- Quest uses a singular, fast-switch LCD panel with a per-eye resolution of 1832×1920, and a refresh rate of up to 120.
- The headset supports physical interpupillary distance (IPD) adjustment at 58 mm, 63 mm, and 68 mm, adjusted by physically moving the lenses into each position.
- Tracking: Supports 6 degrees of freedom head and hand tracking through integrated Oculus Insight technology.
- Storage: 256GB
- Display Resolution: 1832×1920 per eye.
- Audio: Integrated speakers and microphone; also compatible with 3.5mm headphones.
- Battery Life: You can expect between 2-3 hours based on the kind of content you are using on Quest 2; closer to 2 hours if you are playing games and closer to 3 hours if you are watching media. At any point, you can check the battery status of your headset in the Oculus App settings or in VR via Oculus Home.
- Charge Time: With the provided USB-C power adapter, Quest 2 will charge to a full battery in about 2.5 hours.
- IPD: Adjustable IPD with three settings for 58, 63 and 68mm.
- Playspace: Stationary or Roomscale supported. Roomscale requires a minimum of 6.5feet x 6.5 feet of obstruction-free floor space.

Software Specifications: Oculus Quest 2 runs an Android-based operating system. To conduct first-time setup, a smartphone running the Meta Quest app must be used.

Figure 26. Oculus Quest 2

4.3.2. Gaming Laptops

To build VR-PMP and run it there is a need for a PC that can run VR and handle a load of running it without any frame drops or lag because frame drops cause cybersickness in VR.

To ensure smooth performance we used two laptops which are the Lenovo legion 7 Gen 6 and the MSI GP76 Leopard 11UG-1050IT.

Lenovo Legion 7 has the following specifications:

- CPU: 11th Generation Intel® Core™ i7-11800H Processor (2.30 GHz, up to 4.60 GHz with Turbo Boost, 8 Cores, 16 Threads, 24 MB Cache)
- GPU: NVIDIA® GeForce RTX™ 3070 Laptop GPU, 8GB GDDR6, listed boost clock 1560MHz, achieved boost clock 1620MHz, maximum graphics power 140W.
- RAM: 16GB DDR4 3200 MHZ
- OS: Windows 11
- Storage: 1TB SSD
- Display: 16"

MSI GP76 Leopard 11UG-1050IT has the following specifications:

- CPU: 11th Generation Intel® Core™ i7-11800H Processor

- GPU: NVIDIA® GeForce RTX™ 3070 Laptop GPU, 8GB GDDR6.
- RAM: 16GB DDR4 3200 MHZ
- OS: Windows 11
- Storage: 512GB SSD
- Display size: 17.3"

Chapter 5. Results

5.1. FGM 1 Results

The data that was collected during FGM 1 was:

- the participants were asked to fill in the questionnaire in Table 2
- user data such as number of collisions, total time, success rate

The success rate was calculated as a ratio of number of successful attempts to total number of attempts.

The questionnaire answers were analyzed and then the following criteria were obtained:

- Game Design
- Usability
- Gameplay
- Sense of Presence
- Mental Load
- Physical Load
- Motion Sickness

These criteria were obtained by grouping the answers of relevant statements from the questionnaire.

- Game Design criterion score was obtained by grouping the first two statements of the questionnaire in Table 2 which were:
  - ❖ I like the colors used in the video game.
  - ❖ The video game menu design is visually pleasing.
- Usability criterion score was obtained using the following two statements:
  - ❖ I understand all the windows/writings in the scene.
  - ❖ The instructions are clear enough.

- Gameplay criterion score was obtained using the following statement.
  - ❖ This gaming experience was fun.
- Sense of presence criterion score was obtained using the following statement.
  - ❖ Did you feel immersed in the virtual environment, or did you feel like you were in the real room with us? Did you hear sounds or other people?
- Mental load criterion score was obtained using the following statement.
  - ❖ I think that I do not need to learn a lot of things before using VR-PMP
  - ❖ The experience was mentally demanding.
- Physical load criterion score was obtained using the following statement.
  - ❖ The game was easy to use.
  - ❖ I found the headset and controller comfortable.
  - ❖ The experience was not physically demanding.
- Motion Sickness criterion score was obtained using the following statement.
  - ❖ I felt sweaty.
  - ❖ I felt queasy.
  - ❖ I felt oriented.
  - ❖ I felt tired.
  - ❖ I felt dizzy.
  - ❖ It was easy.
  - ❖ I felt safe.

Each of the previous statements were presented to the participants and they had to give the statement a score that ranges from 0 to 5 where 5 is strongly agree and 0 strongly disagree. Each criterion was given a score which was the average of the answers given by participants.

Participants were grouped into 3 groups which are adult clinicians, pediatric clinicians and end users, and the average of the answers of these groups were calculated. These averaged values were used along with a Likert Scale to obtain the following figures (Figure 27, 28, and 29).

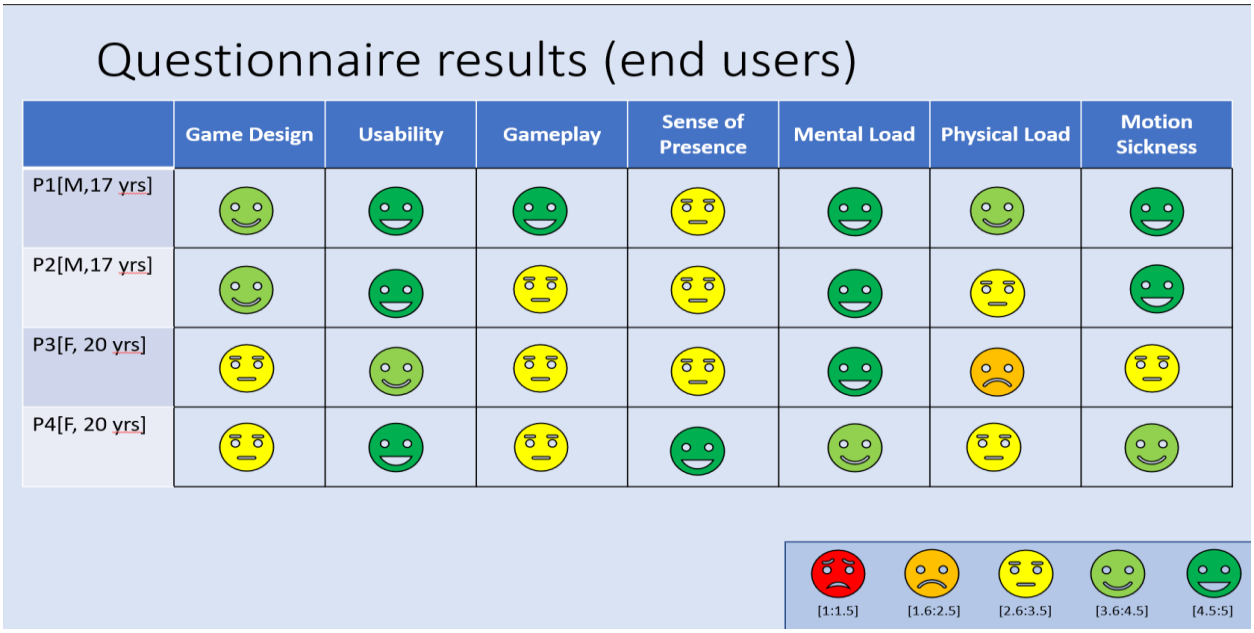


Figure 27. First questionnaire for the end users' group.

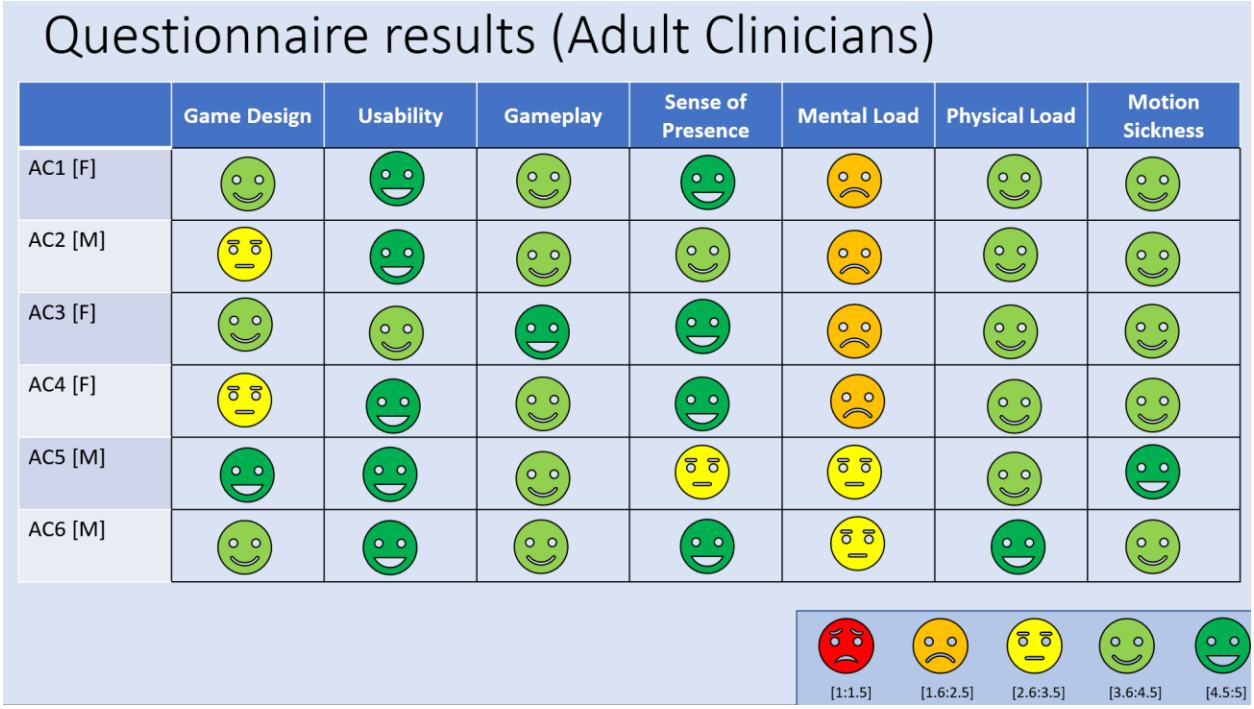


Figure 28. First questionnaire for the adult clinicians' group.

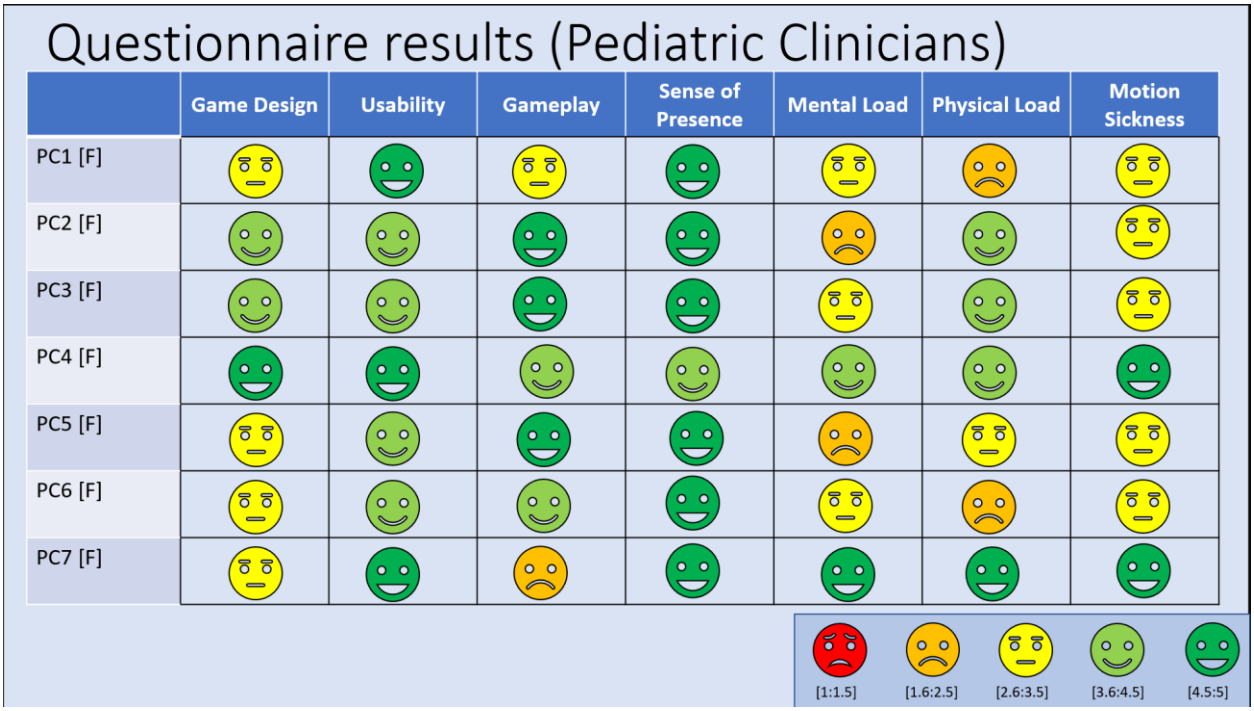


Figure 29. First questionnaire for the pediatric clinicians' group.

Based on the feedback that was received the following changes were implemented to the second version of VR-PMP.

- The court scenario was completely replaced by an innovative design.
- The color scheme of the basketball court was changed.
- A new cybersickness mode was added.
- The study protocol was modified, and new questionnaires were added.
- A new city scenario was added.

5.2. FGM 2 Results

The data that was collected during the second FGM was:

- user data such as number of collisions, total time, trajectory data, player name, and in the court mode the number of coins collected.
- participants filled in the following questionnaires.

- ❖ MSAQ
- ❖ IPQ
- ❖ GDQ

The trajectory data that were collected is compared to a baseline by calculating the RMSE (root mean square error) value, this value was calculated in Matlab R2022a and then the data was plotted also using Matlab.

The trajectory data and other data was saved as a text file for security on the same PC.

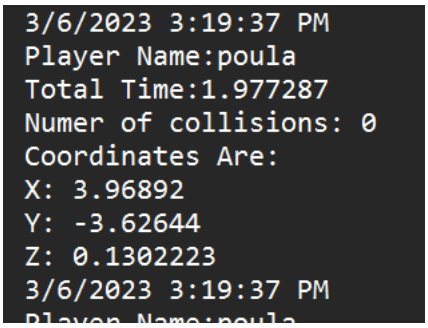


Figure 30. Sample of the data saved in the text file.

Figure 30 it shows that there is a timestamp for every data entry in the text file and the data that is saved is:

- player name
- total time (up to that point)
- number of collisions
- x, y, and z coordinates of the avatar in the virtual environment

The saving of this data is done using a C# script in unity that invokes repeating of a function every half a second, so the stream of data is continuous which is significant in case of trajectory data.

The analysis of the data collected produced the results reported in Figure 31.

Participants	Gender	Age	Total time (Seconds)	number of collisions	number of scenarios played	Scenarios Played	Trajectory MSE X	Trajectory MSE Y	Average MSE X	Average MSE Y
P01	M	37	165	1	4	CH, FE, ZE, ZH	For CH:1.1303 For FE:0.4917 For ZE:1.1264 For ZH:3.4146	For CH:5.5671 For FE:7.9964 For ZE:4.5223 For ZH:9.7896	1.54	6.97
P02	F	16	107	0	1	ZM	For ZM:2.0502	For ZM:10.5204	2.05	10.52
P03	M	35	113	0	2	FM, ZM	For ZM:4.072 For FM:0.232	For ZM:12.088 For FM:8.0426	2.15	10.06
P04	F	24	309	0	2	CM, ZM	For ZM:2.8828 For CM:1.2671	For ZM:10.5301 For CM:5.7693	2.07	8.1497
P05	M	25	69	0	2	CM, ZH	For CM:1.7473 For ZH:3.9079	For CM:5.9542 For ZH:8.8679	2.82	7.41
P06	M	25	66	0	3	CH, CM, ZM	For ZM:0.9506 For CH:0.7382 For CM:0.9625	For ZM:9.2317 For CH:4.7609 For CM:5.6301	0.88	6.54
Baseline	M	27		0	6	CH,CM,FE,FM,ZM,ZH				

Figure 31. Data collected and calculated RMSE

In Figure 31 we had the following data saved for each participant:

- Gender
- Age
- Total time (in seconds)
- Number of collisions
- Number of scenarios played
- The RMSE with respect to X
- The RMSE with respect to Y
- The average RMSE

Note that in this version of the VR-PMP the PMP tasks that were used were:

- Zigzag
- Move Forward
- Move Backward
- Turn Right
- Turn Left
- Rotate clockwise around an object
- Rotate counterclockwise around an object

The abbreviations for the scenarios in Figure 31 are as follows:

- CH: clockwise scenario on hard difficulty
- FE: forward scenario on easy difficulty
- ZE: zigzag scenario on easy difficulty
- ZH: zigzag scenario on hard difficulty
- ZM: zigzag scenario on medium difficulty
- FM: forward scenario on medium difficulty
- CM: clockwise scenario on medium difficulty

The trajectory data was plotted to give a visual representation of how the participant is performing compared to a baseline. In this case, the baseline was estimated on me (male, 27 years old, able-bodied) due to the fact that I developed the game. I repeated each task 5 times and then I averaged the obtained trajectories to obtain the baseline reference. Some examples are reported in Figures 32-34 for some participants.

In the future, there will be a control group that will help define the trajectory baseline.

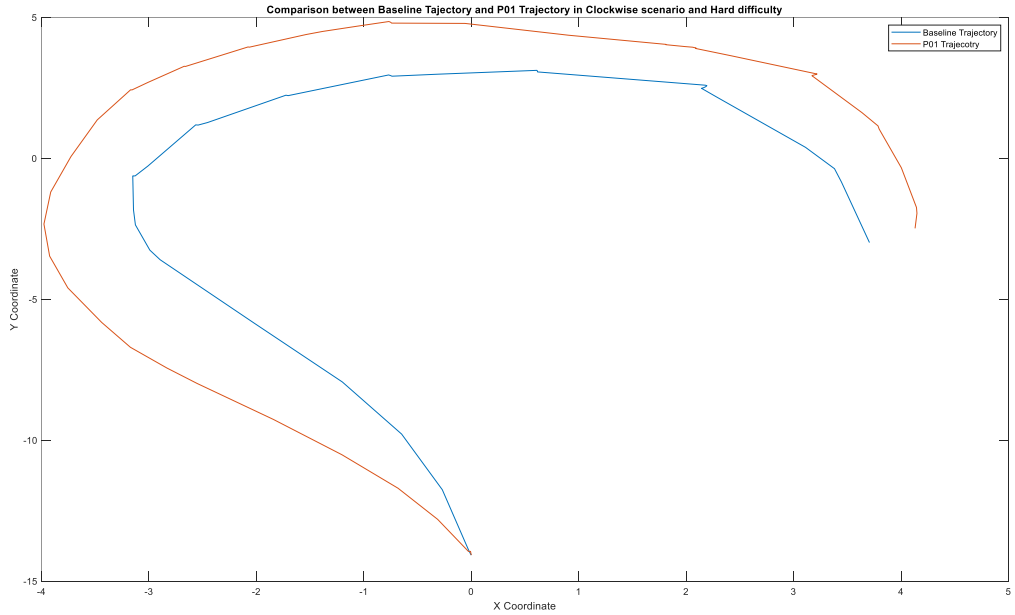


Figure 32. The trajectory of P01 plotted against a baseline in the CH scenario.

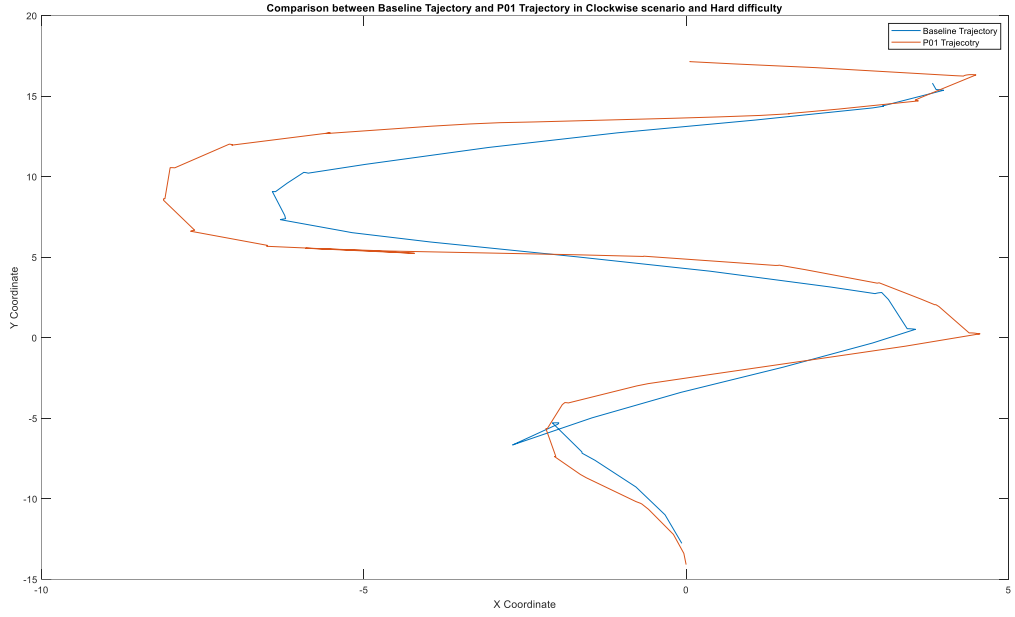


Figure 33. The trajectory of P01 plotted against a baseline in the ZH scenario.

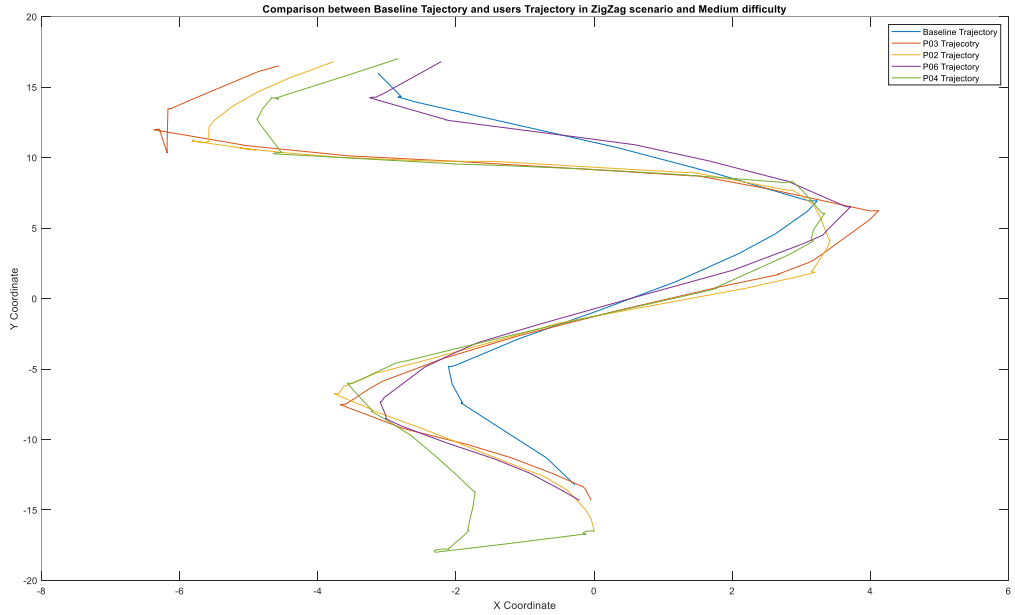


Figure 34. Trajectories of 4 participants against a baseline in the ZM scenario.

The results of the questionnaires were analyzed in Matlab and visualized using a boxplot and the results reported in Figure 35 were obtained.

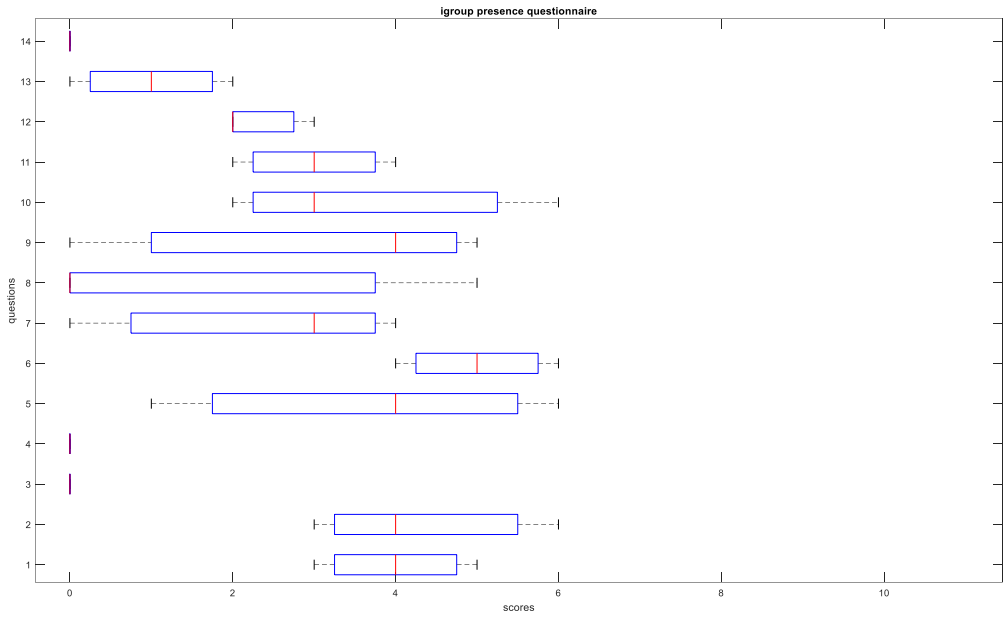


Figure 35. Boxplot of IPQ for FGM 2

By examining the Boxplot, we can deduce the following considerations about the participants:

- They all answered question 3 with zeros which means they all did not sense that they were just perceiving images, their experience was that they felt connected to the environment, and they felt "present" in the scenario they were completing.
- They also answered question 14 with all zeros which means that they did not have problems differentiating between the virtual world and the real world.
- They answered question 4 with all zeros which means that they felt present in the Virtual world and had a sense of presence as if they were their avatar.

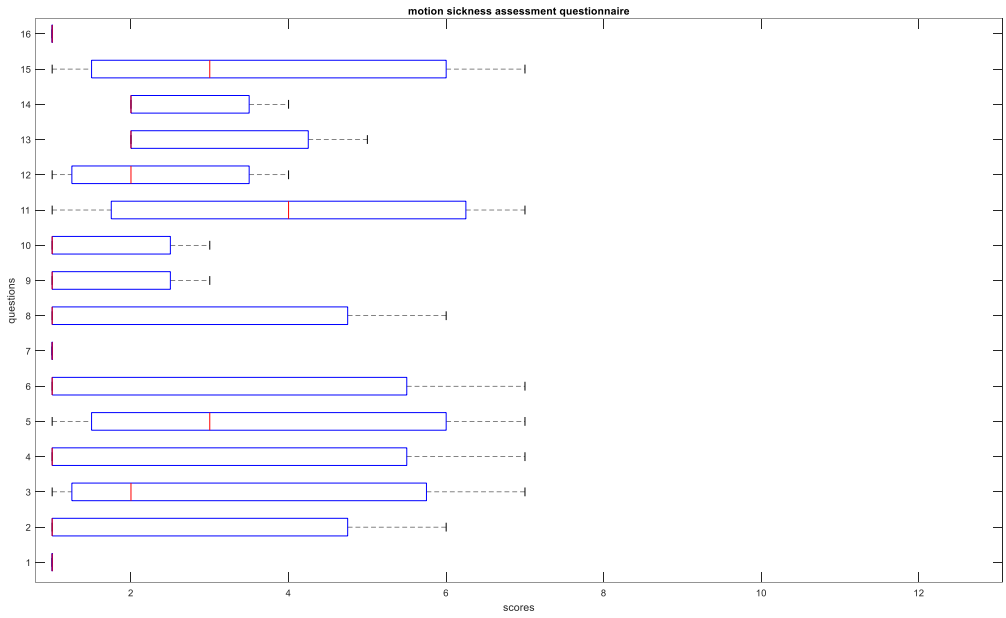


Figure 36. Boxplot of MSAQ for FGM 2

By examining the Boxplot reported in Figure 36, we can deduce the following about the participants:

- They all answered question 16 with zeros which means they did not feel anxious during their time inside the virtual environment.
- They answered question 7 with zeros which means they were not sleepy during the test, so VR-PMP is considered engaging.
- They also answered question 1 with zeros which means that they did not feel a stomachache during the test, so no physical side effects to VR-PMP.

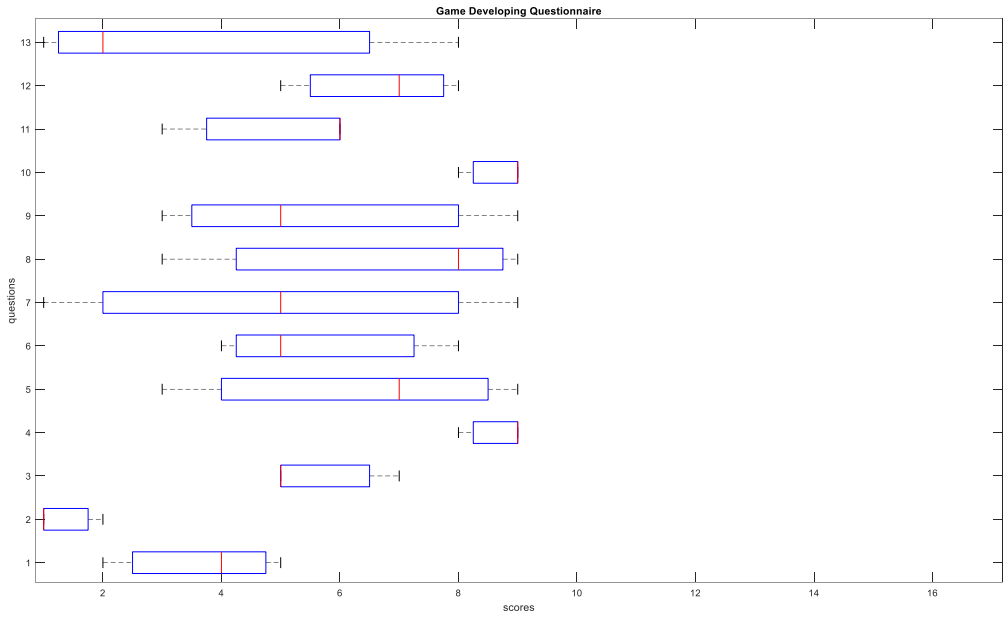


Figure 37. Boxplot of GDQ for FGM2

By examining the Boxplot reported in Figure 37, we can deduce the following about the participants:

- By looking at the boxplot for question 10 we can see that the participants agree that the application is easy to use
- The boxplot of question 2 indicates that the participants disagree that the color scheme of the game is tiring because the spread of the score is limited in the low range which indicates disagreement with the statement they were given during the questionnaire.
- The box plot of question 4 indicates that the participants have all found it easy to understand the instructions written in the game and found them clear.

Based on the feedback that was received the following changes were introduced to the third and final version of VR-PMP.

- The study protocol was modified, the city scenario will precede the cybersickness mode in the following FGMs.
- In addition to the 7 PMP tasks there are now 20 completely new PMP tasks.

5.3. FGM 3 Results

This meeting involved the final version of PR-PMP and new study protocol. So, at the end I had the following data to analyze.

- Total time, number of collisions, trajectory data
- The results of the following questionnaires
  - ❖ NASA-TLX pre and post the VR session
  - ❖ MSAQ
  - ❖ GDQ
  - ❖ IPQ

First: I analyzed the results of the questionnaire in Matlab and got the following findings.

- For NASA-TLX pre and post, I decided to use a paired t-test because the sample size is 5 which is less than 30 so the t-test here is the optimal hypothesis test (25).

  The t-test was applied to every question in the NASA-TLX before and after to see if VR-PMP caused a rise in the mental or physical load on the participants.

  Before applying the t-test according to NASA-TLX guidelines the score obtained from participants must be multiplied by 5 in case of even numbers and in case of odd values we subtract 1 first then multiply by 5.

  In the end the following p-values were obtained for the questions:

  P1=0.3383,

  P2=0.5401,

  P3=0.1138

  P4=0.1707

  P5=0.7489

  P6=0.2821

Since all the p-values are all higher than 0.05 then we can hypothesize that VR-PMP did not increase mental or physical stress level in participants.

- For GDQ, IPQ and MSAQ, I used a boxplot to visualize and analyze the participants' responses and the following plots were obtained.

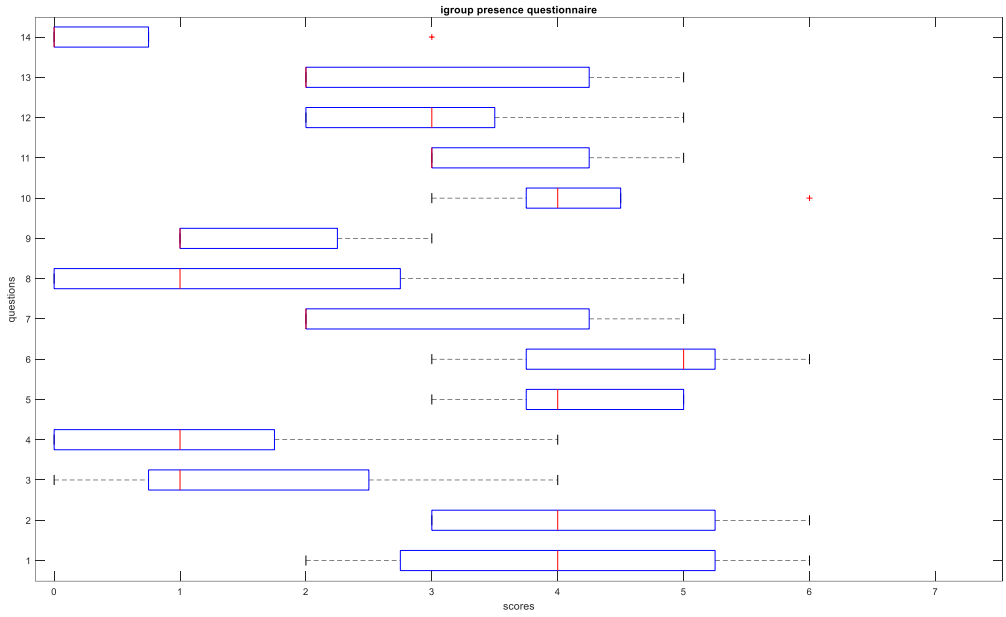


Figure 38. Boxplot of IPQ for FGM 3

Examining the boxplot reported in Figure 38, for IPQ for FGM 3, we can deduce the following.

- The participants agree on question 10 that the virtual world was fascinating with a score of 3 and with one outlier that answered that question with a 6 which means fully agree.
- The participants agree on question 14 that the virtual world did not seem more realistic than the real world, except one outlier who gave a score of 3 to that question on a scale that has a maximum of 6 and minimum of 0.

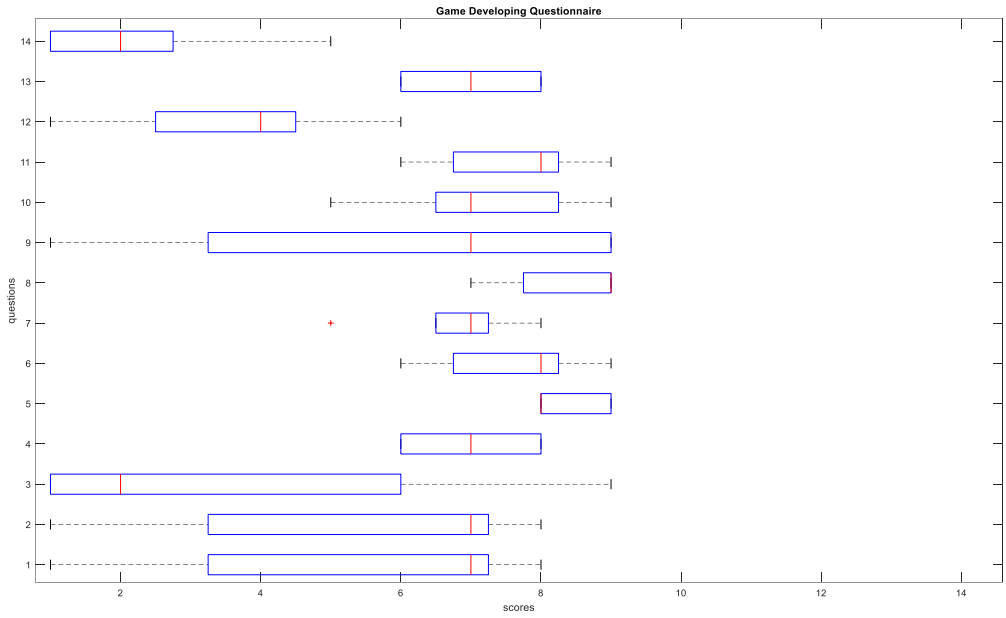


Figure 39. Boxplot of GDQ for FGM 3

Examining the boxplot for GDQ for FGM 3 (Figure 39), we can deduce the following.

- The participants agree on question 5 that the game is fun!
- The participants agree on question 7 that they were not annoyed by the noises or other people around them, which is an indication of a sense of immersion.
- The participants agreed on question 8 that the reward system implemented in VR-PMP was engaging and increased their focus on finishing the task.
- The participants agree on question 14 that the game is not tiring.

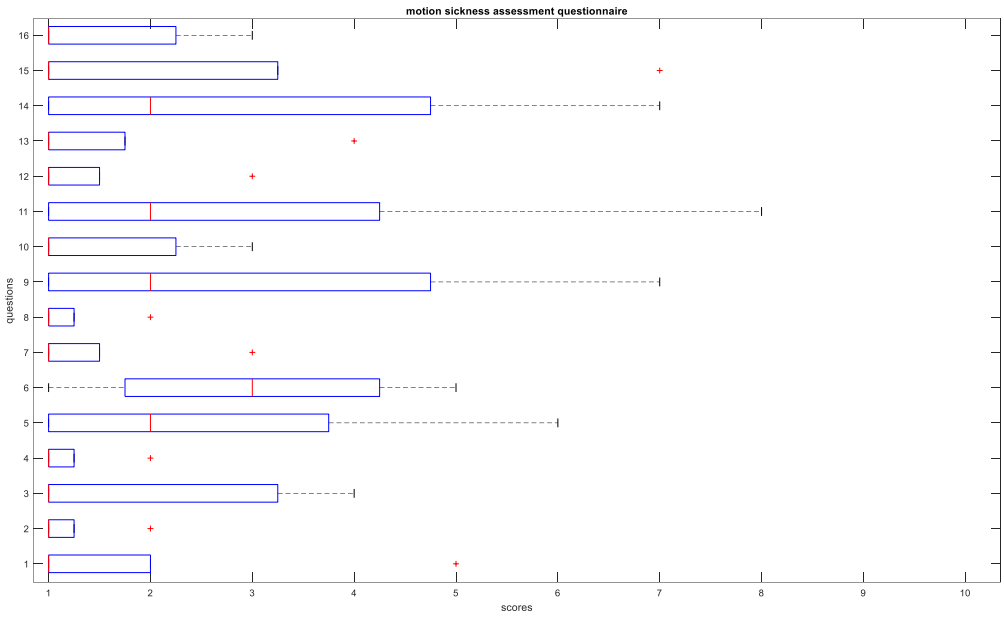


Figure 40. Boxplot of MSAQ for FGM 3

Examining the boxplot for MSAQ for FGM 3 (Figure 40), we can deduce the following.

- The participants agree on question 2 that the game did not cause them to feel fainted with only one outlier that answered with a score of 2 (on a scale that ranges from 1 to 9) out of a sample of 5.
- The participants agree on question 4 that the game did not cause them to feel sweaty with only one outlier that answered with a score of 2(on a scale that ranges from 1 to 9) out of a sample of 5.
- The participants agreed on question 7 that the game did not cause them to feel sleepy with only one outlier that answered with a score of 3 out of a sample of 5.
- Two participants reported to feel disoriented but with a score value that is close to the median of the scale (score values of 4 and 7).
- One participant reported feeling nauseated and answered question 11 with a score value of 8.

Then, I analyzed the trajectory of the participants against the baseline that was calculated using 5 trials that were all performed by me. Two examples for tasks 12 and 20 are reported in Figures 41 and 42, respectively.

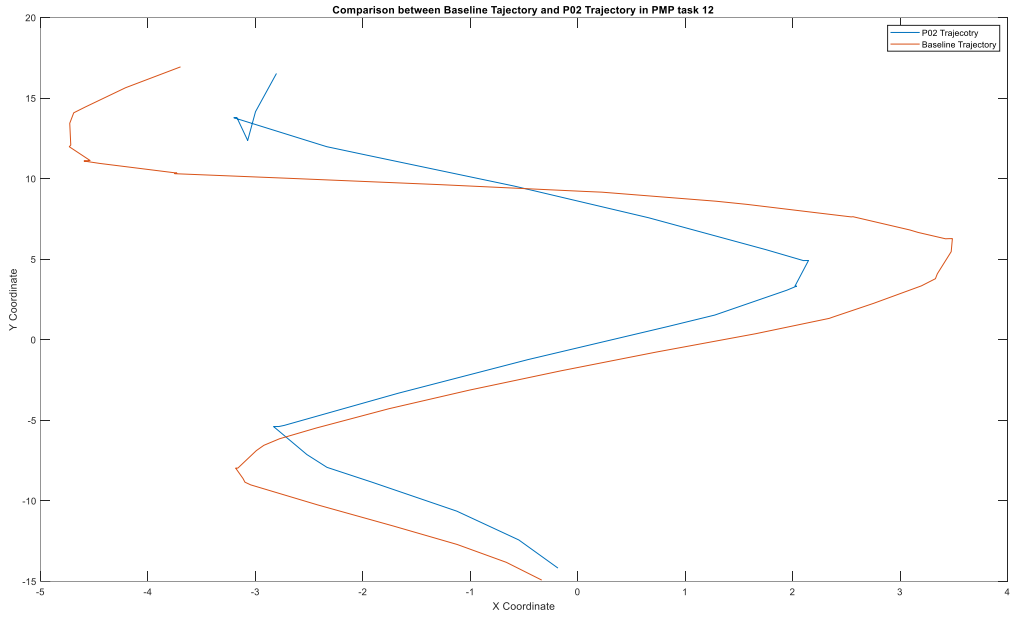


Figure 41. P02 trajectory vs the baseline in task 12

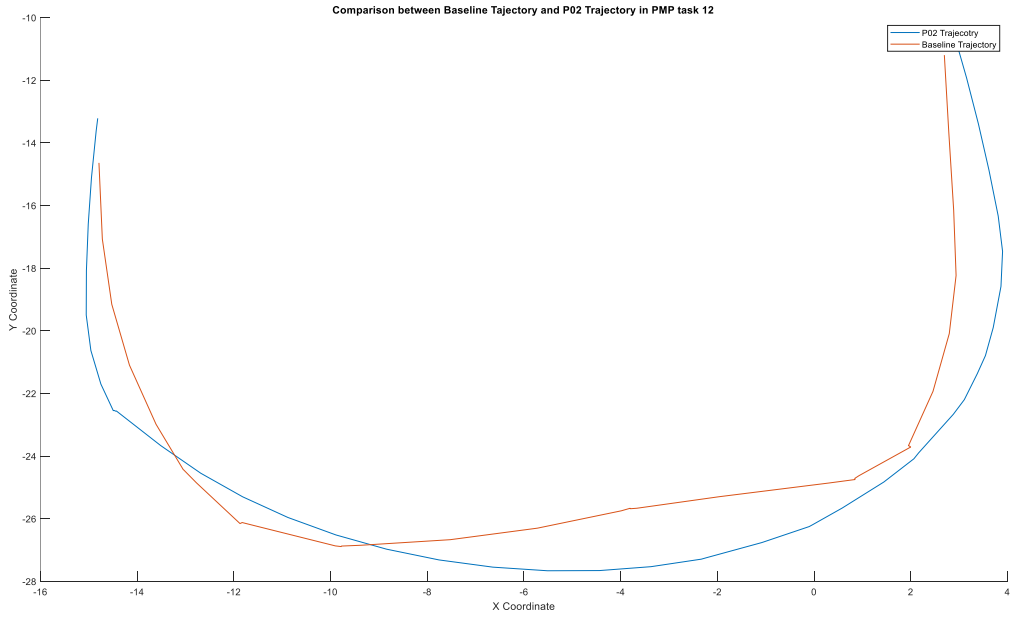


Figure 42. P02 trajectory vs the baseline in task 20

5.4. FGM 4 Results

This section presents the results obtained during FGM 4 where participants evaluated the final version of VR-PMP. The same study protocol used in FGM 3 was used. I analyzed the following data:

- Total time, number of collisions, trajectory data
- The results of the following questionnaires
  - ❖ NASA-TLX pre and post the VR session
  - ❖ MSAQ
  - ❖ GDQ
  - ❖ IPQ

First: I analyzed the results of the questionnaire in Matlab and obtained the following findings:

- Same as with FGM 3, I used paired t-test to analyze the data of the NASA-TLX In the end the following p-values were obtained for the 6 questions of NASA-TLX:
  P1=0.9282
  P2=0.1169
  P3=0.1552
  P4=0.8240
  P5=0.3189
  P6= 0.3822

  Since all the p-values are all higher than 0.05 then we can hypothesize that VR-PMP did not increase mental or physical stress level in participants.

- For GDQ, IPQ and MSAQ, I used a boxplot to visualize and analyze the participants' responses and the following plots were obtained.

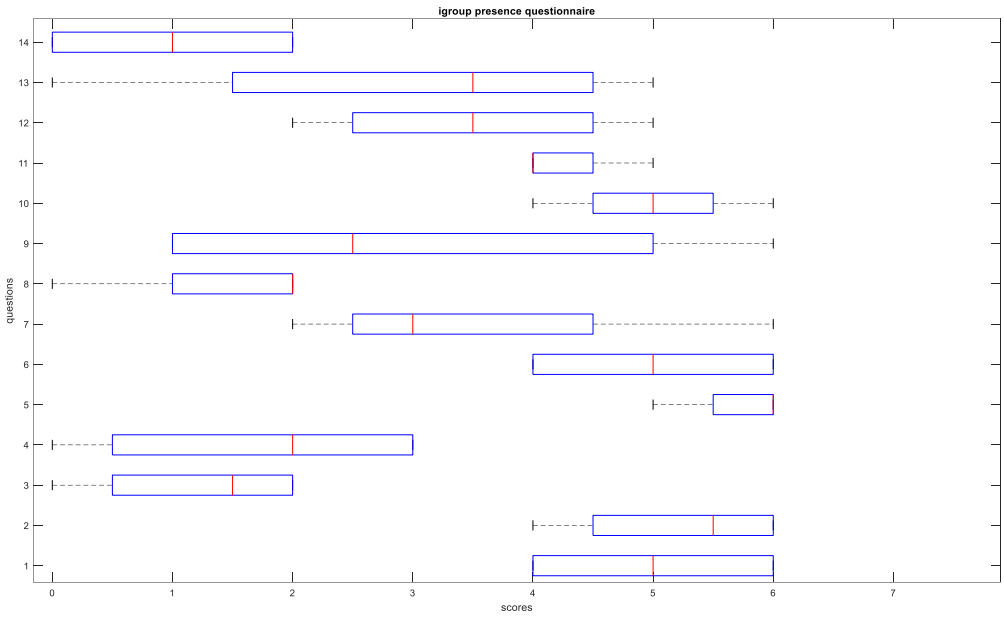


Figure 43. Boxplot of IPQ for FGM 4

Examining the boxplot for IPQ for FGM4 (Figure 43), we can deduce the following considerations:

- The participants agree on question 5 that their actions were replicated accurately in the virtual environment.
- The participants agree on question 11 that the world seems moderately realistic.

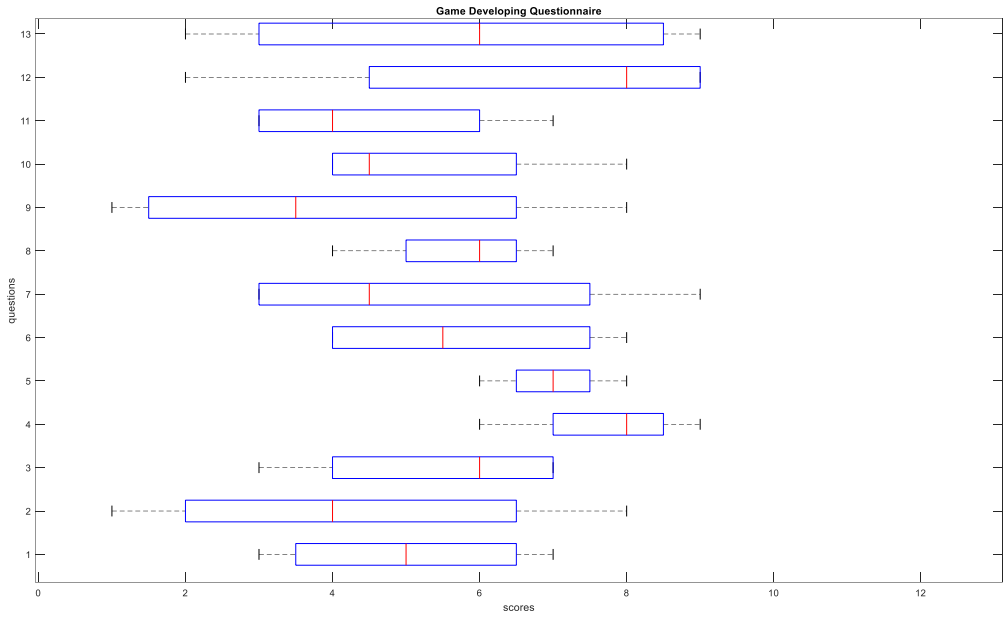


Figure 44. Boxplot of GDQ for FGM 4

Examining the boxplot for IPQ for FGM 4 (Figure 44), we can deduce the following.

- Same as with the results of FGM 3, the participants found the game to be fun.
- The participants also agreed that the reward system implemented is engaging and exciting.

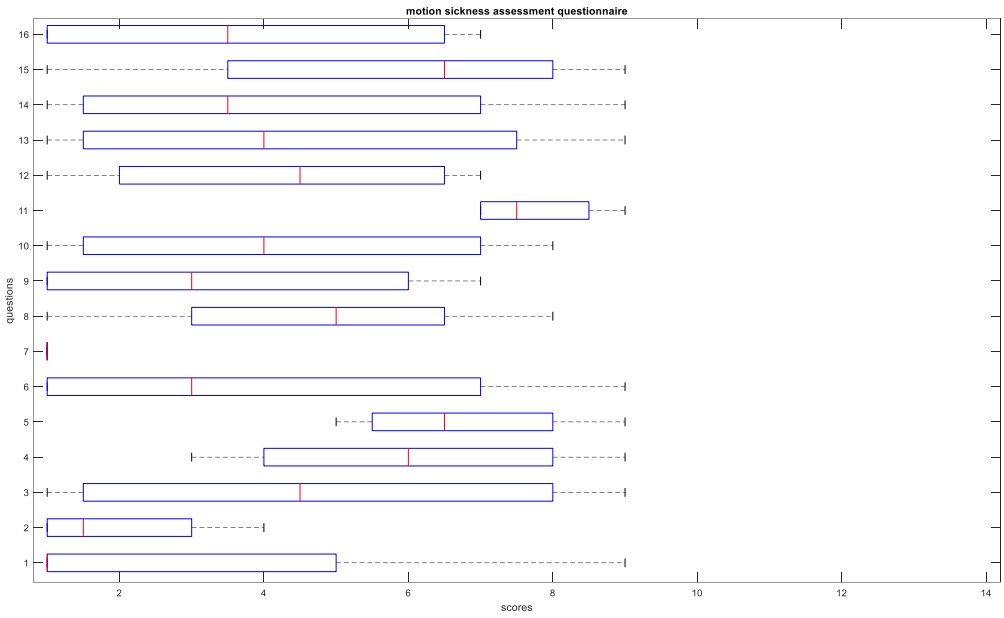


Figure 45. Boxplot of MSAQ for FGM 4

Examining the boxplot for MSAQ for FGM 4 (Figure 45), we can deduce the following considerations:

- The participants agreed that they felt nauseated after using VR-PMP
- The participants agreed that they did not feel like fainting after using VR-PMP

Then, I analyzed the trajectory of the participants against the same baseline that was used in FGM 3. Two examples for tasks 12 and 20 are reported in Figures 46 and 47, respectively.

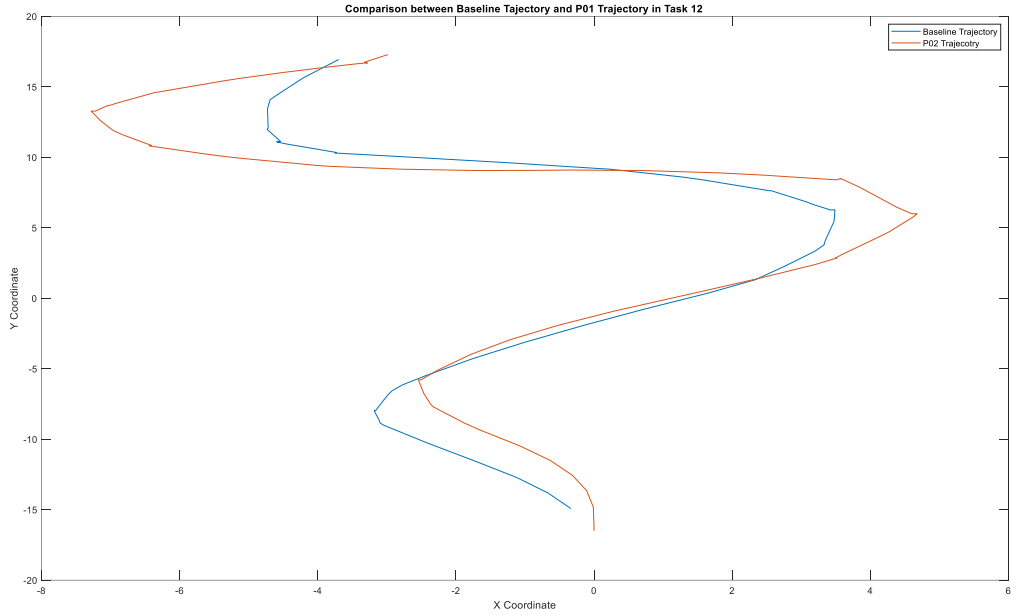


Figure 46. P01 trajectory vs the baseline in task 12

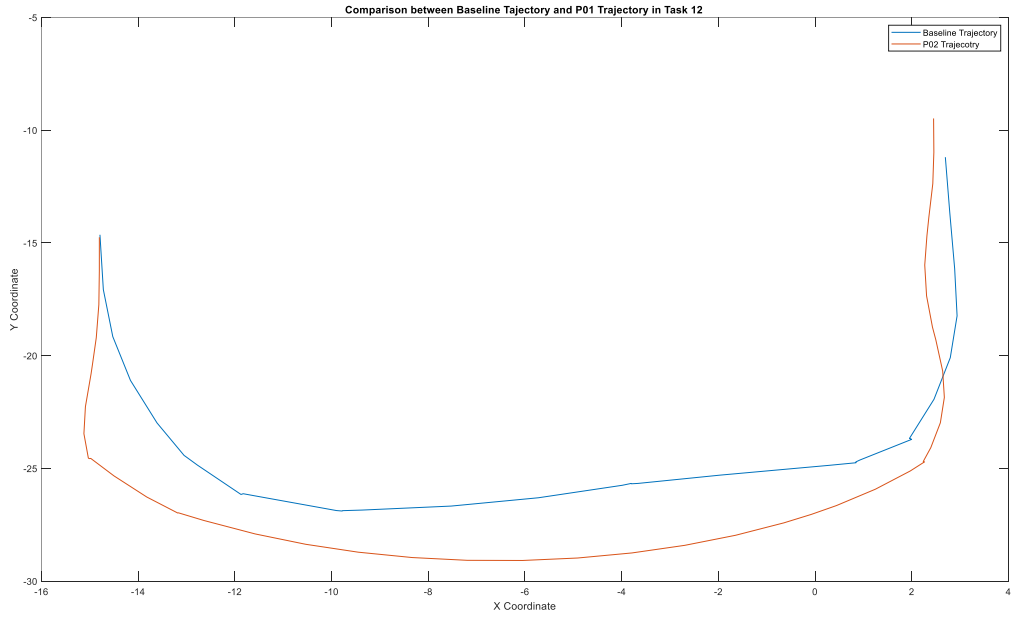


Figure 47. P01 trajectory vs the base line in task 20

Chapter 6. Discussion and Future Work

6.1. Discussion

Virtual reality (VR) constitutes a portable solution to perform safe training. To date, no existing VR simulators have been developed to assess users' driving skills. Also, the existing VR simulators allow controlling movements with joysticks or hand trackers, but they are unusable for individuals with severe upper limb motor impairments.

After analyzing the results of all four focus group meetings, we can deduce that VR-PMP is a step in the right direction to having an alternative training method that does not require individuals to visit rehabilitation centers for powered wheelchair training which will save time and effort for the individuals and their families, and at the same time it will reduce the overburnt situation in the rehabilitation centers allowing to provide assistance to a greater number of patients.

After analyzing the questionnaires for FGM 3, it can be noted that the participants were all engineers who spend most of their time using computers and monitors which can explain why most of them did not suffer from severe cybersickness symptoms (one participant reported mild cybersickness symptoms) although they are not VR users. On the other hand, the participants in FGM 4 were clinicians who spend most of their time interacting with patients, their questionnaires results reflect that they suffered from more serious cybersickness symptoms, and one participant was not able to finish all 20 the PMP tasks of the PMP mode.

The results of the questionnaires together with the data collected during the usage of VR-PMP show that despite the cybersickness that some patients might have to deal with at the beginning of training, VR-PMP is a viable option for powered wheelchair training.

6.2. Future Work

One of the features of VR-PMP is that it can have more than one input system, so for individuals with severe motor disabilities who have no control over their upper limbs, in this context, brain-computer interfaces (BCIs) represent a potential candidate as an innovative control interface. A limited number of studies have explored the development of alternative control interfaces based on electromyography, eye-tracking, and electroencephalography (EEG) solutions but currently, there is a lack of clarity related to the best interface that should be used to control VR systems. Also, related to the EEG-BCI control interface there is a lack of clarity related to the type of paradigm more appropriate for VR systems. In the future, these questions can be addressed and VR-PMP may help start a new generation of training protocols for individuals with severe motor disabilities.

The data collected using VR-PMP (e.g., time, number of collisions, RMSE) can be used to calculate a PMP score that will be given as feedback at the end of the PMP test. This score will be calculated using a formula that relates all the performance metrics.

In closing, VR-PMP and the alternative access pathway based on an EEG-BCI system would allow a larger number of children to have access to powered wheelchairs improving their driving skills and reducing the risk of abandonment of the technology, but more testing and validation are required.

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