DEPARTMENT OF COMPUTER SCIENCE

JOÃO MIGUEL DUARTE VIANA
Bachelor in Science and Computer Engineering

FROM AUGMENTED TO VIRTUAL REALITY: EXPLORING THE VIRTUALITY CONTINUUM IN PARKINSON'S DISEASE THERAPY

MASTER IN COMPUTER SCIENCE AND ENGINEERING

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"Can you hear the music?
Yes, I can."

— Niels Bohr and J. Robert Oppenheimer,
Oppenheimer (2023), Christopher Nolan
(Dialogue in film)

Abstract

Parkinson's Disease (PD) is a progressive neurological disorder that affects movement through symptoms such as tremors, rigidity, and slowness, with a strong impact on patients' quality of life. Since current treatments are mainly symptomatic, new complementary strategies are needed. One of the main challenges is the lack of motivation in patients, which affects their adherence to exercise plans. In this context, interactive tools that can engage patients play an important role.

This dissertation explores the use of immersive technologies for PD therapy, focusing on how different levels of immersion influence the user experience. A serious game, Fruit Picker XR, was developed for the Meta Quest platform, supporting a progression from Augmented Reality (AR) with fewer virtual elements to fully immersive Virtual Reality (VR). This design makes it possible to test multiple steps along the virtuality continuum, instead of just comparing AR and VR as two extremes.

Two user studies were carried out. The first compared AR and VR versions with healthy participants and people with PD. The second extended this work by testing three different levels of immersion in a refined version of the game integrated with a therapeutic platform. Results from both studies showed that PD patients found AR easier and less demanding, while VR offered stronger immersion but higher workload. The intermediate level in the second study suggested a possible balance, combining accessibility with greater sense of presence. Usability scores were positive overall, and eye-tracking data provided additional insights into how attention shifted across the different immersion levels.

The study confirms the potential of immersive technologies for rehabilitation, while also pointing out their limitations. Future work should include tests with larger groups of PD patients, improvements to the questionnaires to make them more suitable for clinical populations, and longitudinal studies to assess therapeutic effectiveness. This work has already been disseminated in two co-authored scientific publications, and provides a basis for further research on the use of immersive technologies in therapy.

Keywords: Parkinson's Disease, User Experience, Virtual Reality, Augmented Reality, Virtuality Continuum, Serious Games for Rehabilitation

Resumo

A doença de Parkinson (DP) é uma doença neurológica progressiva que afeta o movimento, com sintomas como tremores, rigidez e lentidão, e um forte impacto na qualidade de vida. Como os tratamentos atuais são sobretudo sintomáticos, são necessárias estratégias complementares. Um dos principais desafios é a falta de motivação, que reduz a adesão aos planos de exercício; por isso, ferramentas interativas capazes de envolver os pacientes podem ser relevantes.

Esta dissertação explora o uso de tecnologias imersivas na terapia da DP, analisando como diferentes níveis de imersão influenciam a experiência do utilizador. Foi desenvolvido o jogo sério Fruit Picker XR para a plataforma Meta Quest, permitindo uma progressão da Realidade Aumentada (RA) para a Realidade Virtual (RV) totalmente imersiva. Este design possibilita testar várias etapas ao longo do continuum da virtualidade, em vez de comparar apenas RA e RV como extremos.

Foram conduzidos dois estudos. O primeiro comparou RA e RV com participantes saudáveis e pessoas com DP. O segundo testou três níveis de imersão numa versão refinada do jogo, integrada numa plataforma terapêutica. Em ambos, os pacientes com DP consideraram a RA mais fácil e menos exigente, enquanto a RV aumentou a sensação de imersão, mas com maior carga de trabalho. O nível intermédio sugeriu um possível equilíbrio entre acessibilidade e presença. As pontuações de usabilidade foram, no geral, positivas, e os dados de rastreamento ocular ajudaram a compreender mudanças de atenção entre níveis de imersão.

O estudo confirma o potencial das tecnologias imersivas para a reabilitação, apontando também limitações. Trabalho futuro deverá incluir amostras maiores de pacientes, questionários mais adequados a populações clínicas e estudos longitudinais para avaliar eficácia terapêutica. Este trabalho foi divulgado em duas publicações científicas em coautoria e fornece uma base para investigação futura.

Palavras-chave: Doença de Parkinson, Experiência de Utilizador, Realidade Virtual, Realidade Aumentada, Continuo de Virtualidade, Jogos Sérios para Reabilitação

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Acronyms

AR Augmented Reality *(pp. ix, 1–4, 6, 13–17, 19–21, 24–27, 29–31, 33–35, 37, 39, 51, 53, 67, 73, 74, 79, 81)*

CL Cognitive Load *(p. 53)*

HMD head-mounted display *(pp. 14, 17)*

IPQ Igroup Presence Questionnaire *(p. 33)*

MR Mixed Reality *(pp. 6, 13, 14, 16, 17, 27, 31)*

PD Parkinson's Disease *(pp. iv, 1–4, 6–12, 18, 21–28, 30, 33–35, 37, 39, 51, 53, 67, 70, 78, 83, 84)*

SGs Serious Games *(pp. 3, 11–13, 27)*
SUS System Usability Scale *(p. 32)*

UI User Interface *(p. 39)*

VR Virtual Reality *(pp. 1–4, 6, 13–15, 17, 20–22, 25–31, 33–35, 37, 39, 51, 53, 67, 74, 76, 79, 81)*

XR Extended Reality *(pp. 14, 17, 27)*

1

Introduction

The chapter introduces PD, describing the burden of the condition on patients and the shortcomings of current therapeutic approaches. Herein, it puts forward the potential of immersive technologies, such as Virtual Reality (VR) to AR, to innovate therapy in PD. The chapter outlines the motivation behind this research, sets the context for the study, and presents the proposed solution, which involves the development of an interactive therapeutic game. Finally, the structure of this dissertation document is briefly described.

1.1 Motivation

PD is a progressive neurodegenerative disorder of the central nervous system associated with severe motor control impairment and a wide range of non-motor symptoms. According to the Parkinson's Foundation [50], more than 10 million people worldwide are living with PD, and this number is expected to increase as the population ages. Core motor symptoms include tremors, bradykinesia, rigidity and postural instability. Complications caused by non-motor symptoms of the disease, such as cognitive decline, mood disorders, sleep disturbances and autonomic dysfunction, further reduce the quality of life of patients and their families [30].

Current treatments for PD focus mainly on the symptomatic level, using pharmacological interventions (e.g., levodopa) and various forms of physiotherapy [1]. While potentially effective in relieving symptoms, using pharmacological interventions as a form of treatment is not known to alter the natural history of the disease. In most cases, they are associated with side effects that undoubtedly limit their effectiveness over the long term. There is a growing need for new therapeutic strategies to provide more durable benefits and improve patients' quality of life.

One of the biggest challenges in PD therapy is keeping patients motivated. Regular exercise has been shown to significantly benefit people with PD, improving motor function, reducing the risk of falls and improving overall health [23]. However, traditional exercise programs often fail to engage patients, leading to poor adherence and sub-optimal outcomes.

Advanced immersive technologies such as VR, AR and mixed reality provide the platform for creating new forms of engaging and interactive therapeutic environments. They would transform traditional exercise routines into immersive activities that motivate patient participation. VR and AR can provide real-time feedback and adapt exercises to individual needs, making therapy more enjoyable and effective [35].

1.2 Context

On a global scale, the prevalence of PD is increasing. It represents a significant challenge to healthcare systems, affecting millions of people and their relatives. The degeneration of dopamine-producing neurons in the brain leads to primary motor symptoms, including tremors, rigidity, and slowness of movement and speed (bradykinesia). Additionally, severe non-motor symptoms include cognitive decline, depression, and sleep disturbances, which significantly complicate the disorder and alter the quality of life for patients [50].

The economic burden of PD is considerable, encompassing direct medical costs and indirect costs such as lost productivity and caregiver burden. Prado Jr. et al. (2020) [56] estimated that a patient incurs costs exceeding USD 6000, corresponding to 23% of direct costs (medication and medical assistance) and the remainder (77%) representing indirect costs resulting from lost productivity. These figures underscore the pressing need for efficacious therapeutic strategies that can alleviate the symptoms of PD and reduce the economic burden of PD [54].

This dissertation is part of the MoveONParkinson project, which aims to enhance the exercise module of its platform by making it more gamified and intelligent. The long-term objective of this project is to develop serious games for VR that will enable patients to remain active in managing their disease. However, it should be noted that not all patients or stages of disease may be suitable for VR. Consequently, this work is focused on creating AR versions of these games that closely align with the corresponding VR implementations. The aim is to then compare both approaches and construct a model that guides their application, thereby defining the conditions and limits for their use.

The integration of immersive technologies into PD therapy presents many challenges. These include ensuring accessibility and affordability, as well as providing adequate training on their usage for both patients and healthcare providers. Crucially, the effectiveness of these technologies must be validated through rigorous clinical trials to prove their benefits and identify any potential risks or limitations.

The study carried out in this dissertation aimed to address the main following research question and its subquestions:

- **Main RQ:** How does the level of immersion, from augmented to virtual reality, influence the experience and performance of Parkinson's patients playing a serious game?
  - **RQ1:** How does immersion affect usability and workload?

– **RQ2:** How does immersion affect presence and motivation?

– **RQ3:** How does immersion affect in-game performance and attention (eye-tracking)?

1.3 Solution

This dissertation investigated the application of immersive technologies in the therapeutic management of individuals with Parkinson's disease. A Serious Games (SGs) was designed to facilitate interactive activities aimed at enhancing motor skills and engagement. The game was implemented for both VR and AR platforms, focusing on evaluating their relative strengths and limitations in rehabilitation contexts.

Previous studies, such as Pinho et al., demonstrated that VR can support the rehabilitation of patients with Parkinson's disease, offering favourable cost-effectiveness [54]. Building on this foundation, this dissertation contributed empirical evidence regarding the comparative capabilities of VR and AR for therapy.

The game was developed in the Unity engine, a flexible platform for immersive applications. It integrated hand tracking and eye tracking to enable intuitive interaction and to record user focus and engagement. Eye-tracking data, combined with performance metrics, were used to assess usability, workload, and presence during gameplay, providing insights into cognitive load and user experience [59].

The research focused on studying the limitations and effectiveness of VR and AR in therapeutic applications for PD. Specifically, it evaluated the impact of immersion levels across the virtuality continuum using standardized questionnaires (SUS [13], NASA-TLX [25], IPQ [58], Paas [48]), eye-tracking data, and in-game performance measures.

Two user studies were conducted. **Study 1** compared AR and VR versions of the game with both healthy adults and a small cohort of participants diagnosed with early-stage Parkinson's disease. **Study 2** was carried out exclusively with healthy participants and focused on assessing immersion across the virtuality continuum. In this second study, the system was extended to five designed immersion levels, of which three (AR, AV, VR) were selected for evaluation. The analysis examined usability, workload, presence, and performance across these chosen conditions.

The overarching outcome of this work was the development and evaluation of *Fruit Picker XR*, a serious game that demonstrates the feasibility of applying immersive technologies, from AR to VR, in rehabilitation for Parkinson's Disease.

1.4 Contributions

This dissertation has a few important contributions to be made in the area of therapeutic applications using immersive technologies for PD.

- **Comparative analysis of AR and VR for PD therapy:** This research empirically evaluated the strengths and limitations of Augmented Reality and Virtual Reality for rehabilitation tasks in Parkinson's Disease. By comparing usability, workload, presence, and performance across immersion levels, it provides evidence to guide the design of future therapeutic systems.

- **Extended Reality Serious Game:** A new version of the game *Fruit Picker XR* was developed, spanning multiple levels of the virtuality continuum. The system integrates hand tracking, eye tracking, and therapist-driven configuration through the Play platform, offering a flexible and engaging therapeutic tool.

- **Play platform integration:** The *Fruit Picker XR* game was integrated with the therapeutic platform *Play*, enabling therapist-controlled configuration of game parameters and systematic collection of gameplay data. This connection demonstrated the feasibility of linking immersive rehabilitation tools with existing therapeutic infrastructures.

- **User studies:** Study 1 compared AR vs VR with 31 healthy participants and 4 early-stage PD participants; Study 2 (healthy, N=18) evaluated three selected immersion levels from a five-level design.

- **Scientific publications:** The results of this work were disseminated through international publications. The first paper was published at the 2025 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW) [15], presenting early results from the second-phase prototype. A second paper, based on the extended study with multiple immersion levels, was submitted and will be presented at the 15th International Conference on Current and Future Trends of Information and Communication Technologies in Healthcare (ICTH 2025), to be held in Istanbul, Turkey. These publications confirm the relevance of the research to both immersive technologies and healthcare contexts.

1.5 Document Structure

- **Chapter 1 — Introduction:** Introduces PD and the motivation for applying immersive technologies, from AR to VR, in rehabilitation. States the objectives and research questions, outlines the serious game approach adopted, and previews the structure of the dissertation.

- **Chapter 2 — Background and Related Work:** Reviews the clinical background on PD; synthesizes strategies for game-driven rehabilitation (serious games, gamification) and XR concepts (virtuality continuum, devices, development frameworks); and surveys related work on AR/VR for PD and related neurological conditions, highlighting the research gaps addressed in this study.

- **Chapter 3 — Solution Context and Approach:** Presents the design principles for serious games in PD, the methodological approach to prototype development, the *Fruit Picker XR* game, the five immersion levels across the virtuality continuum, introduction of integration with the *Play* platform, the process of selecting the most suitable headset and interaction modalities, and the evaluation metrics guiding the study.
- **Chapter 4 — System Design and Implementation:** Details hardware selection, gameplay mechanics, user interface and visual design, the software architecture and components, integration with external platforms, and the prototype development phases resulting in a multi-level continuum prototype.
- **Chapter 5 — Results and Discussion:** Reports findings from two user studies: (i) a comparison of AR versus VR gameplay and (ii) an evaluation of different immersion levels. Analyses draw on standardized questionnaires (SUS, NASA-TLX, IPQ, Paas), eye-tracking data, and in-game performance metrics, and implications are discussed with respect to the research questions.
- **Chapter 6 — Conclusions and Future Work:** Summarizes the main contributions and limitations of the research and outlines directions for future development and evaluation.

2

Background and Related Work

This chapter reviews prior studies, research, and projects pertinent to the topics explored in this dissertation. The content is structured into the following sections:

- **Parkinson's Disease:** This section provides a comprehensive overview of PD, detailing its symptoms and current treatment methodologies.
- **Game-Driven Rehabilitation Strategies** This section discusses the concept of serious games and gamification, their role in healthcare, and their application in PD rehabilitation.
- **Technology:** This section explains the technologies employed in this project, including immersive systems spanning from AR to VR.
- **Related Work:** The final section highlights recent innovations in VR, AR, and Mixed Reality (MR) technologies, focusing on their implementation within medical and therapeutic settings.

2.1 Parkinson's Disease

Parkinson's Disease (PD) is a progressive neurodegenerative disorder characterized by motor symptoms such as tremors, rigidity, and slow movement (bradykinesia). It results from the loss of dopamine-producing neurons in the brain. PD has a significant impact on patients' quality of life, and while current treatments focus on symptom management, innovative technologies such as VR and AR offer new therapeutic possibilities.

2.1.1 Definition

PD is a condition that gradually affects the system and the functions controlled by the nerves in the body. The symptoms develop slowly, with a sign being a slight tremor in one hand. While tremors are common, stiffness or a decrease in movement speed can also occur due to this disorder.

In the stages of PD, individuals may display facial expressions, reduced arm swinging during walking, and speech that may become quieter or less clear. Symptoms of PD worsen as the condition advances over time.

PD causes nerve cells in the basal ganglia to degenerate, reducing dopamine production due to decreased connections within the basal ganglia (Figure 2.1). This leads to a loss of control over muscle movements, resulting in symptoms like slow movement (bradykinesia), shaking, coordination issues and difficulties with walking and posture [39].

While there is no cure, PD medications can greatly alleviate its symptoms. In some cases, healthcare providers may recommend surgery to target areas of the brain and enhance symptom management[45].

The main risk factor for PD is age, with the average age around 70 years old patients and a significant rise with the older the person gets, but it can happen very rarely in cases before 50 years old. Men are more affected than women, and heredity plays a role, with 15-25 % of PD patients having a familiar with the disease, which is linked to genetic mutations. The last risk is exposure to pesticides, normally in rural areas, has associated with an increasing risk of developing PD[39].

The main cause of PD is still unknown, though some cases provided insight that it can be hereditary and traced to genetic mutations. But in most cases, the PD is not hereditary. So the disease results in a combination of unknown environmental factors and genetics [39].

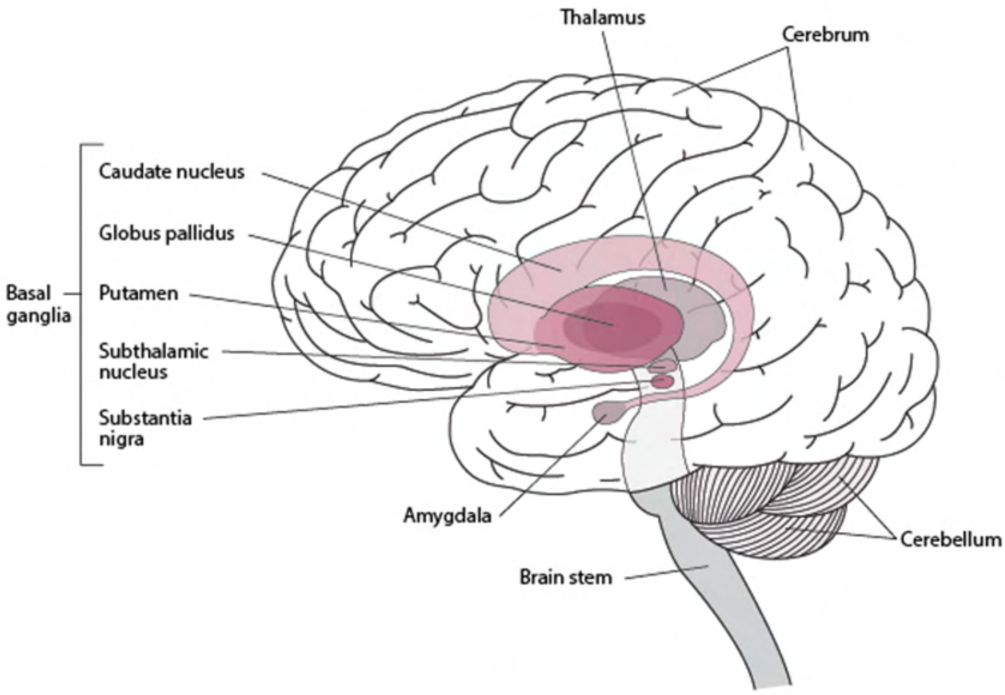


Figure 2.1: Basal ganglia [39]

2.1.2 Symptoms

PD is characterized by a variety of symptoms that progressively worsen over time, significantly impacting a person's quality of life. The four main symptoms of PD are[45, 30]:

- **Tremor** - Rhythmic shaking, called tremor, normally begins in a limb, usually on the hand or fingers. This tremor associated with PD has a characteristic rhythmic back-and-forth motion that involves the thumb and forefinger. This is more commonly known as a pill-rolling tremor. This is most obvious when the hand is at rest. The shaking may decrease when you are doing some tasks.

- **Rigid muscles** - Muscle stiffness, or resistance to movement, may occur in any body part. This stiffness affects most people with PD. The rigidity can be painful and limit the range of motion

- **Impaired posture and balance** - The posture may become stooped, contributing to the imbalance of the person and increasing the risk of falling.

- **Bradykinesia** - Bradykinesia means slowness of movement and speed, and is hard to initiate. This translates into difficulty in performing everyday tasks such as brushing the teeth. This encourages people to be less active, which can lead to joint stiffness and muscle weakness.

There are more non-motor symptoms that can be associated with the disease, such as depression, emotional changes, swallowing problems, chewing and eating problems, speaking problems, urinary problems, constipation, skin problems, sleep problems, and sensory problems.

2.1.3 Stages

The Hoehn and Yahr scale is a classification system for PD disability, with five stages. Stages 1-2 are classified as early-stage PD, stages 2-3 as mid-stage PD, and stages 4 and 5 as advanced-stage PD[51].

- **Stage 1** - During this stage, the patient has soft symptoms that usually do not interfere with daily activities. Some of the symptoms that may occur are tremors.

- **Stage 2** - At this stage, the symptoms worsen, with the appearance of rigidity and an increase in tremors. Daily activities become more challenging and require more time to complete.

- **Stage 3** - This stage is designed as mid-stage, with a principal symptom being the loss of balance. The patient experiences a reduction in their capacity to engage in activities of daily life, although they are still able to live alone.

- **Stage 4** - This stage represents a turning point, with symptoms having fully developed and causing severe disability. While the patient is still capable of walking, the use of an assistive device such as a cane is advisable. The patient requires substantial assistance with their daily activities, and living alone is no longer possible.

- **Stage 5** - This is the final stage of the disease, during which the patient experiences stiffness that can cause a total loss of mobility, making them incapable of walking or standing. Their quality of life significantly decreases, and they require considerable assistance to perform their daily activities.

It is crucial to identify the correct stage of the disease to make the most appropriate treatment for the patient. It is important to note that the progression of PD can be different from one patient to another, with some individuals having a faster progression of the disease than others.

2.1.4 Treatment

The main focus of PD treatments is the management of symptoms and delaying the progression of the disease because there is no cure available. Low production of dopamine in the body is one of the main things caused by PD hence, some treatments were designed to deal with it.

Treatment can be divided into 3 categories: **pharmacological**, **surgical** and **physiotherapy**.

2.1.4.1 Pharmacological treatments

Pharmacological treatments are the most common way to treat PD.

One of the treatments is the use of dopamine agonists, which mimic the effects of dopamine in the brain. Examples of this treatment include substances such as pramipexole, ropinirole and rotigone. They are often used in the early stages of the disease.

Another treatment is levodopa, which is the most effective treatment for motor symptoms. This substance itself is not dopamine, but is a way to get it, which means it is a substance that the body can convert into dopamine. The blood-brain barrier is a selective barrier that protects the brain from harmful or helpful substances entering the brain. But Levodopa is an exception, being able to pass through it. This capability makes levodopa one of the most effective treatments, as it can pass the blood-brain barrier. Carbidopa is a substance that is typically used in combination with levodopa, which prevents levodopa from being converted to dopamine outside the brain, allowing more levodopa to reach the desired location [1].

In addition, there are further pharmacological treatments, including the use of MAO-B and COMT inhibitors, which block the breakdown of dopamine and increase the effect of levodopa. Finally, anticholinergics are used to control the tremors of the patient.

2.1.4.2 Surgical treatments

Another potential treatment option is surgical intervention, which may be considered for patients who do not respond well to medication. This procedure involves the implantation of electrodes in specific brain regions, such as the subthalamic nucleus or the globus pallidus. These electrodes deliver electrical impulses that modulate the neural circuits involved in motor control. This treatment has been shown to significantly reduce motor symptoms and medication requirements, thereby improving the quality of life of the patient. It should be noted that, although the procedure is relatively low risk, there are potential complications that can arise, including infection, bleeding and a negative effect on speech and balance [1].

2.1.4.3 Physiotherapy

Physiotherapy represents a crucial aspect of treating the symptoms associated with PD. The primary goal is to enhance the physical functionality and overall quality of life of those afflicted with PD through a variety of exercises and therapeutic techniques.

According to the Parkinson's Outcomes Project [49]. Making physical activity to at least 2.5 hours a week can slow Parkinson's symptoms progression.

These are the main types of exercises that can be done by patients with PD [53]:

- **Stretching** - Stretching should be done with the help of a physiotherapist. It is crucial to stretch the arms, legs, and the shoulder and pelvic girdles.
- **Gait** - In gait training, it is recommended that the patient attempt to correct and avoid a dragging gait by taking longer strides and increasing the range of motion of the trunk and arms. One may also utilize the floor as a reference point by marking it with indelible markers, navigate around obstacles, and practice walking in all directions, including forward, backward, and sideways.
- **Relaxation** - This technique should be performed at the commencement of the session in order to reduce stiffness, tremors and anxiety. This is achieved through rhythmic activities, which include slow and careful rocking of the trunk and limbs.
- **Postural exercises** - It is essential to perform postural exercises with the torso extended and in front of a mirror in order to facilitate awareness of correct posture.
- **Breathing exercises** - During breathing exercises, the physiotherapist uses the arm stick to guide the patient's breathing, encouraging breathing through the diaphragm and greater control of breathing.
- **Balance and coordination** - Balance and coordination training is carried out through sitting and standing activities, rotation of the trunk in sitting and standing positions, tilting the body, exercises involving changes of direction and speed, grasping objects and getting dressed.

- **Active and strengthening exercises** - Active and muscle-strengthening exercises should preferably be performed sitting or standing, using arm and leg movements, torso rotations, sticks, elastic bands, balls and light weights.

PD can make daily tasks frustrating and time-consuming. Physical therapists become essential partners, and family involvement in treatment is crucial to encourage activities at home, as long breaks can hinder progress. Exercises should be prescribed based on a physiotherapist's assessment, with goals set for the short, medium, and long term. Treatment plans will be adjusted as the condition changes. Physiotherapy is needed for life, so it is good to have attractive sessions of exercises, to have a better dedication from the patient and then good and consistent result will be obtained [53].

2.2 Game-Driven Rehabilitation Strategies

The increasing popularity of video games has led to their recognition as valuable tools in therapeutic settings, representing a paradigm shift in the traditional perception of video games as a form of entertainment [20]. The utilization of video games in mental health interventions has emerged as a significant development, offering engaging and interactive methods to address a wide range of psychological conditions, including anxiety, depression, PTSD, and addiction, as well as in the recovery of conditions such as PD. The immersive nature of video games provides a controlled environment in which patients can develop coping strategies, improve cognitive skills, and practice emotional regulation. Furthermore, the accessibility of gaming therapy, coupled with its ability to resonate with individuals in diverse age groups, has contributed to its growing popularity. As research continues to investigate the therapeutic benefits of video games, their role in mental health is expected to expand, seamlessly integrating into contemporary treatment regimens [44].

Research has indicated that incorporating games into rehabilitation sessions can improve patient motivation levels, thus addressing one of the primary challenges in therapeutic interventions: patient disengagement resulting from the repetitive nature of exercises. The principles of game design are believed to offer significant information on developing more engaging and effective rehabilitation programs [57].

2.2.1 Serious Games in Health and Rehabilitation

Serious Games (SGs) are digital games explicitly designed for purposes beyond entertainment, such as training, education, or therapy [34]. In healthcare, SGs serve as engaging therapeutic tools intended to promote positive health outcomes while maintaining an enjoyable experience for patients [18]. They have been applied across a wide range of conditions – from physical rehabilitation to cognitive training – to enhance patient motivation, adherence, and functional recovery [18]. In the context of PD, many serious-game interventions take the form of exergames (exercise-oriented video games) that use motion capture interfaces (e.g. Microsoft Kinect or Leap Motion) and virtual reality environments to target motor impairments [47]. A systematic review of SGs for PD found that most projects focused on improving motor symptoms like bradykinesia and gait, often involving clinicians in the design and using multiple assessment tools to track patient outcomes [47]. Notably, recent evidence suggests that such game-based rehabilitation is generally safe and can achieve motor improvement outcomes comparable to traditional physiotherapy. For example, exergame-based therapy in PD has been shown to be feasible and at least as effective as conventional exercise programs for improving balance and mobility [22]. These findings underscore the potential of serious games as a viable adjunct or alternative in neurorehabilitation, provided they are well-designed to meet patients' needs (e.g. customizable difficulty and simplicity for older users) and evaluated with scientific rigor [47].

2.2.2 Gamification in Health and Rehabilitation

Gamification refers to the integration of game-design elements (points, challenges, feedback, leaderboards, etc.) into non-game contexts (such as exercise routines or therapeutic activities) to increase user engagement and motivation [19]. In health and rehabilitation, gamified approaches are increasingly used to encourage adherence to treatment and to make repetitive or strenuous tasks more enjoyable. For instance, mobile health apps and wearable fitness devices often employ reward points, progress bars, and social competitions to promote physical activity and healthy behaviors [69]. Systematic reviews indicate that such gamification interventions can lead to modest yet positive improvements in exercise participation and health outcomes, though results vary and depend on design quality [69]. In the specific case of Parkinson's disease, gamification has been applied by embedding game-like features into physiotherapy and motor training programs with the aim of countering apathy and sustaining long-term patient engagement. A recent scoping review identified over 80 technology-based PD rehabilitation studies incorporating gamification elements [12]. Commonly used elements included real-time performance feedback, point scoring, leveling systems, and occasional rewards – with feedback/progress indicators present in 98% of the surveyed interventions and points in 86% [12]. These gamified systems were often delivered via mainstream video game consoles or computer platforms adapted for rehabilitation exercises [12]. By infusing standard therapy with game-like incentives and challenges, gamification strategies seek to make rehabilitation more engaging, which can improve patients' adherence to exercise regimens and potentially enhance therapeutic effectiveness. However, experts note that many current gamified health interventions lack a strong theoretical grounding in game design and motivation science, highlighting the need for more deliberate and user-centered gamification frameworks in clinical practice [12].

2.2.3 Comparison between Serious Games and Gamification

Serious games and gamification are related but distinct approaches. A *serious game* is a complete game created with a primary purpose beyond entertainment, such as rehabilitation, whereas *gamification* refers to adding game elements (points, feedback, levels) to existing non-game activities [19, 67]. In healthcare, serious games often provide immersive environments tailored to therapeutic goals, for example exergames for Parkinson's disease [47, 22], while gamification is typically used to enhance adherence to conventional therapy or mobile health applications by boosting motivation through rewards and challenges [69, 12]. Both approaches harness game mechanics to improve engagement, but differ in scope: serious games deliver the intervention *as a game*, whereas gamification augments existing activities with playful elements. Recognizing this distinction helps select the most suitable strategy for each therapeutic context.

2.3 Technology

2.3.1 Immersive Technologies

Immersive technologies encompass a variety of digital tools and platforms designed to create simulated environments or enhance real-world experiences, engaging users in highly interactive encounters. These technologies blur the lines between physical and digital worlds, offering users a heightened sense of presence, immersion, and interactivity. Key components of immersive technologies include Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), each with unique capabilities and applications [6].

These technologies have attracted significant interest across multiple industries, including healthcare, education, entertainment, and more [9]. In healthcare, VR, AR, and MR are increasingly used to improve medical education [37], simulate surgeries, enhance patient outcomes, and enable remote consultations. For example, VR simulations provide a safe, controlled environment for medical students and professionals to practice surgical techniques, visualize anatomy, and engage in patient interactions. AR applications offer real-time guidance and visualization during surgeries, allowing surgeons to overlay digital information, such as patient anatomy and imaging data, onto the surgical field [14]. MR technology supports collaborative decision-making and visualization by overlaying medical data and diagnostic images onto the physical environment, enabling healthcare providers to interact with virtual objects and explore complex medical data in real-time [9].

Furthermore, immersive technologies are employed to facilitate patient rehabilitation, manage chronic conditions, alleviate pain and anxiety, and enhance mental health through immersive therapeutic interventions, virtual reality exposure therapy, and relaxation experiences. Recent developments have identified VR and AR as promising tools within SGs contexts [21].

2.3.2 Virtuality Continuum

The virtuality continuum is a concept that illustrates the full spectrum of possibilities between the entirely physical world and the fully digital (Figure 2.2). It spans from the real environment, through AR, where digital elements are overlaid on the real world, to augmented virtuality (AV), where real-world elements are incorporated into a virtual environment, and finally to fully immersive VR, where the entire environment is computer-generated. MR is situated midway along the continuum, integrating both the real and virtual worlds [62].

In 1994, the researchers Paul Milgram and Fumio Kishino [43] first introduced the concept of the virtuality continuum, also known as the reality-virtuality continuum.

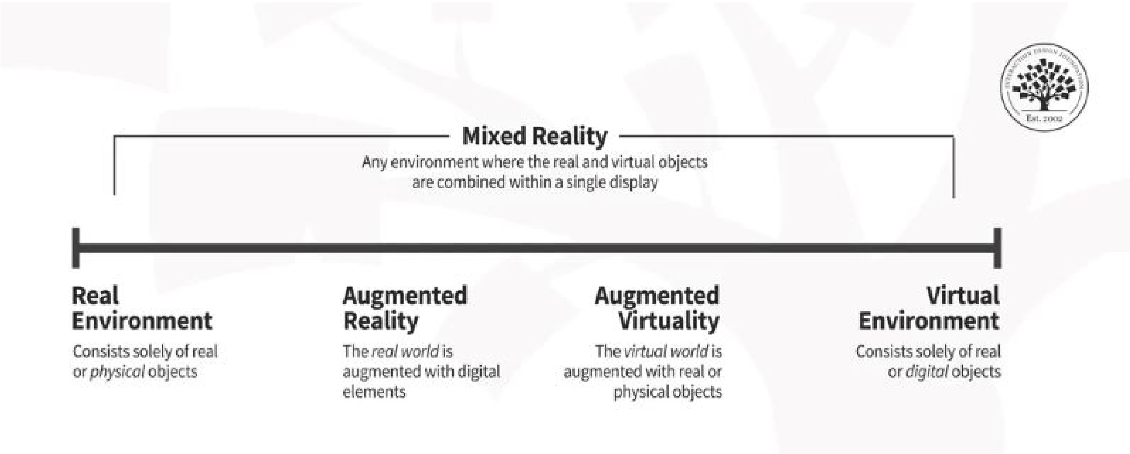


Figure 2.2: Virtuality Continuum [62]

Extended Reality (XR) is an umbrella term that encompasses any technology that alters reality by adding digital components to the physical or real world (Figure 2.3). This blurring line between the physical and the digital world is a defining characteristic of XR. XR includes AR, MR, VR, and any other technology that is yet to be developed [62].

2.3.2.1 Virtual Reality

VR is the utilization of technology to create simulated environments. VR enables the user to be situated within a three-dimensional experience that may either simulate or be distinct from the real world. The user's perspective is afforded by a screen that presents a 360-degree field of view, in contrast to the conventional flat screen. Additionally, VR has the capacity to stimulate the majority of human senses, including vision, hearing, touch, and even smell [7].

VR has come a long way from its origins to the advanced technology it is today. The idea can be traced back to 1935 when Stanley G. Weinbaum's story "Pygmalion's Spectacles" described immersive goggles as science fiction at the time. In the 1950s, Morton Heilig created the Sensorama, a machine that could simulate a world by reproducing the five senses. In 1968, Ivan Sutherland developed the first head-mounted display (HMD), known

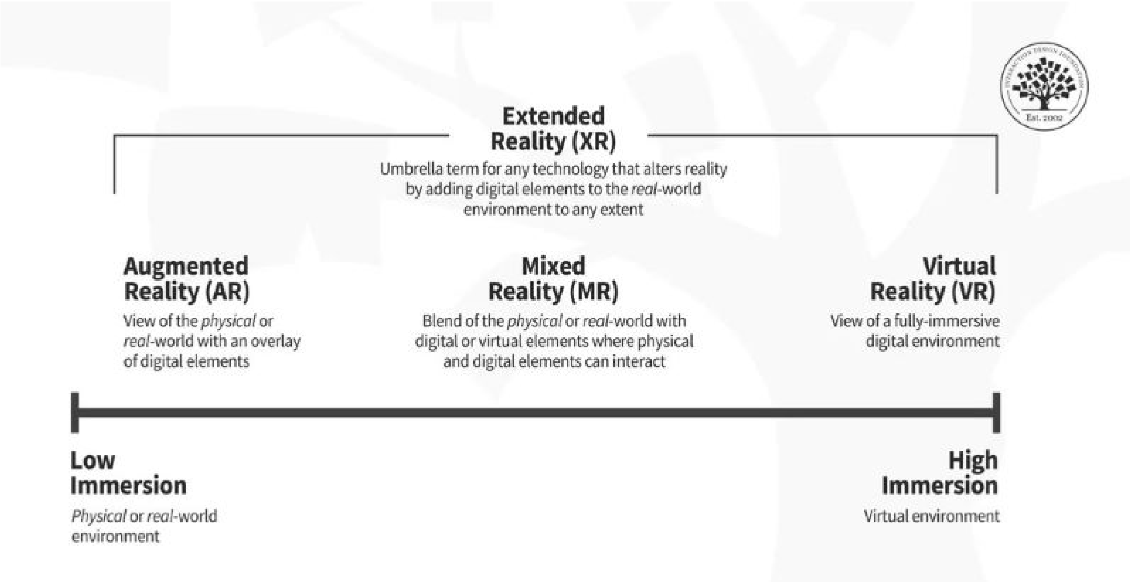


Figure 2.3: Representation of current XR technologies according to the spectrum of immersion [62]

as the Sword of Damocles because of its heavy weight, that introduced 3D tracking and AR [17].

The 1970s saw further advancements in the field of interactive digital art, with the creation of the first virtual reality flight simulator by General Electric. The 1980s saw the emergence of commercial virtual reality technology, with the establishment of Jaron Lanie's VPL Research, which gave rise to the term "VR" [17].

In the 1990s, VR applications in gaming and therapy continued to gain popularity. Notable examples included NASA's use of VR for Mars Rover simulations and VR therapy for post-traumatic stress disorder (PTSD). However, in the early 2000s, due to the high costs and limited success of earlier VR products, there was a decline in interest [17].

The resurgence of VR commenced in the 2010s, initiated by the founding of Oculus VR by Palmer Luckey and the commercial success of the Oculus Rift. This resulted in Meta's acquisition of Oculus VR, which identified significant potential in this device. Following the success of Meta Quest, other major companies, including Sony with the Playstation VR and Apple with Vision Pro, showed interest. VR has evolved beyond gaming, with applications in healthcare, education and even virtual tourism [17].

2.3.2.2 Augmented Reality

AR is a technology that enhances users' real-world views by incorporating digital overlays with artificial objects (Figure 2.4). In this context, the real world is viewed directly or via a device such as a camera to create a visual representation, which is then augmented with computer-generated inputs such as still graphics, audio or video. AR differs from VR in that it enhances the user's experience of the real world, rather than creating an entirely new experience [7].

AR experiences are close to the physical world end of the virtuality continuum. The capacity to overlay digital objects onto the tangible world is transforming numerous sectors, including gaming, education, healthcare, and manufacturing [62].

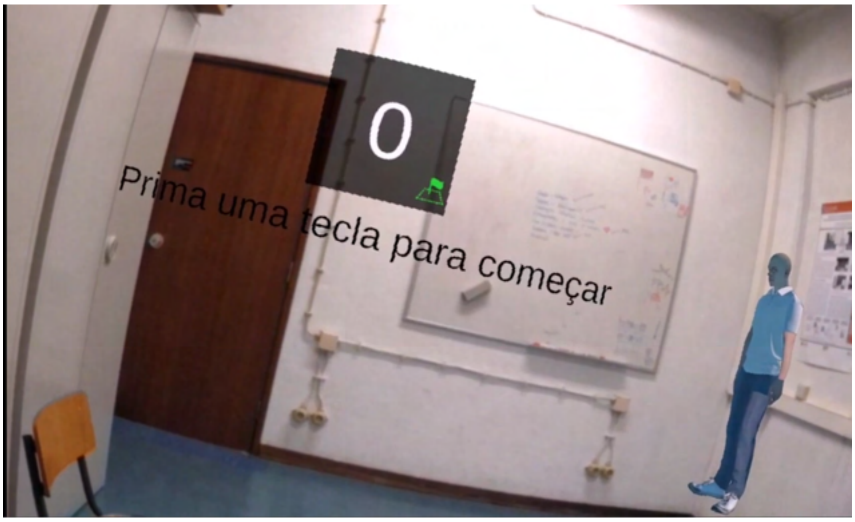


Figure 2.4: AR example

2.3.2.3 Mixed Reality

Milgram and Kisihnio[43] characterised MR as a spectrum that spans from purely physical to pure VR, with MR representing varying degrees of fusion between the ends of the spectrum. The definition of MR is the one that confuses specialists the most. A study conducted by Speicher revealed that there is considerable confusion among specialists regarding the definition of MR. M et al. revealed that several experts and studies defined MR as being intrinsically linked to AR (a superior version), which is a continuum of which AR is a part. The simultaneous use, or the same application of AR and VR, is a synonym of AR, and even just a definition introduced for marketing contexts. Therefore, MR is a continuum between the real environment and the external virtual environment (excluding extreme cases), incorporating VR into this same environment [61].

Despite the lack of consensus on the definition of MR, this project will adopt the position that the definition encompasses "not only the superposition of digital elements into the real-world environment but also their interaction". Consequently, MR encounters will gather data from their surroundings and adapt accordingly [61].

The definition we use for MR is a technology that allows the integration of digital elements into the real-world environment and enables interaction between them. In an MR experience, users can perceive and interact with both digital and physical elements. As a result, MR experiences receive input from the environment and adapt accordingly [61, 62].

In summary to gain an understanding of the key terms associated with these emerging technologies [62].

- AR is a view of the real world, or physical world, with an overlay of digital elements.
- MR is a view of the real world, or physical world, with an overlay of digital elements where physical and digital elements can interact.
- VR is a fully immersive digital environment.
- XR is an umbrella term that encompasses all of these different technologies, including AR, MR, and VR. As these technologies continue to evolve, it is important to understand the distinctions between them.

2.3.3 Devices

The most conspicuous aspect of VR is the HMD. Given that humans rely heavily on vision, display technology is frequently the most striking distinction between immersive VR systems and conventional interfaces [7].

VR headsets, also known as head-mounted displays, position the screen in front of the user's eyes, following their head movements. Some VR headsets, such as the HTC Vive and Oculus Rift, require a console or computer to function, with the video being transmitted from the device to the headset. Other headsets, such as Google Daydream and Samsung Gear VR, use a smartphone that fits into the headset to display the video [40].

VR headsets typically utilise either two liquid crystal display (LCD) panels (one for each eye) or a single display with two separate video feeds. These headsets also feature lenses positioned between the user's eyes and the screen, which help to focus and reshape the image for each eye. By angling the two 2D images, the lenses create a stereoscopic 3D effect, which is similar to how our eyes perceive the world slightly differently [7].

To ensure user comfort, VR headsets must maintain a minimum frame rate of 60 frames per second. However, modern headsets have been developed to surpass this standard, with the Oculus and HTC Vive operating at 90 frames per second and the PlayStation VR at 120 frames per second [7].

For VR work to be executed properly, it is essential that the image in front of the user moves in accordance with the user's head movements. This is achieved through the use of a head-tracking system, which is capable of measuring the user's head position in terms of the x, y, and z axes. The term "degrees of freedom" (DoF) in VR refers to the number of ways a user can move and look around in a virtual environment. There are two types of DoF (Figure 2.5): three-dimensional (3Dof) and six-dimensional (6Dof) [8].

3-DoF tracks rotational movement only [8]:

- Pitch: Up and down rotation.
- Yaw: Left and right rotation.
- Roll: Tilting side to side.

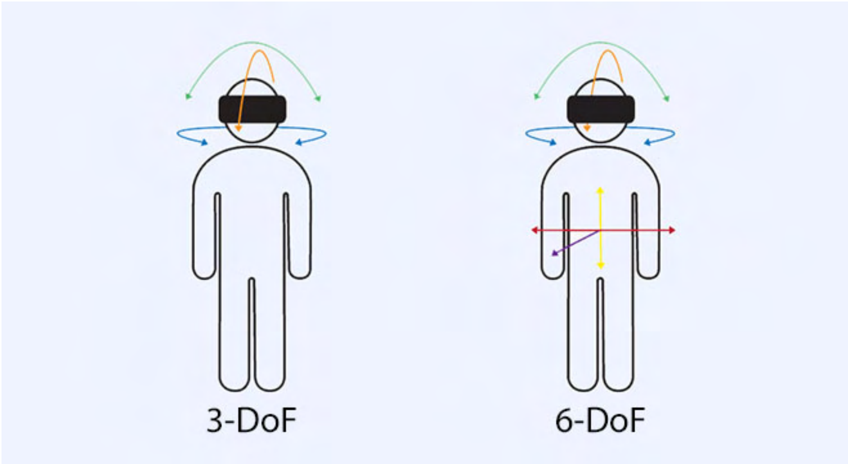


Figure 2.5: 3-Dof and 6-Dof VR Headset [8]

This technology is well-suited to passive experiences, such as viewing 360-degree videos, in which the viewer remains stationary but can observe the scene from different directions [8].

6-DoF tracks both rotational and translational movement [8]:

- Pitch, Yaw, Roll
- Surge: Moving forward and backwards.
- Sway: Moving side to side.
- Heave: Moving up and down.

This enables a fully immersive experience, whereby users can physically move around within the virtual space. This is an essential feature for interactive applications such as virtual reality gaming, training simulations, and complex interactive applications.

2.3.3.1 XR equipment

This section presents a selection of the most advanced XR devices currently available from leading industry manufacturers, including Meta and Pico (Figure 2.6). These devices represent the pinnacle of immersive technology, offering sophisticated features and capabilities that have the potential to enhance therapeutic interventions for individuals with PD [28, 29].

- **Meta Quest Pro :** This device boasts advanced tracking capabilities, encompassing not only eye and face tracking but also body and hand tracking. The high-resolution display, with its advanced colour accuracy, ensures an all-encompassing visual experience. The device is equipped with a high-resolution RGB camera, which is a notable improvement over the Quest 2's greyscale camera. This enhances the device's capabilities for more sophisticated AR experiences. The Quest Pro has been ergonomically designed for extended periods of use, ensuring user comfort. Additionally, the processing power in the Meta Quest Pro is capable of handling complex VR applications. Furthermore, the headset's improved spatial audio provides a more immersive experience by accurately reproducing real soundscapes [26, 28].

- **Pico 4 Enterprise:** This device offers precise hand and positional tracking, a high-resolution display, and a wide field of view, thereby ensuring a significantly enhanced level of user immersion. The device is equipped with a front-facing camera that supports AR applications, thereby facilitating the creation of a versatile and immersive experience. Additionally, the Pico 4 Enterprise incorporates integrated eye-tracking technology, which enhances interactivity and personalisation by monitoring the user's attention. This is particularly advantageous for applications that require precise focus and interaction. The device features an ergonomic design that ensures comfort over extended periods of use and a lightweight construction that reduces fatigue. Advanced inside-out tracking eliminates the need for external sensors. It supports high refresh rates and low latency, enabling it to keep pace with fast-paced VR applications and ensure smooth and responsive interactions [28, 29].

Figure 2.6: Meta Quest Pro and Pico 4 Enterprise [28]

2.3.4 Game Development

Game development engines are a popular choice among developers because they facilitate the creation of games by eliminating the necessity to reinvent the wheel. Additionally, they permit the reuse of a significant amount of functionality and manage to render 2D/3D graphics, collision, physics, sound, scripting, and other processes. Some game engines, such as CryEngine and Unreal Engine, are not suitable for beginners due to their complexity and steep learning curves. Conversely, other engines, such as Gamemaker Studio, are accessible for beginners but may have limitations. Unity is a game engine that occupies a middle ground between those that are more accessible to beginners and those that are more advanced. It is still considered a beginner-friendly engine, offering a wide range of functions [68].

Unity is a popular 2D and 3D game engine that is compatible with a wide range of platforms, including VR and AR. The Unity game engine already incorporates several essential features necessary for game development, including physics, 3D rendering, collision detection, and animation, as mentioned earlier. It is of great importance to be able to create games more rapidly and effectively. Unity is renowned for its Asset Store, through which developers can upload their creations and make them available to the public for purchase or free download. Other competitors include Unreal Engine, CryEngine and a new game engine similar to Unity called Godot. Unity is the optimal choice for the following reasons [60]:

- The user-friendly interfaces of Unity make it accessible to beginners.
- The extensive documentation and video tutorials provided by the community help developers learn and master various aspects of game development.
- Unity employs C# as its primary programming language, which is beginner-friendly.
- Unity's multi-platform support enables developers to create projects for a range of gaming devices, including PS4, PC, and AR/VR experiences.
- The Unity Asset Store offers a catalogue of assets, including 3D models, textures, and scripts, which can be utilised to optimize the development process.

If the objective is to create a game with high-resolution graphics, then the Unreal Engine is the optimal choice. Additionally, the Unreal Engine scripting language is C++, which offers greater flexibility but is more challenging to learn. As previously stated, the learning curve is steep, with the initial stages requiring significant effort, but the subsequent stages offer significant rewards. It is important to note that engines have both strengths and limitations. Therefore, the selection of the most appropriate engine for a given project depends on the specific requirements and preferences of the project [27].

2.3.4.1 Eye tracking

Eye-tracking technology is sophisticated equipment that scans and measures the movement and focus of your eyes. This helps researchers understand what exactly a user is looking at and how within a visual environment. In the case of VR and AR, eye-tracking enables interactivity and deepens the understanding of user behaviour [32].

This technology uses sensors and cameras to detect the positions/movements of the eyes. This collected data can include information about where the user is looking, how their eyes are moving and how long they are fixating on certain objects. All this information is then processed in real-time to provide interactive feedback and update the virtual world according to the user's attention and focus [32].

Applications of Eye-Tracking in VR and AR [32]:

- **Enhanced Interaction:** Eye-tracking allows for more natural interaction methods. For example, users can select objects by looking at them, reducing the need for physical controllers and making the experience more immersive.
- **Attention and Engagement Measurement:** By analyzing where and how long users focus their gaze, developers can gain insights into user engagement and attention. This can help in adjusting content to maintain user interest and ensure that key information is being noticed.
- **Adaptive Content Delivery:** Eye-tracking can be used to dynamically adjust the difficulty level or content based on the user's focus and attention, creating a more personalized and effective user experience.
- **Research and Data Collection:** Eye-tracking provides valuable data for research, allowing developers to study user behaviour, cognitive load, and the effectiveness of different design elements. This data can be crucial for improving user interfaces and enhancing overall experience.

Eye-tracking technology provides an advantage in immersive environments because it can extract more information about how users interact with the environment and experiences. It contributes to more natural and intuitive interactions, increases the level of user engagement and provides detailed analysis that will be useful in refining and improving the virtual experience. It will help eye-tracking to reveal more about how patients interact with therapy in a therapeutic environment, helping to tailor effective treatment plans for Parkinson's patients [59, 32].

Challenges and considerations when implementing eye tracking:

Although the benefits of eye-tracking technology are enormous, there are some challenges and considerations when implementing it.

- **Accuracy and calibration:** High levels of accuracy are required for data collected through eye tracking. This requires highly accurate calibration procedures that involve each user individually, as the anatomical structure of the eye, differences in eye movements, and many other aspects vary between individuals [31].
- **Privacy and ethics:** Eye-tracking data contains very personal information. It is essential to adhere to strict data privacy standards and obtain informed consent from users. Ethical considerations will also dictate that the data be used transparently and for no other purpose than the intended one [10].

2.4 Related Work

In recent years, there has been a surge in interest in the application of VR and AR in therapeutic settings, particularly for conditions such as Alzheimer's disease and PD.

These technologies offer innovative methods to enhance cognitive and motor functions, providing an immersive and interactive environment that motivates patients and improves the consistency of therapeutic exercises.

2.4.1 Immersive VR Exergame for Parkinson's Disease Rehabilitation

This study addresses the significant challenge faced by patients with PD in maintaining regular exercise routines due to various barriers that affect their motivation to engage in exercise programs. The primary objective of this study was to create a motivating and engaging VR environment that could enhance motivation and provide medical benefits [16].

Figure 2.7: Screenshots of game prototype [16]

The exergame (Figure 2.7) is designed to enhance motor skills, particularly finger movements and hand-eye coordination. It was developed using the HTC Vive device and the Unity engine. The game's principal objective is to complete simple yet engaging tasks, such as shooting balloons in different virtual environments. The instant visual and haptic feedback provides the patient with a sense of engagement and accomplishment while exercising [16].

The study was conducted with five early-stage PD patients, who found the game enjoyable and easy to use. Despite some usability challenges, including difficulty selecting options due to hand tremors, the feedback was positive. The system Usability Scale yielded an average of 90, indicating that the user had a good experience [16].

The game was iteratively improved based on user feedback, resulting in various levels of difficulty, a leaderboard, and enhanced visual and audio elements. These improvements enhanced the game's engagement and suitability for the specific needs of PD patients [16].

This study is pertinent to the current research exploring the use of VR and AR for therapeutic purposes in PD. It demonstrates the potential of immersive VR environments to provide motivation and effective exercise experiences, which may lead to improvements in motor functions and quality of life for PD patients.

2.4.2 Comparison AR and VR for Physiotherapy on Parkinson's Disease

The study "Immediate Effect of Augmented Reality, Virtual Reality and Neurofunctional Physiotherapy on Postural Control and Executive Function of Individuals with Parkinson's Disease", by Araújo et al. [4], explores the immediate benefits of using non-fully immersive AR, VR, and traditional physiotherapy on individuals with PD. This research provides valuable insights into how these technologies can enhance the motor and cognitive functions of PD patients.

The whole sample size was 40, with mild-to-moderate PD. Each patient underwent one session each of AR, VR, and Neurofunctional Physiotherapy (NPT). The duration per session was 50 min and was spaced out by an interval of 7 days. Pre-and-post-treatment sessions were done for each session on all the subjects to measure postural control (PC) and executive function (EF) [4].

- **Postural Control (PC):** A force platform-based assessment that measures ground reaction forces to estimate how well an individual can balance and remain stable. The platform measures several parameters that provide insight into an individual's ability to maintain their posture effectively.
- **Executive Function (EF):** Trail Making Test measured EF. This is a neuropsychological test used to evaluate visual attention and task switching. The test is in two parts: Part A asks the participant to connect numbered circles consecutively, while Part B asks the participant to connect alternately numbers and letters.

AR has significantly improved postural control and executive function in all three modalities. The study indicated an improvement in balance and cognitive functions after the AR sessions. Finally, the time taken to complete TMT part B was reduced in all three groups within the modalities, which means improved executive function [4].

The AR intervention was performed through the game called WebCam Mania, in which users needed to interact with virtual elements superimposed on a natural environment using a webcam and computer screen. In the VR intervention, the Nintendo Wii Fit Plus game was used; among its exercises were those that trained stability limits, gait, turning, direction changes, steps, upper limb movements, hip and trunk mobility, and double tasks. It is important to note, however, that while these interventions are described as AR and VR, they do not involve high-end immersive devices typically associated with these technologies, such as AR glasses or VR headsets like the Meta Quest [4].

In the differences in improvements by all three modalities between postural control and executive function, there was no statistical significance. This indicates that AR and VR have the same effect as traditional NPT for improvement in the motor and cognitive functions of patients with PD. On the other hand, AR exhibited a unique benefit of an increase in the amount of time the participants could maintain a one-legged stance; this effect seems to be advantageous during balance training [4].

Lastly, Araújo et al. maintained that AR and VR afford similar immediate benefits in NPT, including integrating such technologies as viable alternatives to pharmacological treatment in patients with PD. This supports the rapid expansion of research on the use of immersive technologies in medical rehabilitation and the possibility that AR and VR can contribute immediately to increased therapeutic potential and quality of life for PD patients [4].

2.4.3 Augmented Reality for Early Alzheimer's Disease Diagnosis

Alzheimer's Disease (AD) is a progressive neurodegenerative disorder marked by steady memory loss and declining ability to think, culminating in fully developed impairment of daily functions. This is a common form of dementia that affects many people worldwide [65].

Vovk, Patel, and Chan (2019) present an innovative approach to early AD diagnosis using AR. This study presents the system developed using Microsoft HoloLens in an attempt to diagnose early-onset Alzheimer's through a game environment that focuses on spatial memory. This cognitive function was one of the first to deteriorate due to the disease. This work can provide insights into the possibilities of new technologies in medical diagnostics and is relevant for using AR and VR when diagnosing PD [65].

The AR game developed for early AD diagnosis involves multiple levels aimed at testing spatial memory through interactive tasks (Figure 2.8) [65]:

- Introduction Level: Users familiarize themselves with the HoloLens and basic interactions.
- Recognition Task: Users identify and eliminate virtual objects placed in incorrect locations.
- Pattern Separation: Users recall and identify the original placement of hidden objects.
- Pattern Completion: Users detect changes in the appearance of objects.
- Pattern Recognition: Users assemble parts of an object from distinct elements.

Figure 2.8: Illustration of the level. Here the user will see the object selection for the first time.[65]

This game structure effectively engages users and provides a robust tool for assessing spatial memory, demonstrating AR's potential to enhance diagnostic accuracy and patient engagement in medical contexts [65].

The AR system demonstrated its potential through the simulation of a real-world experience for the development of ecologically valid tools for diagnosis. The HoloLens-based environment for gameplay has been helpful in successfully testing spatial memory, which is one of the best ways to early diagnose AD in an engaging and effective manner compared with traditional verbal and paper-based tests [65].

This study showed that AR could be used to overcome some limitations of traditional diagnosis by means of interactive and immersive testing environments. The AR game successfully discriminated between patients with early AD and normal subjects through pattern separation and pattern completion tasks. This is important because it demonstrates the potential for AR to improve diagnostic accuracy, which is an important goal in researching PD [65].

The participants stated they were more engaged and motivated with AR. Immersive HoloLens games, real-time feedback, and an interactive environment have been noted as the three ingredients in maintaining participation in procedures to provide diagnoses by the patient. This is very relevant since similar engagement strategies could be adapted in VR and AR applications for PD rehabilitation and diagnosis [65].

The current research indicated the need for validation in actual clinical environments to be able to generalize, but further research may be conducted regarding adaptability to different rooms. This resonates with the objective of what is possible with VR and AR, in terms of PD treatment and diagnosis, through continuous improvement/adaptation of these technologies towards successful integration into clinical practice [65].

The paper provides an excellent example of the use of AR to enhance diagnostics and patient engagement studies through the use of VR and AR in PD research.

2.4.4 Other Relevant Work

2.4.4.1 Augmented Reality Dual-Task Gait Training in Parkinson's Disease

Alberts *et al.* [2] evaluated an AR-based dual-task gait training platform (the DART system using a HoloLens headset) versus traditional therapist-led dual-task training in a randomized controlled trial with 47 PD patients. After 8 weeks of training, both the AR group and the traditional therapy group showed significant improvements in gait parameters (including increased walking speed, longer step length, and higher cadence) under single- and dual-task conditions [2]. Crucially, the AR-based training was found to be non-inferior to the in-person therapy – the gains in gait performance with DART were statistically equivalent to those achieved with a physical therapist [2]. These results demonstrate that an AR-guided exercise program can deliver comparable motor improvements to conventional therapy, potentially increasing access to effective gait and balance training for PD patients.

2.4.4.2 Combined AR and VR Gait Rehabilitation for PD

Gulcan *et al.* [24] explored a rehabilitation approach combining AR and VR for gait training in PD. In their study, 30 PD patients were divided into two groups: one group received 6 weeks of intensive gait training incorporating both AR and VR exercises (alongside conventional physiotherapy), while the control group received only conventional therapy. The AR/VR-enhanced training group exhibited significant improvements in motor function, balance, and gait compared to baseline – for example, better UPDRS-III motor scores, higher Berg Balance Scale scores, and faster Timed Up-and-Go performance [24]. While the control group showed some gains (notably in balance scores), the AR/VR group's improvements were substantially greater in most outcome measures [24]. The authors conclude that practicing walking and balance tasks in enriched virtual environments (with varied, increasingly difficult scenarios) can facilitate motor learning and yield superior rehabilitation outcomes for PD patients, beyond what standard therapy alone achieves.

2.4.4.3 Virtual Reality vs. Conventional Therapy in PD Rehabilitation

Several studies have focused on purely VR-based rehabilitation in PD. Pazzaglia *et al.* [52] compared a 6-week VR rehabilitation program (using interactive video-game exercises) against a traditional physical therapy program in 51 PD patients. Their randomized trial found that the VR group achieved greater overall improvements than the conventional therapy group. In particular, patients training with VR showed significantly larger gains in balance (Berg Balance Scale), gait adaptability (Dynamic Gait Index), and even upper-limb functional scores, whereas the conventional therapy led only to modest changes [52]. The VR-based therapy also improved aspects of quality of life. These findings indicate that an engaging VR rehabilitation program can outperform standard exercise therapy in enhancing motor skills and balance in PD, likely by increasing patient motivation and providing rich sensorimotor feedback.

2.4.4.4 Efficacy of VR-Based Rehabilitation: Meta-Analysis Evidence

A recent meta-analysis by Kwon *et al.* [33] aggregated the results of numerous controlled trials to determine the overall effectiveness of VR interventions for PD. This comprehensive review confirms that VR-based rehabilitation has significant benefits for people with PD. In pooled analyses, VR training led to marked improvements in patients' balance and gait outcomes compared to control conditions or no intervention [33]. The authors report that VR interventions produced clinically meaningful gains in postural stability and functional mobility, reinforcing that VR is a promising tool to complement conventional PD therapy. These meta-analytic results support the growing consensus that VR can effectively improve motor function and balance in PD patients, validating the positive outcomes seen in individual trials.

2.5 Chapter 2 Summary

This chapter establishes the foundations for the dissertation by reviewing PD, game-driven rehabilitation, immersive technologies (AR/VR/MR), and recent related work. It highlights how SGs and gamification can mitigate one of the main challenges in PD therapy, long-term adherence to repetitive exercises, by increasing motivation, engagement and feedback. It also frames XR along the virtuality continuum (from real-world to fully virtual) as an opportunity to deliver safe, repeatable, and adaptable rehabilitation tasks, with literature suggesting AR/VR interventions can be feasible and often comparable to conventional therapy for outcomes such as balance, gait, and postural control.

The chapter also outlines key challenges relevant to this thesis: high variability across PD stages and symptoms (e.g., tremor and bradykinesia) affecting interaction design, the importance of usability/comfort for older users, ambiguity in MR definitions across studies, and ethical/privacy considerations when collecting sensitive data such as eye tracking. Overall, it motivates the thesis approach of exploring configurable immersion levels and measurable interaction to support personalized PD rehabilitation.

3

Solution Context and Approach

This chapter introduces the context of the proposed solution and the approach taken to develop it. It outlines how prior work informed the first prototype, summarizes the iterative development across three phases, and presents the design rationale that guided the system towards supporting different immersion levels for people with PD.

3.1 Design Principles for Serious Games in PD

The development of *Fruit Picker XR* builds upon the foundations of the MoveONParkinson project, which investigated how digital technologies, such as VR and gamification, can support people with PD by providing new tools for physical exercise and cognitive stimulation. As reported in that work, the design of therapeutic serious games must account for the specific needs of this population, ensuring that the activities are both motivating and safe.

From the literature and the MoveONParkinson experience, several design principles can be identified as fundamental when creating serious games for people with PD:

- **Motivation and Enjoyment**: Games should be engaging and enjoyable, avoiding frustration. Motivational feedback is preferable over competitive or negative reinforcement, considering that most patients are elderly.

- **Feedback and Rewards**: Positive feedback (visual, audio, or textual) and rewarding systems help maintain adherence. Rewards should emphasize encouragement rather than punishment, to reduce discouragement.

- **Incremental Challenge**: Difficulty should increase progressively to avoid boredom if too easy or demotivation if too hard. This can be achieved through adjustable parameters or multiple levels.

- **Accessibility**: The design should account for motor impairments and cognitive limitations, offering options for seated play, left/right hand use, or visual accessibility (e.g., colorblind modes).

- **Relatability**: Game environments should feel familiar and relevant to patients, drawing from daily-life activities to increase engagement and meaning.
- **Session Evaluation**: Collected data (scores, levels, progress) should allow therapists to monitor performance and track improvements over time.

These principles serve as guiding values for the design of *Fruit Picker XR*. While the MoveONParkinson project placed greater emphasis on motivational models and clinical adoption, This dissertation focuses primarily on the exploration of immersion along the AR–VR continuum. Nevertheless, the aforementioned principles remain embedded in the design choices that shaped the gameplay mechanics, the use of baskets and fruits, and the integration with the *Play Platform*

3.2 Hardware Selection

The appropriate hardware had to be selected to support the system's intended functionalities, particularly the implementation of AR and the capture of user interaction data. Three headsets were considered: the Meta Quest 2 (Figure 3.1a), the Meta Quest 3 (Figure 3.1b), and the Meta Quest Pro (Figure 3.1c).

(a) Meta Quest 2 (b) Meta Quest 3 (c) Meta Quest Pro

Figure 3.1: Comparison of Meta Quest headsets

The Meta Quest 2 was excluded early on due to the poor quality of its passthrough capabilities, which are limited to a low-resolution monochrome feed. This makes it unsuitable for delivering a realistic or convincing AR experience, which is essential for the lower-immersion phases of the Virtual Continuum addressed in this work.

By contrast, the Meta Quest 3 features a high-resolution, full-colour passthrough camera that significantly improves the user's perception of the physical environment during gameplay. This makes it a strong candidate for delivering high-quality AR and MR experiences.

The Meta Quest Pro was also evaluated as a compelling alternative. While its passthrough quality is slightly inferior to that of the Quest 3, it offers built-in eye tracking capabilities that enable the collection of valuable gaze-related data for evaluating user engagement and cognitive responses. Its ergonomic design, including more balanced weight distribution and an adjustable fit, also makes it more comfortable for extended use, which is important for therapeutic contexts involving individuals with PD.

Ultimately, the Meta Quest Pro was chosen as the primary development and testing platform, as its unique combination of eye tracking, adequate passthrough performance and improved comfort offered the best compromise in support of the dissertation objectives (Table 3.1).

Table 3.1: Comparison of selected Meta headsets [66]

Feature	Meta Quest 2	Meta Quest 3	Meta Quest Pro
Passthrough Quality	Monochrome, low-res	Full-color, high-res	Color, mid/high-res
Eye Tracking	No	No	Yes
Hand Tracking	Yes	Yes	Yes
Comfort / Ergonomics	Basic	Improved	Advanced
Release Year	2020	2023	2022
Approx. Price (€)	300	500	1000

3.3 Prototype Development Approach

The solution was developed iteratively across three main phases, allowing the project to evolve from an initial adaptation of an existing prototype into a configurable system designed to explore different levels of immersion.

In the first phase, the game from the MoveOnParkinson project was extended with an AR mode, providing a starting point for testing how AR elements could support therapeutic exercise. In the second phase, a new version of the game was developed from scratch, maintaining the core fruit-catching mechanics but introducing hand tracking and eye tracking features, while also supporting both AR and VR modes. The third phase expanded this foundation into a configurable system with five immersion levels along the Virtual Continuum, enabling therapists to adapt the environment to each patient's needs.

A detailed description of each phase, including design decisions and implementation aspects, is presented in Chapter 4.

3.4 The Serious Game: *Fruit Picker XR*

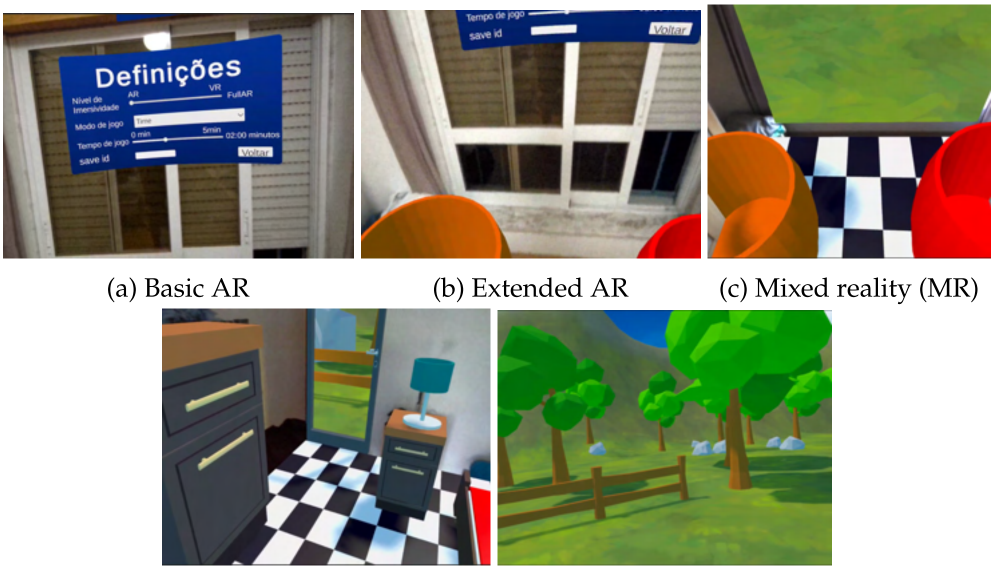
Before detailing the immersion levels, it is important to introduce the serious game that serves as the basis of this dissertation. *Fruit Picker XR* is an interactive rehabilitation game designed to encourage upper-limb movement and coordination in people with PD. The core mechanic consists of fruits that appear in front of the player and move in their direction, requiring the player to catch them and place them into the correct baskets.

The game is intentionally flexible, allowing both physical and virtual props to be used. In AR configurations, real cardboard baskets can be placed in front of the player and digitally tracked through invisible colliders, while in higher levels of configurations, the baskets are rendered virtually. The therapist can configure game parameters such as fruit spawn rate, speed, and session duration via the integration with the *Play Platform*, ensuring that the exercise can be tailored to individual therapeutic goals.

This design establishes a common gameplay foundation across all immersion levels, enabling a fair comparison between AR to VR experiences while maintaining therapeutic relevance.

3.5 Exploration of the Virtual Continuum

The literature highlights that the transition between AR and VR is not abrupt but instead a continuous spectrum, described by Milgram et al. as the *Reality–Virtuality Continuum*. In this work, the continuum is operationalized through five immersion levels implemented in the prototype *Fruit Picker XR*. Each level was defined according to the degree of substitution or integration between real and virtual elements, ensuring a gradual progression along the spectrum.



(a) Basic AR (b) Extended AR (c) Mixed reality (MR)

(d) Augmented Virtuality (e) Virtual Reality

Figure 3.2: Immersive levels of *Fruit Picker XR*.

- **Level 1 – Basic AR**: Real physical baskets are used, complemented with invisible virtual colliders that enable fruit collection detection within the real environment through passthrough (Figure 3.2a).
- **Level 2 – Extended AR**: The physical baskets are replaced by virtual baskets anchored in the physical environment, with passthrough still active (Figure 3.2b).
- **Level 3 – Mixed Reality (MR)**: Introduction of additional virtual elements (virtual floor, virtual windows) and transparent occlusion to ensure spatial coherence between real and virtual objects, characterizing an MR scenario (Figure 3.2c).

- **Level 4 – Augmented Virtuality (AV)**: The environment includes multiple virtual elements (furniture, doors, decoration) while maintaining passthrough, creating a mixed overlay between real and virtual (Figure 3.2d).
- **Level 5 – Virtual Reality (VR)**: A fully virtual experience with no integration of the physical environment. Only virtual baskets remain active, eliminating dependency on real elements (Figure 3.2e).

Table 3.2: Feature configuration across immersion levels in *Fruit Picker XR*.

Feature / Element	Level 1	Level 2	Level 3	Level 4	Level 5
Virtual Fruits	X	X	X	X	X
Passthrough (AR)	X	X	X	X	–
Virtual Baskets	X (real implied)	X	X	X	X
Virtual Floor	–	–	X	X	–
Real Furniture Occlusion	–	–	X	–	–
Windows (virtual)	–	–	X	X	–
Furniture (virtual)	–	–	–	X	–
Ceiling (virtual)	–	–	–	X	–
Virtual Scene	–	–	X	X	X

Table 3.2 summarizes the configuration of features across the five immersion levels. Furniture refers to grouped virtual elements such as tables, storage, wall art, bed, doors, lamp, couch and screen. Real furniture occlusion denotes scanned real objects rendered with a transparent material, enabling them to appear in front of the virtual floor for spatial coherence. The virtual scene becomes perceivable starting from Level 3, since virtual openings (windows or ceiling) reveal an external virtual environment. This mapping clarifies how the experience gradually transitions from real-world anchored interactions in AR (Levels 1–2), to mixed integration of real and virtual content in MR (Levels 3–4), and finally to a fully virtual context in VR (Level 5).

3.6 Integration with the Play Platform

A fundamental principle of the project is the integration with the *Play Platform*, which allows therapists to configure sessions, adjust game parameters in real time, and collect performance metrics. This ensures that the system is not limited to a standalone game but fits into a therapeutic framework adapted to the individual needs of patients.

3.7 Evaluation Metrics

The evaluation of the solution focuses on four main dimensions:

- **Usability**: measured with the System Usability Scale (SUS) [13], a validated questionnaire that provides a global usability score.

- **Workload**: evaluated using the NASA-TLX [25], which captures perceived workload across six dimensions: mental, physical, and temporal demand, performance, effort, and frustration.
- **Presence**: assessed with the Igroup Presence Questionnaire (IPQ) [58], which evaluates spatial presence, involvement, and experienced realism of the environment.
- **Cognitive Load**: assessed through complementary approaches. Subjective perception of mental effort was measured using the Paas scale [48], which is closely related to the mental demand dimension of the NASA-TLX but provides a more direct evaluation of perceived cognitive strain. In addition, NASA-TLX dimensions and objective *eye-tracking* metrics (fixation duration, saccades) were included as further indicators of workload and cognitive processing [46, 11, 63].

By integrating standardized questionnaires with physiological measures, the evaluation provides a multidimensional perspective of user experience across immersion levels. supporting a richer comparison of AR to VR conditions in the context of PD.

4

System design and Implementation

This chapter describes the development of the proposed solution, which examines how the Virtual Continuum spanning from AR to VR can be leveraged in a Serious Game to encourage and support physical exercise for individuals with PD. The findings discussed in the previous chapters form the basis for defining the system's adaptive and motivational elements, which are explained here along with the architecture and design of the solution. The game prototype developed for the different levels of immersion are also introduced, outlining their goals, requirements, core functionalities, and configurable aspects.

4.1 Prototype Development Phases

The proposed prototype was developed through three iterative phases. In the first phase, the functionality of a game from a previous project [55] was improved by adding an AR level. The second phase involved building a new game from scratch with the same core concept, expanded to include both AR and VR environments. During this phase, players could use hand tracking and additional eye tracking features were integrated to collect valuable data for system evaluation. The third and final phase introduces different levels of immersion within the Virtual Continuum and includes various optimizations based on insights gained in the second phase.

4.1.1 First phase

The main objective in this initial phase was to integrate AR capabilities into an existing game developed during a previous project.

The original concept for Fruit Picker XR was inspired by a simple sketch developed during the preliminary study of a previous project[55]. The initial idea involved grabbing fruits from a table and placing them into the correct basket, with movements that were later refined to resemble aerobic exercises similar to those performed in conventional therapy sessions for people with PD. In this virtual world, the fruits spawn at varying heights and distances, requiring the player to extend their upper limbs, reach in multiple directions, and perform repeated grabbing motions. The difficulty progressively increases by varying the spawning angles and speeds, and by introducing reward mechanisms such as bonus points for using a specific hand. In the context of this dissertation, the main

(a) VR version of the game

(b) AR version of the game

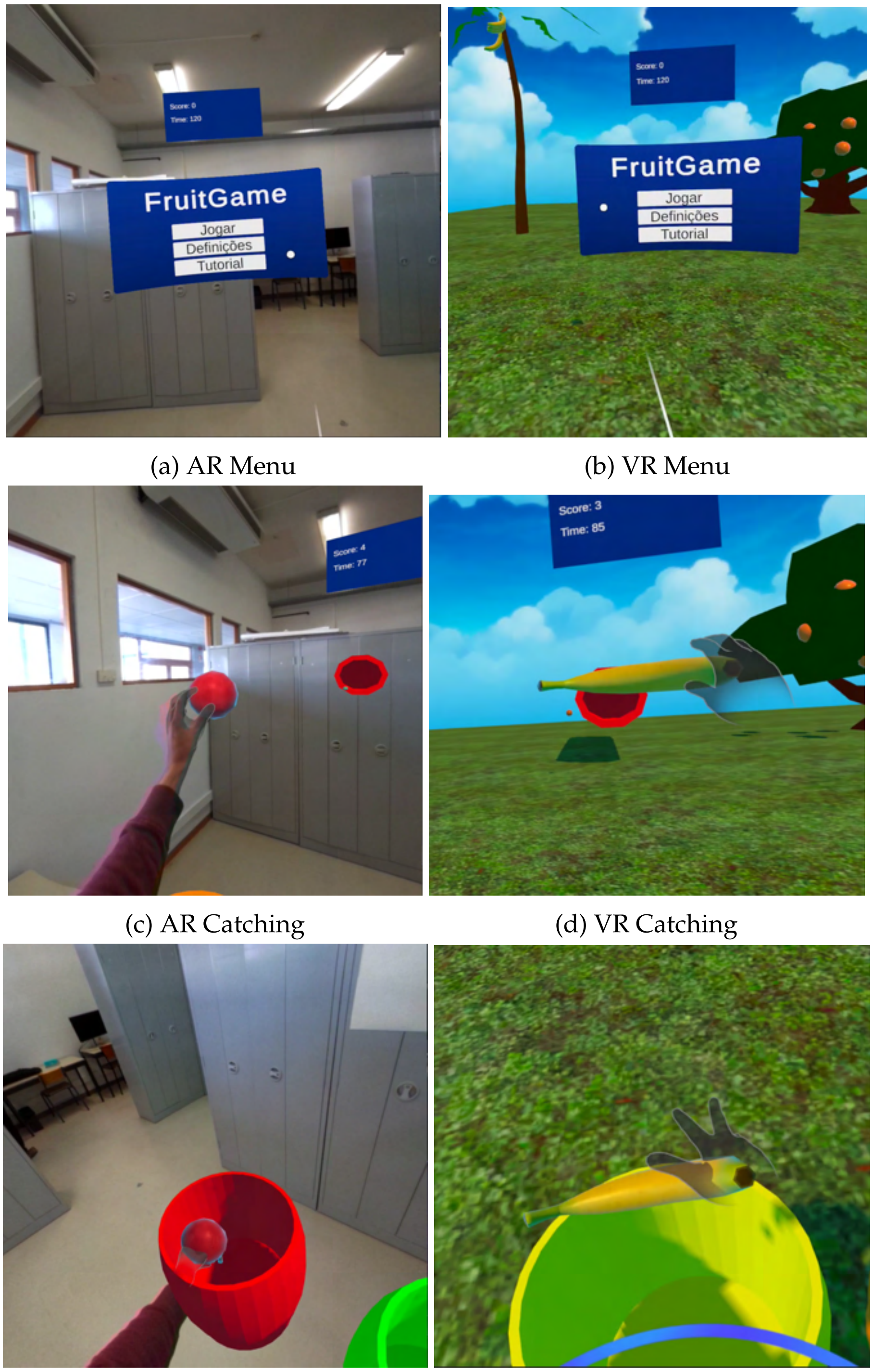
Figure 4.1: Comparison between the VR and AR versions of the game.

goal was to build on this existing concept and extend its capabilities by integrating AR functionalities. This addition supports the core objective of investigating how different levels of immersion from AR to VR can motivate and adapt physical exercise for people with PD. In the first phase of the prototype, the original game was enhanced with AR elements to allow players to interact with virtual fruits within their real environment, aiming to create a more flexible and accessible training scenario. This extension bridges the gap between the fully virtual experience of the earlier project and the broader Virtual Continuum explored in this dissertation

4.1.2 Second phase

The main feature implemented in this phase was the integration of eye tracking into a newly developed version of the game, which was rebuilt from scratch while preserving the original concept of catching fruits and placing them in corresponding baskets. In addition to eye tracking, this version also introduced hand tracking as the primary interaction method, eliminating the need for physical controllers. This change made the gameplay more intuitive and accessible, especially for users with Parkinson's Disease, as it allowed for a more natural interaction using only hand gestures.

The game was developed to support both AR and VR modes, marking a significant step forward along the Virtual Continuum. These modes could be easily configured within the same prototype, enabling controlled comparison between different levels of immersion. Eye tracking was primarily used to collect gaze data during gameplay, allowing further analysis of visual attention, focus, and engagement metrics, particularly relevant for evaluating cognitive responses in therapeutic contexts. This version of the game was later evaluated through a structured user study, where both healthy participants and individuals with PD interacted with the AR and VR modes. The gameplay experience, system usability, and player engagement were analyzed to assess the effectiveness and adaptability of this prototype, laying the groundwork for the next phase focused on multiple immersion levels.



(a) AR Menu (b) VR Menu

(c) AR Catching (d) VR Catching

(e) AR Fruit Placement (f) VR Fruit Placement

Figure 4.2: Screenshots of the AR and VR versions of the game from the 2nd phase.

4.1.3 Third phase

The third phase expanded the game into a configurable system supporting multiple immersion levels along the Virtual Continuum, from AR to fully immersive VR. This design enables therapists to select the most appropriate environment for each player—taking into account comfort, motor abilities, and sensitivity to immersive technologies—while preserving the same core gameplay loop.

Building on Phase 2, the core mechanics (catching fruits and placing them in the correct baskets) were retained, and the system was restructured for optimisation and configurability:

- **Immersion Levels.** Five distinct levels were implemented, progressively replacing real-world elements with virtual ones until reaching a fully virtual environment.

- **System Refinements.** The main virtual scene (assets and layout) was revised to improve visual clarity and spatial consistency across levels. To reduce target confusion when multiple fruits were nearby, basket color contrast was increased so that each target is more distinct during fast-paced gameplay. An accessibility mechanism was also added: when a fruit enters the interaction zone near the user's hand, it decelerates briefly to facilitate the catching motion, particularly for users with reduced motor precision. In practice, participants who initially struggled improved once they understood the gesture mechanic, leading to more consistent performance.

- **PLAY Integration.** The game now supports logging in from the headset to connect to the *Play* platform, enabling session configuration from a PC and adjustment of selected parameters while the session is running.

By introducing progressive immersion levels with targeted configurability and *Play*-based session control, this phase provides a more personalized and adaptable therapeutic experience while maintaining the benefits of core exercise-based gameplay.

4.2 Gameplay Concept and Mechanics

The proposed system is a serious game designed to support physical and cognitive engagement for individuals with PD. The core gameplay revolves around catching virtual fruits as they move through the environment and placing them into the corresponding colored baskets. This concept encourages repeated upper limb movements, hand-eye coordination, and spatial attention, all of which are relevant in therapeutic contexts.

The players interact with the game through the use of natural hand gestures, facilitated by hand tracking [64], eliminating the requirement for physical controllers. This design choice has been shown to reduce barriers to entry, increase accessibility, and create a more intuitive experience for users, particularly those who may experience motor limitations.

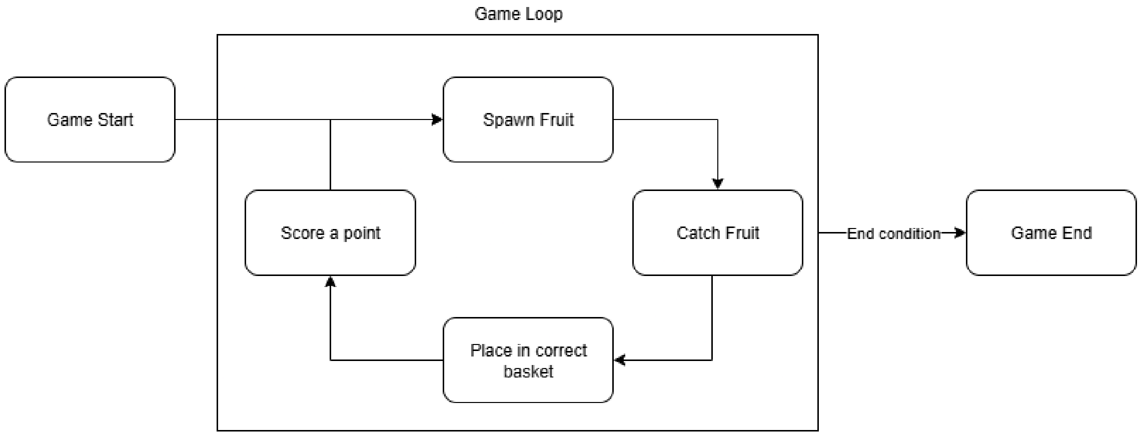


Figure 4.3: Fruit Picker XR game loop

The game follows a straightforward loop (Fig. 4.3) in which virtual fruits are spawned in front of the player and move toward them from various positions and angles. The player must reach out, grab the fruit using hand gestures, and place it into the correct colored basket. Upon successful placement, the player scores a point.

This gameplay cycle repeats until a predefined end condition is met. The end condition is determined by the selected **game mode**. The game supports the following three end conditions:

- **Time Limit** – the game ends when a countdown timer reaches zero;
- **Score Limit** – the game ends when the player reaches a predefined score;
- **Lives Limit** – the game ends when the player exceeds the number of allowed incorrect placements.

These configurable end conditions make the game adaptable to different user profiles and therapeutic contexts, allowing flexible session planning and personalized difficulty.

The game includes four distinct fruit types, each associated with a specific colored basket (Figure 4.4) to support simple, intuitive sorting based on color recognition. The mapping is as follows:

- **Banana** → Yellow basket
- **Apple** → Red basket
- **Pear** → Green basket
- **Orange** → Orange basket

This color-based categorization is intentionally designed to reduce cognitive complexity and support quick decision-making during gameplay.

Figure 4.4: Fruit Picker XR baskets and the corresponding fruit

Designing the game for use in VR and AR environments required several considerations, particularly due to the target population of individuals with PD. The gameplay had to remain simple, intuitive, and cognitively light in order to minimize potential frustration or confusion. At the same time, the game was structured to promote repetitive, purposeful upper-limb movements that align with physical therapy goals. By combining ease of use with motivational mechanics, such as immediate feedback, scoring, and visual engagement, the game aims to encourage participation and stimulate motor activity in a way that is both accessible and therapeutically relevant.

A scoring system provides immediate feedback and motivation. Players earn points by successfully placing each fruit into the correct basket. No points are awarded for incorrect placements or missed fruits. This simple scoring logic reinforces task accuracy and encourages players to remain focused throughout the session.

The core mechanics remain consistent across all levels of immersion, from AR to VR. This consistency ensures that gameplay comparisons across the Virtual Continuum can be made while keeping the task requirements stable. Adjustments in background environment and object rendering are handled according to the level of immersion, but the rules and objectives of the game remain unchanged.

4.3 User Interface and Visual Design

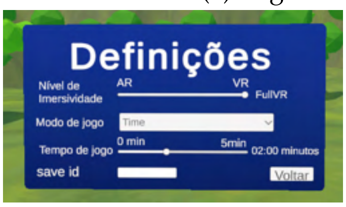
The User Interface (UI) and visual design of the system were developed with a strong focus on simplicity, accessibility, and consistency. Given the target population — individuals with PD — the interface had to be intuitive and easy to interpret, minimizing cognitive load and avoiding unnecessary complexity. All elements were designed to be visually clear and comfortable to interact with, regardless of the level of immersion (AR or VR).

The interface includes several essential components: The interface is composed of several essential components designed to facilitate navigation and provide relevant feedback throughout the gameplay experience:

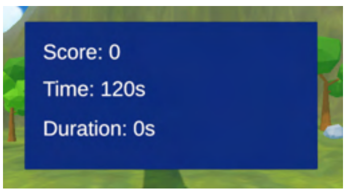
- **Login Screen:** Allows the user to log in with a registered account or continue as a guest, in case they prefer not to connect to the platform (Figure 4.5a).
- **Main Menu:** Provides access to the core functionalities of the game, including starting a session, launching the tutorial, or entering the settings menu to configure parameters such as game mode or difficulty (Figure 4.5b).
- **Settings:** Enables the user to adjust the immersion level, set the duration of the game session, and choose the preferred game mode (Figure 4.5c).
- **In-Game UI:** Displays real-time gameplay information. This includes a timer and score counter, as well as additional indicators depending on the selected game mode, such as the number of remaining lives, the target score to reach, or the time left to complete the session (Figure 4.5d).
- **Post-Game Screen:** Shows a summary of the player's performance, including the final score, and provides a button to exit the game (Figure 4.5e).

(a) Login Screen

(b) Main Menu



(c) Settings



(d) In-Game UI

(e) Post-Game Screen

Figure 4.5: UI interface of the game.

4.4 System Architecture Overview

This section describes the architecture of the *Fruit Picker XR* prototype, outlining its main components and how they interact to support the AR and VR game experiences. The goal is to provide a clear overview of the system's structure (Figure 4.6) before detailing each module in the following subsections.

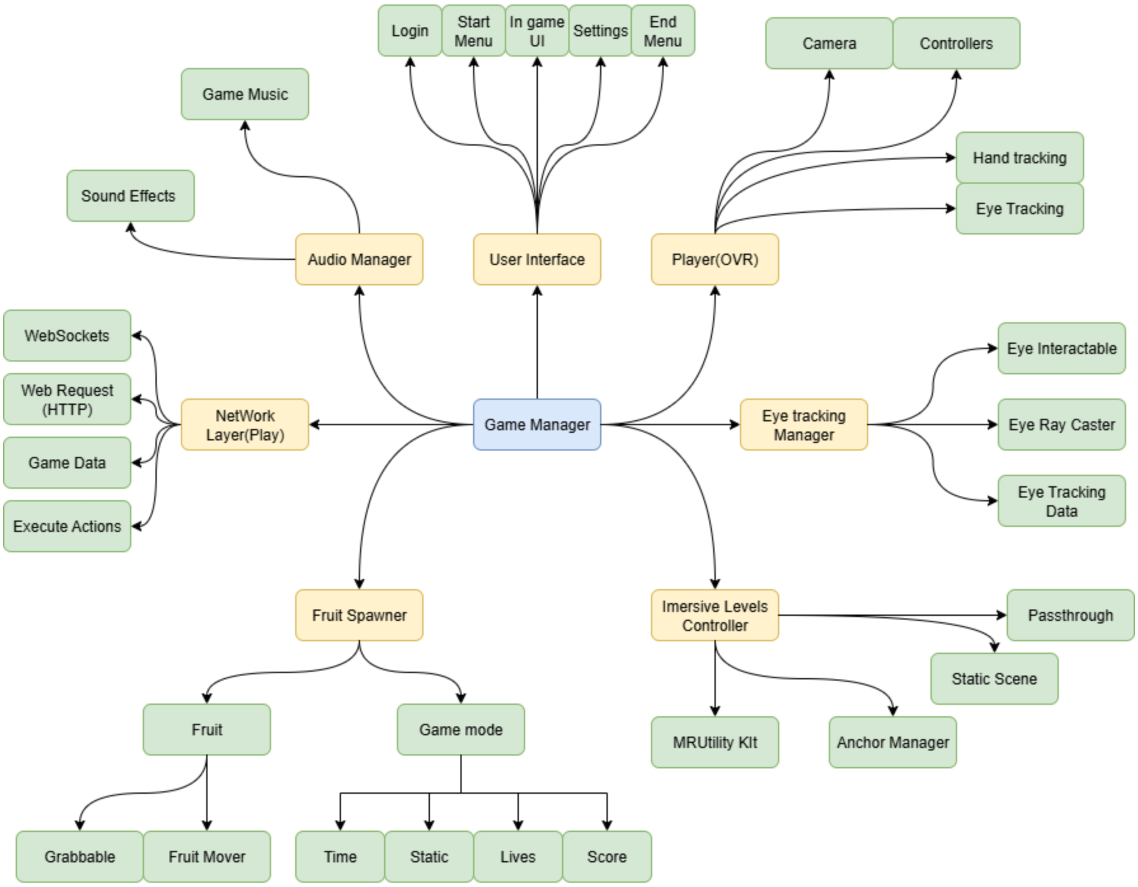


Figure 4.6: Fruit Picker XR game architecture

4.4.1 Components

Here are the main components that comprise the game's architecture. Each one has a distinct responsibility within the system, and together they ensure that the application can adapt across different immersion levels while maintaining consistent gameplay.

4.4.1.1 User Interface

The User Interface (UI) presents the login screen, main menu, in-game HUD (timer, score, and mode-dependent indicators), and post-game summary. The layout is consistent across immersion levels to reduce cognitive load and support comparability between AR and VR conditions.

4.4.1.2 Network Layer (Play)

The game connects to the *Play* platform to authenticate players, manage sessions, receive configuration parameters, allow real-time adjustments, and transmit game data. This integration is divided into three logical parts: HTTP requests, a WebSocket channel, and the execution actions layer.

Login and HTTP requests
The connection to the platform begins with a login procedure. When the user provides valid credentials, the game authenticates with the Play backend and stores the session token. From this moment, an authorized communication channel is established. Through HTTP requests, the game can also perform logout operations, declare a new game execution before starting a session, and submit final results at the end of gameplay.

WebSockets (real-time channel)
After authentication, a persistent WebSocket connection is opened. This channel enables bidirectional communication during gameplay, so that the therapist can send configuration changes while the session is running. Examples include adjusting fruit speed, changing spawn rate, or toggling auxiliary features. The WebSocket client handles the delivery of these updates in real time, ensuring that they are safely integrated into the game state.

Execution Actions (applying configuration)
The execution actions layer is responsible for interpreting and applying the configuration received from the platform. This includes both the initial setup provided at the start of a session and the subsequent changes delivered through the WebSocket channel. Parameters managed at this stage include:

- the selected **immersion level**;
- whether the **tutorial** is enabled;
- the **game mode** (time limit, score limit, lives limit, or static fruits);
- the **fruit parameters** (e.g speed, spawn interval, and possibility to spawn fruits manually).

By centralising the application of configuration, this layer ensures that all modules in the game operate consistently under the parameters chosen by the therapist.

4.4.1.3 Player (OVR)

The Player module encapsulates headset, camera, and tracking-specific functionality exposed by the Meta XR/OVR stack, including headset pose, hand tracking poses, and scene passthrough for AR. It exposes normalized inputs to the rest of the game so that higher-level systems remain hardware-agnostic.

4.4.1.4 Game Manager

The Game Manager acts as the central hub of the application, maintaining access to all other main managers (See to Figure 4.6, highlighted in yellow boxes) while ensuring that the session lifecycle is executed consistently. Its coordination role is especially relevant for the *Fruit Spawner* (responsible for object spawning and gameplay modes), the *Immersive Controller* (which applies the correct immersion level and environment configuration), and the *Network Layer* (which handles communication with the PLAY platform). Through these connections, the Game Manager guarantees that the overall flow of the application remains synchronized and that gameplay unfolds under coherent control.

4.4.1.5 Fruit Spawner

The *Fruit Spawner* controls when and where fruits appear, how they move through the scene, and how they interact with the player's hands and baskets. It operates under session parameters, including the selected game mode and pacing.

Game modes
The spawner supports four game modes:

- **Time Limit:** the session runs until the countdown expires.
- **Score Limit:** the session ends when the player reaches a predefined score.
- **Lives Limit:** the session ends when the player misses a certain number of fruits.
- **Static Fruit:** fruits are spawned close to the player in fixed positions, without movement, to support less demanding interaction (has the same end condition with time limit).

Spawn positions and trajectories (Fruit Mover)
Fruits are instantiated in front of the player at configurable ranges of distance and height, and from lateral offsets to obtain upper-limb reach in multiple directions. Their trajectories are always linear, moving directly toward the player. The velocity of these trajectories can be adjusted through configuration parameters. Each fruit is assigned a movement controller that updates its position and signals despawn when the interaction ends.

Grabbing and interaction (Grabbable)
Controller-free interaction is implemented via hand tracking. Each fruit exposes a graspable collider; when the player's hand pose meets the grasp condition (proximity plus a valid pinch/closed pose), the fruit becomes attached to the corresponding hand, switching to a kinematic state (i.e., no longer affected by physics and directly following the hand transform). Releasing the grasp (pose change or distance threshold) detaches the fruit,

and placing it in a basket triggers a rule check: correct placements score a point, while incorrect placements or timeouts are registered as misses.

4.4.1.6 Immersive Level Controller

The *Immersive Controller* is responsible for adapting the system to the selected level of immersion along the Virtual Continuum. Instead of changing the core gameplay mechanics, it configures which virtual and real-world elements are visible and active during the session. This is achieved through the combination of passthrough control, scene management, and prefab anchoring.

Mixed Reality Utility Kit (MRUK)
The controller integrates the *Mixed Reality Utility Kit (MRUK)*, provided by Meta [42], which is responsible for scanning the physical environment and generating a spatial representation of the room. MRUK captures surfaces such as walls, floor, and real furniture, producing anchors that can be used by the application. At this stage, MRUK only provides the scan; it does not decide how those elements are represented in the game.

Static Scene
The static scene refers to the virtual environment elements, such as trees, rocks, or mountains, that provide the background setting of the game. These assets become fully visible in the higher immersion levels, particularly in the VR level, while in lower levels they remain minimal or absent.

Passthrough Control
The controller can toggle passthrough rendering on or off depending on the selected level. In AR-oriented levels, passthrough is enabled to display the real environment, augmented with virtual elements such as fruits and baskets. In higher-immersion levels, passthrough is disabled, and the player is fully surrounded by a virtual environment.

Anchor Prefab Manager
The *Anchor Prefab Manager* determines which real-world furniture identified during the MRUK scan is replaced with virtual prefabs. For example, furniture such as tables or chairs may be virtualized in higher immersion levels, while at lower levels the same objects remain physical. This selective virtualization enables a gradual transformation of the player's environment, aligning with the intended immersion level.

In summary, the Immersive Level Controller acts as the layer that enforces immersion-specific configurations. It relies on MRUK to obtain a spatial scan of the room, uses the static scene system to apply level presets, toggles passthrough when required, and virtualizes selected real-world objects through the Anchor Prefab Manager.

4.4.1.7 Eye Tracking

The Eye Tracking Manager is responsible for monitoring the player's gaze and producing data that can be analysed later. It is organised into three main parts.

Eye-interactable objects
Only selected objects in the scene are registered as *eye-interactables*. These include fruits, baskets, interface elements, and background or scene components. Each object is assigned a type label, allowing dwell time to be aggregated both per object and per category. Frames in which the gaze ray does not hit a specific target are counted as **background**, ensuring that all gaze time is assigned to a category.

Ray Caster
A gaze ray is cast each frame from the current eye direction into the scene. The ray only collides with eye-interactable objects, ignoring all other geometry. When a hit occurs, the manager identifies which object and type were looked at; if no valid target is hit, the frame is recorded as background.

Eye Tracking Data
The manager generates two types of data:

- **Gaze duration:** the total time the player spent looking at each category of eye-interactable (e.g., 40 seconds on fruits, 15 seconds on baskets, 20 seconds on background).
- **Eye velocity samples:** per-frame measurements of how quickly the gaze direction changes, stored for later analysis of visual effort or cognitive load.

All records are time-stamped and linked to the session identifier, allowing them to be aligned with gameplay events and other performance metrics.

4.4.1.8 Audio Manager

The *Audio Manager* is responsible for controlling the sound layer of the game, ensuring that audio feedback is delivered at appropriate moments to reinforce the player's interaction with the environment. Rather than embedding sound logic inside each game object, this component centralizes the management of audio, reducing redundancy and ensuring consistency across the system.

The *Audio Manager* stores all the sound samples used in the game, such as those associated with fruit spawning or other gameplay events. When a sound needs to be played, the corresponding game object does not handle it directly; instead, it sends a request to the *Audio Manager*, specifying the sound by name. The manager then retrieves and plays the corresponding audio sample, ensuring that auditory feedback is consistent and synchronized with the visual gameplay. This centralized approach also simplifies maintenance, as new sounds can be added or modified in a single location.

4.5 Software Components and Tools

The game was developed using **Unity 3D**, a widely adopted game engine with strong support for virtual and augmented reality. Unity's flexibility allowed for the implementation of custom interaction mechanics, including hand tracking and eye tracking. All scripting was done in C#, using **Rider** as the main development environment.

To fully support the capabilities of the Meta Quest headsets, the project was developed exclusively with the **Meta XR SDK**. This allowed direct integration of hand tracking for natural interaction, passthrough for AR-based levels, and eye tracking on the Meta Quest Pro. Additionally, the **Mixed Reality Utility Kit (MRUK)** was used to assist with spatial anchoring and dynamic placement of virtual content in real environments, improving the MR experience.

Version control was handled through **Git** and **GitHub**, providing consistent change tracking and project management during all development phases.

For data collection, **Google Forms** was employed to distribute questionnaires such as SUS, NASA-TLX, IPQ, and Paas, along with demographic surveys. This streamlined the process of obtaining structured participant feedback across conditions.

Data analysis was carried out primarily with **Python**, using libraries such as *Pandas*, *NumPy*, and *Matplotlib* to process CSV logs, calculate questionnaire scores, and generate visualizations. **Microsoft Excel** was also used for preliminary validation and manual inspection of the datasets.

4.6 Platform Integration

In addition to the development of the game itself, this work also explored its integration with the **PLAY platform**. PLAY is a multi-user, web-based system designed to support patients, therapists, and clinics by offering tools for personalization, monitoring, and data analysis [3]. The platform was originally created to extend the potential of serious games in rehabilitation, allowing them to be configured and managed remotely by therapists.

A key motivation for PLAY is to address the limitations of traditional physiotherapy exercises, which are often repetitive and demotivating for patients. Through the platform, therapists can configure game sessions by defining therapeutic actions, structuring them into levels, and tailoring them to the individual needs of each patient. Each patient has a profile that aggregates personal and therapeutic information, enabling session recommendations and the tracking of progress over time. PLAY also provides a repository for storing results and samples, facilitating the later analysis and comparison of data across different patients and sessions.

Technically, PLAY is built on a cloud-based backend with separate frontends for patients, therapists, and administrators. External applications, such as the game developed in this dissertation, can connect through a RESTful web services API. This API supports authentication, configuration, real-time monitoring, and results submission via JSON-based communication, making it possible to extend the platform with third-party therapeutic games.

Within the scope of this project, the integration with PLAY demonstrated how the game could be connected to a broader therapeutic ecosystem. This connection made it possible to receive therapist-defined configurations before and during gameplay (e.g., immersion level, fruit speed, or spawn rate), and to ensure that game results and interaction data were stored centrally for further analysis.

When a patient logs into the game, they are also registered within the therapeutic view of the PLAY platform. From this interface, therapists gain the ability to configure the game parameters according to the needs of each participant. As shown in Figure 4.7, the configuration screen provides direct control over immersion levels (ranging from Basic AR to full VR), game modes (time, score, lives, or static fruit), and additional options such as enabling the tutorial. Sliders allow fine adjustments to gameplay parameters, including total session duration, fruit spawning interval, and fruit speed. Once the parameters are defined, they can be applied in real time, ensuring that each game session is tailored to the therapeutic goals and comfort level of the patient.

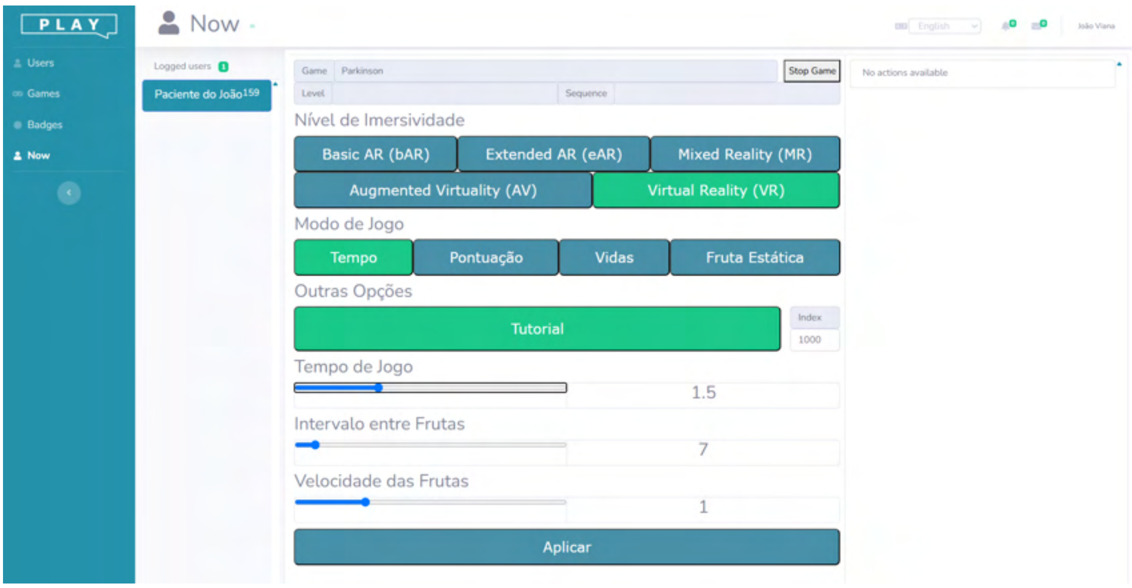


Figure 4.7: PLAY platform configuration screen, where therapists can define immersion level, gameplay mode, and detailed parameters such as fruit speed and spawn interval.

In addition to pre-session configuration, the PLAY platform also provides the ability to adjust parameters in real time while the game is running. As illustrated in Figure 4.8, therapists can dynamically modify variables such as the interval between fruit spawns or their falling speed, and immediately observe the effect in the patient's gameplay. This functionality enables fine-tuning of the exercise intensity according to the participant's performance or fatigue level, ensuring that the session remains both effective and safe.

Figure 4.8: PLAY in-game configuration screen, allowing therapists to adjust gameplay parameters such as fruit interval and speed in real time.

When the game session ends, a result entry is automatically generated in the patient's profile within the PLAY platform. As shown in Figure 4.9, the session summary presents both the gameplay configuration (e.g., immersion level, game mode, fruit speed, and interval) and key performance metrics, such as duration, score, and success rate. This record-keeping allows therapists to monitor the patient's evolution over multiple sessions, compare results across different configurations, and adapt future interventions accordingly. The ability to review detailed outcomes, including session parameters, ensures that the therapeutic process is transparent, trackable, and fully aligned with the patient's clinical goals.

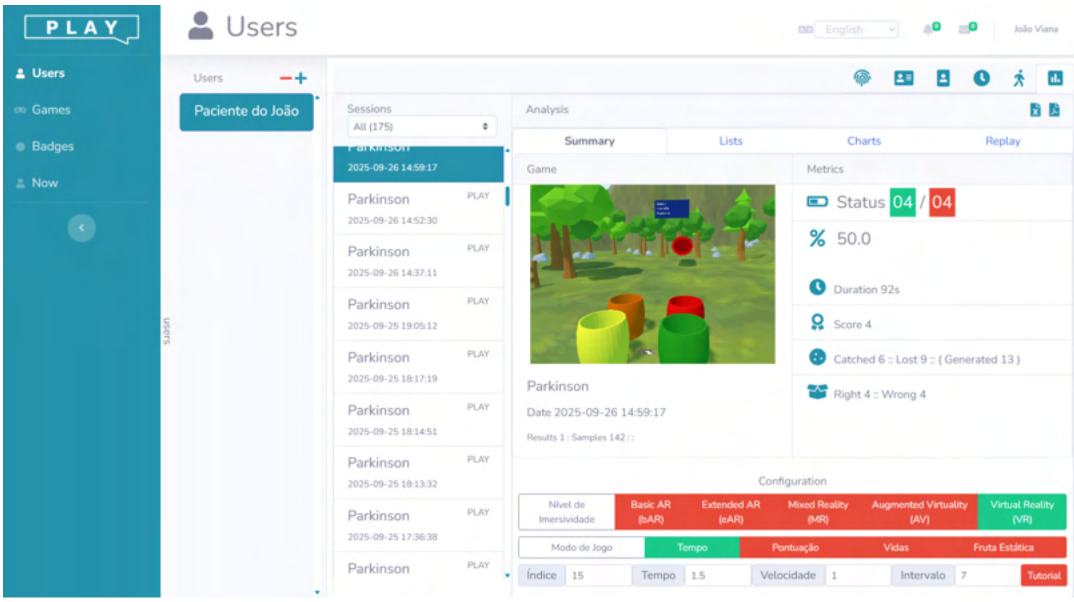
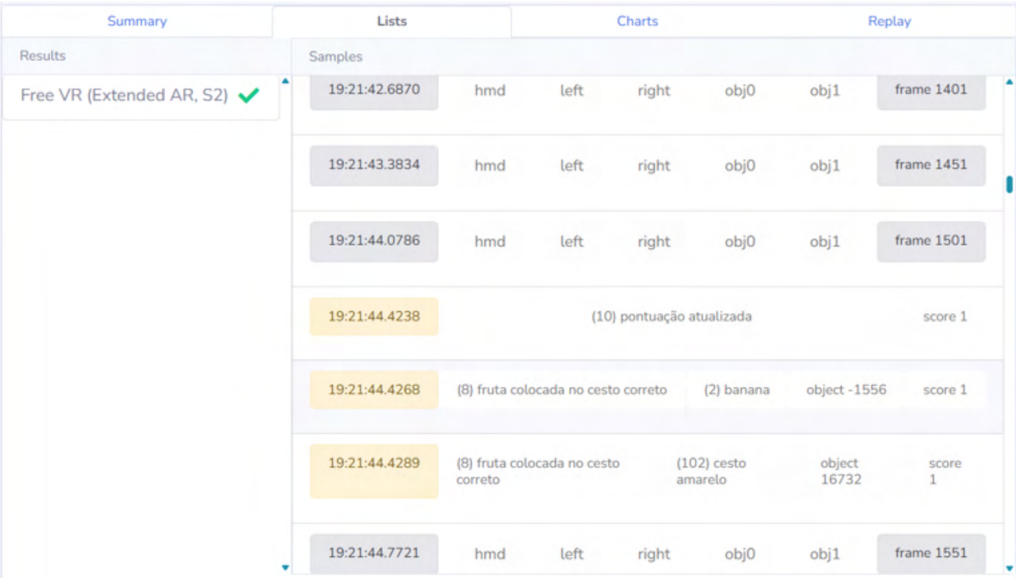
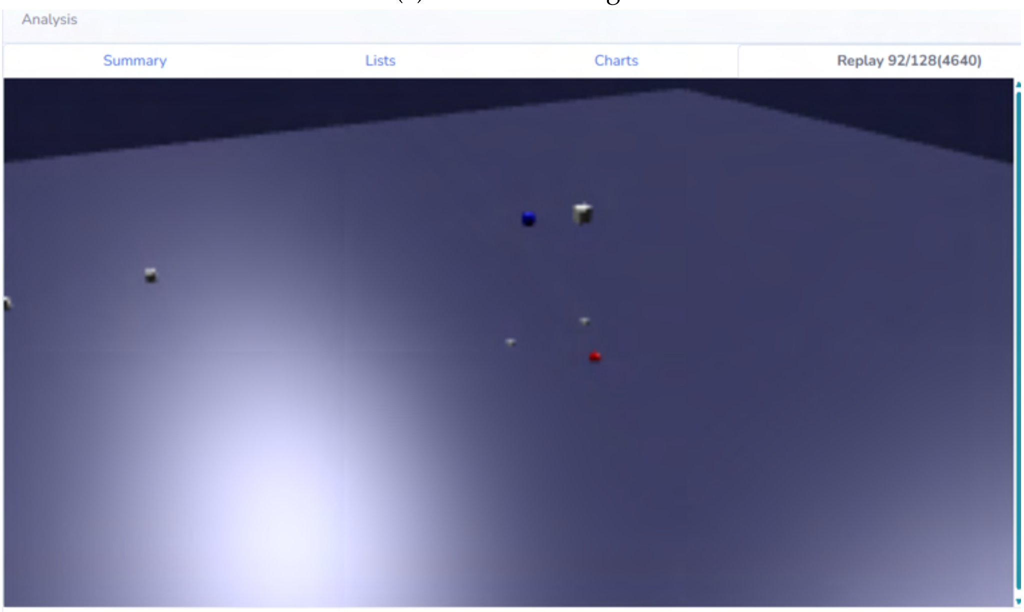


Figure 4.9: Example of a session summary recorded in the PLAY platform, showing the applied configuration and corresponding performance metrics.

Beyond configuration and result summaries, the PLAY platform also records data streams from the game. As illustrated in Figure 4.10a, each interaction is logged with precise timestamps, including the position of the headset and hands, the state of virtual objects (such as fruits and baskets), and key gameplay events (e.g., a fruit being successfully placed in a basket or a score update). This level of detail enables therapists and researchers to analyze not only outcomes but also the underlying actions adopted by the player. An additional feature made possible by this detailed logging is the *replay* mode, shown in Figure 4.10b. Since the positional data of the player and objects is stored chronologically, the platform can reconstruct and visualize the game session. At the current stage, this functionality is still under development and should be regarded as an early prototype rather than a finalized tool. Nonetheless, it demonstrates the potential of using time-stamped gameplay data to reproduce and analyze sessions in detail.



(a) Session data log.



(b) Replay view.

Figure 4.10: Features of PLAY: (a) gameplay data collection and (b) replay of the entire session.

5

Results and Discussion

The present chapter is about the evaluation of the system, which was achieved through two separate rounds of testing conducted with different versions of the game. The initial round concentrated on the second phase of the prototype, which incorporated AR, VR, hand tracking, and eye-tracking features. The second round was based on the final version of the prototype, which introduced multiple levels of immersion across the Virtual Continuum, along with additional optimizations and refinements. Both rounds followed a standardized evaluation protocol designed to assess usability, collect user feedback, and analyze eye tracking data from both control and PD participants.

5.1 First User Study: AR and VR Gameplay Evaluation

The study was divided into two distinct phases: one involving a control group composed of participants without Parkinson's Disease (PD), and another with individuals diagnosed with PD.

The first study involved a control group of 31 participants without PD, who served as a baseline to validate the system's operation within a younger, healthy population. The participants in this study ranged in age from 18 to 50 years (mean = 21.8, SD = 5.84), with a majority being university students or young professionals. The gender distribution of the participants included 24 males and 7 females. In terms of education, 15 participants had completed high school education, 8 held a bachelor's degree, and the remaining 8 had alternative qualifications such as CTeSP or CET Level 5 certificates.

The second sub-phase included four individuals diagnosed with PD (Figure 5.1), aged between 57 and 72 years (mean = 65.0, SD = 6.78). The sample comprised three males and one female, all of whom had completed secondary education. Two participants were in stage 1 of the disease and two in stage 2, according to the standard PD staging scale. The experimental procedure followed a standardized protocol comprising the following steps:

1. **Informed Consent and Identification** – Participants were briefed on the study's purpose and procedures, gave informed consent, and completed an identification questionnaire.

2. **Environment Setup** – The testing space was checked to ensure it was safe and appropriate for gameplay.

3. **Initial Data Setup** – A data folder was created for each participant, labeled with their ID and the first game version (AR or VR).

4. **Headset Preparation** – The headset was calibrated and fitted for comfort and stability.

5. **Tutorial Session** – Participants engaged in a brief tutorial to become familiar with the gameplay mechanics.

6. **Gameplay Session 1** – The first game version (AR or VR) was played for two minutes while eye-tracking data was collected.

7. **Post-Game Questionnaire 1** – Participants evaluated their first experience using a structured questionnaire.

8. **Second Data Setup** – A second data folder was created for the alternate version of the game.

9. **Headset Re-Adjustment** – The headset was reconfigured for the next session.

10. **Gameplay Session 2** – The second version (AR or VR) was played for two minutes while eye-tracking data was recorded.

11. **Post-Game Questionnaire 2** – A second evaluation was completed based on the second experience.

12. **Conclusion** – The session ended with equipment shutdown and a thank-you to participants.

(a) PD patient testing in the AR environment

(b) PD patient testing in the VR environment

Figure 5.1: Examples of PD patients testing the game in both environments

5.1.1 Questionnaires

Two types of questionnaires were used: an identification questionnaire to collect demographic and clinical data, and user questionnaires employing standardized scales to assess usability, workload, cognitive load, and presence.

5.1.1.1 Identification Questionnaires

The identification questionnaire collected demographic information such as age, gender, and educational level, together with questions related to technological familiarity and prior experience with digital games. For participants with PD, additional questions addressed the presence of the disease and its clinical stage. This information was essential to contextualize the results, allowing comparisons between groups with different backgrounds and levels of familiarity with immersive technologies, as well as ensuring that the study considered the specific characteristics of the target population.

5.1.1.2 User Questionnaires

The user questionnaire was developed to capture different aspects of the interaction with the game, including usability, Cognitive Load (CL), mental workload, and the overall sense of presence. For this purpose, several validated scales were employed, namely the NASA-TLX [25], the Paas Scale [48], the IPQ [58], and the System Usability Scale (SUS) [13].

In particular, the evaluation of CL relied on the NASA-TLX and the Paas Scale, while presence and immersion were assessed with the IPQ, emphasizing the sense of "being in" the environment and the degree of engagement experienced. Finally, the usability of the prototype was measured using the SUS scale.

5.1.2 Results

This section presents the main findings from the user study, comparing the AR and VR versions of the game. Results are reported for both the control group and the participants with Parkinson's disease, covering usability, workload, presence, and performance measures.

5.1.2.1 NASA Task Load Index

To assess the subjective workload experienced during the gaming sessions, the NASA-TLX questionnaire was employed. This tool considers six dimensions of workload: mental demand, physical demand, temporal demand, perceived performance, effort, and frustration. Participants rated each dimension on a 7-point Likert scale, with higher values indicating greater levels of perceived workload.

Before presenting the results, it is important to identify the tables containing the NASA-TLX results. Tables 5.1 and 5.2 correspond to the Control Group, showing the relative frequency of responses for both the AR and VR conditions. In turn, Tables 5.3

and 5.4 present the results for the Parkinson's Disease group, also separated by AR and VR gameplay.

Control Group

Table 5.1 presents the NASA-TLX results for the AR game experience in the control group. The overall workload was **30.38 ± 9.04**, indicating a low-to-moderate demand.

For the individual dimensions as shown in Table 5.1, **mental demand (NKM)** was low, with most ratings at 1–2. **Physical demand (NKP)** followed the same trend, also concentrated at lower values. **Temporal demand (NKT)** was slightly higher, mainly at 2–3, suggesting only minor time pressure. **Performance (NKO)** was rated positively, with most participants selecting higher values (5–7), showing they felt successful in completing the task. **Effort (NKE)** remained low, with responses clustered around 1–2. Finally, **frustration (NKF)** was minimal, with 71% of responses at the lowest level, indicating almost no stress or irritation. Overall, the AR game was perceived as manageable, requiring little effort, with high perceived performance and very low frustration.

Table 5.1: NASA-TLX questionnaire results for AR game experience

Questions	1	2	3	4	5	6	7
NKM: How mentally demanding was the task?	0.35	0.39	0.16	0.06	0.00	0.03	0.00
NKP: How physically demanding was the task?	0.29	0.39	0.19	0.06	0.03	0.03	0.00
NKT: How hurried or rushed was the pace of the task?	0.06	0.42	0.26	0.23	0.03	0.00	0.00
NKO: How successful were you in accomplishing what you were asked to do?	0.00	0.00	0.00	0.06	0.19	0.35	0.39
NKE: How hard did you have to work to accomplish what you were asked to do?	0.23	0.42	0.19	0.13	0.00	0.00	0.03
NKF: How insecure, discouraged, irritated, stressed, and annoyed were you?	0.71	0.23	0.03	0.00	0.03	0.00	0.00
NKScore: Overall Score (0-100)	30.38 ± 9.04						

As shown in Table 5.2, the NASA-TLX results for the VR game experience in the control group revealed an overall workload of **18.46 ± 11.60**, which was also low and even lower than in the AR game experience. For the subscales, **mental demand (NKM)** was very low, with most ratings at 1–2 (81%), similar to the AR case. **Physical demand (NKP)** was also low, concentrated at 1–2 (78%), again showing minimal physical strain. **Temporal demand (NKT)** was slightly lower than in AR, with 65% at value 2, suggesting only a mild sense of pacing.

In contrast, **performance (NKO)** received predominantly low ratings, with around 70% of responses at values 1–2, indicating that participants felt less successful in accomplishing the task compared to AR, where higher scores were more frequent. **Effort (NKE)** remained low, with 71% at 1–2, showing little exertion required. Finally, **frustration (NKF)** was minimal, with 77% at value 1, consistent with the AR findings.

Overall, both AR and VR game experiences were associated with low workload, low effort, and minimal frustration. However, while AR participants reported high perceived performance, in VR the performance ratings were noticeably lower, suggesting that participants felt less successful in this modality.

Table 5.2: NASA-TLX questionnaire results for VR game experience

Questions	1	2	3	4	5	6	7
NKM: How mentally demanding was the task?	0.39	0.42	0.13	0.03	0.03	0.00	0.00
NKP: How physically demanding was the task?	0.39	0.39	0.19	0.03	0.00	0.00	0.00
NKT: How hurried or rushed was the pace of the task?	0.06	0.65	0.10	0.16	0.00	0.03	0.00
NKO: How successful were you in accomplishing what you were asked to do?	0.32	0.32	0.06	0.03	0.10	0.10	0.06
NKE: How hard did you have to work to accomplish what you were asked to do?	0.29	0.42	0.16	0.06	0.06	0.00	0.00
NKF: How insecure, discouraged, irritated, stressed, and annoyed were you?	0.77	0.13	0.06	0.00	0.03	0.00	0.00
NKScore: Overall Score (0-100)	18.46 ± 11.60						

Parkinson participants

Table 5.3 summarizes the NASA-TLX results for the AR game experience in the Parkinson's group. The overall workload in the AR game experience was **34.72 ± 10.27**, slightly higher than the control group, but still within a low-to-moderate range. Looking at the subscales, **mental demand (NKM)** was mostly rated at 3 (50%) and 4 (25%), suggesting a moderate cognitive effort. **Physical demand (NKP)** showed higher values than in the control group, concentrated at 2 (50%) and 1–4 (25% each), reflecting some physical strain. **Temporal demand (NKT)** was more spread, with 50% at 3 and 25% at both 4 and 5, indicating a greater sense of pacing and time pressure.

Performance (NKO) was mixed, with responses distributed across the scale, including some high scores (7 with 25%), but also lower ones (1–3), suggesting variability in how participants judged their success. **Effort (NKE)** leaned toward moderate, with 50% at 2 and 25% at 3–4, meaning that more effort was required than in the control group. Finally, **frustration (NKF)** showed a very variable distribution, with responses spread across 1, 2, 4, and 5, indicating heterogeneous experiences among participants. Overall, Parkinson's participants experienced the AR game as somewhat more demanding than the control group, particularly in terms of physical, temporal, and effort dimensions.

While performance perception was variable, the workload remained manageable, highlighting the feasibility of the AR version but also showing the influence of motor and attentional challenges specific to this group.

Table 5.3: NASA-TLX questionnaire results for AR game experience (Parkinson's group)

Questions	1	2	3	4	5	6	7
NKM: How mentally demanding was the task?	0.00	0.25	0.50	0.25	0.00	0.00	0.00
NKP: How physically demanding was the task?	0.25	0.50	0.00	0.25	0.00	0.00	0.00
NKT: How hurried or rushed was the pace of the task?	0.00	0.00	0.50	0.25	0.25	0.00	0.00
NKO: How successful were you in accomplishing what you were asked to do?	0.25	0.00	0.25	0.25	0.00	0.00	0.25
NKE: How hard did you have to work to accomplish what you were asked to do?	0.00	0.50	0.25	0.25	0.00	0.00	0.00
NKF: How insecure, discouraged, irritated, stressed, and annoyed were you?	0.25	0.25	0.00	0.25	0.25	0.00	0.00
NKScore: Overall Score (0-100)	34.72 ± 10.27						

As shown in Table 5.4, the NASA-TLX results for the VR game experience in the Parkinson's group indicated an overall workload **34.72 ± 22.05**, showing a low-to-moderate demand with high variability, which is expected given the small sample size (n=4). Looking at the subscales, **mental demand (NKM)** was mainly rated at 2 (50%) and at 1 or 4 (25% each), suggesting low-to-moderate cognitive effort. **Physical demand (NKP)** showed some dispersion, with half of the responses at 1 (50%) and the remainder at 4 and 5, indicating that while some participants felt no strain, others reported moderate physical demand.

Temporal demand (NKT) was distributed across 2, 3, 4, and 5, showing that perceptions of time pressure varied substantially between participants. **Performance (NKO)** was inconsistent, with responses across 1, 2, 3, and 5, but none at the highest end of the scale, suggesting that participants generally felt less successful than in the AR game. **Effort (NKE)** was mostly rated at 2 (75%) with one response at 4 (25%), pointing to a generally low level of exertion. Finally, **frustration (NKF)** was variable, with responses at 1, 2, 4, and 5, reflecting heterogeneous experiences ranging from no frustration to moderate stress.

Overall, the Parkinson's group perceived the VR game as moderately demanding, with effort and mental demand generally low, but physical and temporal demands more variable. Performance ratings remained modest, and frustration levels were inconsistent, highlighting diverse experiences among the four participants.

Table 5.4: NASA-TLX questionnaire results for VR game experience (Parkinson's group)

Questions	**1**	**2**	**3**	**4**	**5**	**6**	**7**
NKM: How mentally demanding was the task?	0.25	0.50	0.00	0.25	0.00	0.00	0.00
NKP: How physically demanding was the task?	0.50	0.00	0.00	0.25	0.25	0.00	0.00
NKT: How hurried or rushed was the pace of the task?	0.00	0.25	0.00	0.25	0.50	0.00	0.00
NKO: How successful were you in accomplishing what you were asked to do?	0.25	0.00	0.25	0.00	0.00	0.50	0.00
NKE: How hard did you have to work to accomplish what you were asked to do?	0.00	0.75	0.00	0.25	0.00	0.00	0.00
NKF: How insecure, discouraged, irritated, stressed, and annoyed were you?	0.25	0.25	0.00	0.25	0.25	0.00	0.00
NKScore: Overall Score (0-100)	34.72 ± 22.05						

5.1.2.2 Paas Scale

The *Paas Scale* was employed to capture participants' subjective perception of mental effort during gameplay. This instrument consists of a single item asking participants to rate the experienced cognitive load on a 9-point Likert scale, ranging from very low to very high mental demand. Higher values correspond to a greater perceived effort required to complete the task.

By applying the Paas scale across both AR and VR conditions, it was possible to compare how participants perceived the cognitive demands of each mode. This provided a straightforward yet valuable measure of mental workload, complementing the broader evaluation obtained through NASA-TLX and eye-tracking indicators.Prior to the analysis, Table 5.5 reports the Paas scale scores across the two immersion scenes.. These values summarize the perceived cognitive load for each tested level of immersion.

Table 5.5: Paas Scale results for AR and VR game experiences in Control and PD groups.

Group	**AR (Mean ± SD)**	**VR (Mean ± SD)**
Control (N = 31)	1.87 ± 0.76	2.03 ± 0.87
PD (N = 4)	4.50 ± 2.38	3.50 ± 1.73

The Paas Scale was used to assess the perceived cognitive load associated with the AR and VR game experiences. As shown in Table 5.5, the control group reported very low scores in both AR ($M = 1.87, SD = 0.76$) and VR ($M = 2.03, SD = 0.87$), indicating that healthy participants experienced minimal mental effort regardless of modality. 6

By contrast, the PD group reported considerably higher values, with AR ($M = 4.50, SD = 2.38$) slightly exceeding VR ($M = 3.50, SD = 1.73$). These results suggest that individuals with Parkinson's disease perceived a substantially greater cognitive load than controls, with AR being somewhat more demanding than VR. Moreover, the larger variability observed in the PD group highlights individual differences in how participants managed the mental effort required by the tasks.

5.1.2.3 System Usability Scale

Usability was measured with the System Usability Scale (SUS), a well-established questionnaire composed of ten items that alternate between positive and negative statements. Participants rated each item on a 5-point Likert scale, and scores were calculated following the standard SUS method, producing values between 1 and 5. Higher scores indicate better usability, providing an overall view of how accessible and user-friendly the AR and VR systems were perceived to be.Before discussing the usability outcomes, Tables 5.6–5.7 present the SUS results for the Control Group under AR and VR conditions. Tables 5.8–5.9 show the corresponding results for the PD group.

Control Group
Table 5.6 presents the SUS results for the AR game experience in the control group. The overall score was **82.98 ± 10.15**, which corresponds to an "Good" usability rating according to Bangor et al. [5] and a grade of **A** on the Sauro curved grading scale [36]. For the individual items listed in table 5.6, **SUS1** showed that most participants would like to play the game frequently, with ratings concentrated at 4–5. **SUS2** and **SUS4** revealed that the game was not perceived as unnecessarily complex, nor requiring technical support, since responses were strongly skewed towards 1–2. **SUS3** confirmed ease of play, with the majority selecting 4–5.

SUS5 indicated that participants felt the functions were well integrated, with responses clustered at 4–5. Similarly, **SUS6** suggested little inconsistency, as most ratings were at 1–2. **SUS7** showed confidence in learnability, with 61% selecting the highest score.

On the negative items, **SUSK8** showed that the game was not considered cumbersome, as 68% selected 1 and 29% selected 2. **SUSK9** reflected high confidence in playing, with ratings concentrated at 4–5. Finally, **SUS10** suggested that little prior learning was required, with 68% at 1. Overall, the control group perceived the AR game as easy to use, well integrated, and not cumbersome, with strong confidence in playability and learnability.

Table 5.6: Control Group Relative Frequency of SUS answers about the AR game experience

Questions	1	2	3	4	5
SUS1: I think that I would like to play this game frequently.	0.03	0.19	0.23	0.32	0.23
SUS2: I found the game unnecessarily complex.	0.61	0.26	0.06	0.03	0.03
SUS3: I thought the game was easy to play.	0.00	0.00	0.00	0.48	0.52
SUS4: I think that I would need the support of a technical person to be able to play this game.	0.65	0.32	0.03	0.00	0.00
SUS5: I found the various functions in this game were well integrated.	0.00	0.00	0.13	0.65	0.23
SUS6: I thought there was too much inconsistency in this game.	0.29	0.45	0.23	0.03	0.00
SUS7: I would imagine that most people would learn to play this game very quickly.	0.00	0.03	0.06	0.29	0.61
SUS8: I found the game very cumbersome to play.	0.68	0.29	0.03	0.00	0.00
SUS9: I felt very confident playing the game.	0.03	0.03	0.03	0.42	0.48
SUS10: I needed to learn a lot of things before I could get going with this game.	0.68	0.29	0.03	0.00	0.00
SUS Overall Score	82.98 ± 10.15				

As shown in Table 5.7, the SUS score for the VR game experience in the control group was **84.76 ± 9.94**. This corresponds to an "Excellent" usability rating in Bangor's classification [5] and a grade of **A+** on the Sauro scale [36], representing the highest usability range of this study. In the table 5.7, **SUS1** showed that most participants would like to play the game frequently, with ratings concentrated at 4–5, similar to AR. **SUS2** confirmed that the game was not considered unnecessarily complex, with 90% of answers at 1–2, comparable to the AR findings. **SUS3** indicated ease of play, with 65% at value 5, slightly stronger than in AR.

SUS4 showed that participants did not feel technical support was needed, with 68% selecting 1, again aligned with AR. **SUS5** reflected that functions were perceived as well integrated, with ratings concentrated at 4–5, very similar to AR. **SUS6** suggested little inconsistency, with most responses at 1–2, though VR showed slightly more agreement at 2 compared to AR.

SUS7 demonstrated strong learnability, with 61% at value 5, consistent with AR. On the negative items, **SUS8** indicated that the game was not found cumbersome, with 74% at 1, slightly stronger than the AR case. **SUS9** showed high confidence while playing, with ratings concentrated at 4–5, very similar to AR. Finally, **SUS10** indicated that little prior learning was required, with 77% selecting 1, comparable to the AR results.

In general, both AR and VR game experiences were perceived as easy to use, consistent and not cumbersome, with highly similar usability patterns between the two versions.

Table 5.7: Control Group Relative Frequency of SUS answers about the VR game experience

Questions	**1**	**2**	**3**	**4**	**5**
SUS1: I think that I would like to play this game frequently.	0.06	0.13	0.26	0.32	0.23
SUS2: I found the game unnecessarily complex.	0.58	0.32	0.06	0.03	0.00
SUS3: I thought the game was easy to play.	0.00	0.03	0.03	0.29	0.65
SUS4: I think that I would need the support of a technical person to be able to play this game.	0.68	0.23	0.06	0.03	0.00
SUS5: I found the various functions in this game were well integrated.	0.00	0.00	0.06	0.48	0.45
SUS6: I thought there was too much inconsistency in this game.	0.32	0.52	0.13	0.03	0.00
SUS7: I would imagine that most people would learn to play this game very quickly.	0.00	0.00	0.13	0.26	0.61
SUS8: I found the game very cumbersome to play.	0.74	0.26	0.00	0.00	0.00
SUS9: I felt very confident playing the game.	0.00	0.03	0.10	0.35	0.52
SUS10: I needed to learn a lot of things before I could get going with this game.	0.77	0.19	0.03	0.00	0.00
SUS Overall Score	84.76 ± 9.94				

Parkinson participants

Table 5.8 summarizes the SUS results for the AR game experience in the Parkinson's group. The overall score was **75.62 ± 8.75**, which corresponds to a "Good" usability rating according to Bangor et al. [5] and a grade of **B** on the Sauro curved grading scale [36]. In the table 5.9 **SUS1** showed moderate to high interest in playing the game frequently, with ratings concentrated at 3–5. **SUS2** indicated that the game was not seen as unnecessarily complex, with 75% of responses at 2. **SUS3** reflected ease of play, with half of the participants selecting 5.

SUS4 showed that some participants felt they needed technical support, as half of the ratings were at 2. **SUS5** showed positive integration of functions, with responses equally split between 4 and 5. **SUS6** revealed that some inconsistency was perceived, with 75% of responses at 2.

SUS7 demonstrated strong learnability, with 75% selecting 4. **SUS8** indicated that the game was not perceived as cumbersome, with 75% of ratings at 2. **SUS9** reflected high confidence while playing, with half at 5 and one at 4. Finally, **SUS10** was very divided: one participant (25%) selected 1, one (25%) selected 2, and two (50%) selected 4, showing that half of the group felt they needed to learn a lot before playing, while the other half did not.

Overall, the Parkinson's group perceived the AR game as usable and easy to learn, with positive ratings for integration and confidence; however, there was greater variability in technical support, inconsistency, and the learning required before playing, compared to the control group.

Table 5.8: Parkinson Group Relative Frequency of SUS answers about the AR game experience

Questions	**1**	**2**	**3**	**4**	**5**
SUS1: I think that I would like to play this game frequently.	0.00	0.00	0.25	0.50	0.25
SUS2: I found the game unnecessarily complex.	0.00	0.75	0.25	0.00	0.00
SUS3: I thought the game was easy to play.	0.00	0.00	0.00	0.50	0.50
SUS4: I think that I would need the support of a technical person to be able to play this game.	0.00	0.50	0.25	0.25	0.00
SUS5: I found the various functions in this game were well integrated.	0.00	0.00	0.00	0.50	0.50
SUS6: I thought there was too much inconsistency in this game.	0.25	0.75	0.00	0.00	0.00
SUS7: I would imagine that most people would learn to play this game very quickly.	0.00	0.00	0.00	0.75	0.25
SUS8: I found the game very cumbersome to play.	0.25	0.75	0.00	0.00	0.00
SUS9: I felt very confident playing the game.	0.00	0.00	0.25	0.25	0.50
SUS10: I needed to learn a lot of things before I could get going with this game.	0.25	0.25	0.00	0.50	0.00
SUS Overall Score	75.62 ± 8.75				

As shown in Table 5.9, the SUS score for the VR game experience in the Parkinson's group was **74.38 ± 15.46**. According to Bangor et al. [5], this corresponds to a "Good" usability rating, and based on the Sauro scale [36], it falls within grade **B**.

On the table 5.9**SUS1** showed moderate to high interest in playing frequently, with responses at 3–5. **SUS2** indicated that the game was not seen as unnecessarily complex, as all participants selected 2. **SUS3** reflected ease of play, with ratings at 2, 4, and 5, showing mostly positive responses but not as unanimous as in AR.

SUS4 showed that some participants felt they needed technical support, with responses spread across 1–4. **SUS5** indicated that functions were perceived as well integrated, with 75% selecting 4. **SUS6** suggested little inconsistency, with all responses at 1–2.

SUS7 demonstrated good learnability, with 75% selecting 4. **SUS8** confirmed that the game was not considered cumbersome, as all responses were at 1–2. **SUS9** reflected confidence while playing, though ratings were more spread than in AR. Finally, **SUS10** was very variable, with answers equally distributed across 1, 2, 4, and 5, again showing no consensus on prior learning needs.

Overall, the VR game was perceived as usable and easy to learn, consistent with the AR version, though with slightly more variation in ease of play, confidence, and prior learning requirements.

Table 5.9: Parkinson Group Relative Frequency of SUS answers about the VR game experience

Questions	**1**	**2**	**3**	**4**	**5**
SUS1: I think that I would like to play this game frequently.	0.00	0.00	0.25	0.50	0.25
SUS2: I found the game unnecessarily complex.	0.00	1.00	0.00	0.00	0.00
SUS3: I thought the game was easy to play.	0.00	0.25	0.00	0.50	0.25
SUS4: I think that I would need the support of a technical person to be able to play this game.	0.50	0.25	0.25	0.00	0.00
SUS5: I found the various functions in this game were well integrated.	0.00	0.00	0.00	0.75	0.25
SUS6: I thought there was too much inconsistency in this game.	0.25	0.50	0.25	0.00	0.00
SUS7: I would imagine that most people would learn to play this game very quickly.	0.00	0.00	0.00	0.75	0.25
SUS8: I found the game very cumbersome to play.	0.50	0.50	0.00	0.00	0.00
SUS9: I felt very confident playing the game.	0.00	0.25	0.00	0.50	0.25
SUS10: I needed to learn a lot of things before I could get going with this game.	0.25	0.25	0.00	0.25	0.25
SUS Overall Score	74.38 ± 15.46				

5.1.2.4 IGroup Presence

To evaluate the level of immersion and presence reported by participants, the IPQ (Igroup Presence Questionnaire) was applied. This instrument consists of 14 items rated on a 5-point Likert scale and is organized into four subscales: spatial presence, involvement, realism, and general presence. The spatial presence dimension assesses the extent to which participants felt situated within the virtual environment, while the involvement subscale captures their degree of engagement and focus during the experience.

The realism dimension addresses the perceived authenticity of the environment, and the general presence subscale provides an overall measure of immersion. Scores were calculated for each subscale, as well as for an overall presence index, offering a comprehensive view of participants' subjective experience in both AR and VR conditions.Before discussing the presence results, it is important to identify the tables containing the IPQ data.

The full set of IPQ questions, along with their corresponding response ranges, is provided in Annex I.1.1.

Control Group

Table 5.10 presents the IPQ results for the AR game experience in the control group. When compared using the qualitative scales proposed by Melo et al. (2023)[41], the AR control group's IPQ results show a mixed profile of presence. Spatial Presence (M = 4.05, SD = 1.22) lies within the "moderate-to-strong" presence class, indicating users generally felt physically immersed in the AR environment. General Presence (M = 3.79, SD = 1.36) also reaches a "moderate" level, suggesting a decent sense of "being there." However, Involvement (M = 2.14, SD = 0.65) falls substantially below the levels Melo et al. consider acceptable for engagement, and Realism (M = 2.50, SD = 0.72) is slightly under the threshold for "acceptable realism." The overall presence score (M = 3.04, SD = 0.74) positions the AR experience in the lower end of the moderate range under Melo et al.'s benchmarks.

Table 5.10: IPQ results for the AR game experience (Control Group, N=31).

Metric	**Mean ± SD**
General Presence (0–6)	3.79 ± 1.36
Spatial Presence (0–6)	4.05 ± 1.22
Involvement (0–6)	2.14 ± 0.65
Realism (0–6)	2.50 ± 0.72
Overall (mean of sub-scales, 0–6)	3.04 ± 0.74

As shown in Table 5.11, the IPQ results for the VR game experience in the control group revealed, according to the qualitative scales proposed by Melo et al. [41], generally strong levels of presence. Spatial presence reached a mean of 4.64 ($SD = 0.99$), exceeding the benchmark value of 3.99 and falling within the "strong presence" category. General presence was similarly high (M=4.47, SD=1.53), surpassing the benchmark of 3.47 and suggesting that participants reported a clear sense of "being there."

Involvement (M=3.33, SD=1.00) was at the threshold for satisfactory engagement, highlighting that participants were reasonably absorbed in the VR experience. Realism (M=2.57, SD=0.65) was close to the reference value of 2.6, indicating that the environment was perceived as moderately authentic but less convincing compared to other subscales. The overall presence score (M=3.66, SD=0.70) was above the benchmark mean of 3.47, positioning the VR condition as a satisfactory immersive experience according to Melo et al.'s interpretative scales.

It is also noteworthy that VR control values were generally higher than those observed in the AR control group, particularly in involvement and overall presence, suggesting that VR provided a more consistent sense of immersion.

Table 5.11: IPQ results for the VR game experience (Control Group, N=31).

Metric	**Mean ± SD**
General Presence (0–6)	4.47 ± 1.53
Spatial Presence (0–6)	4.64 ± 0.99
Involvement (0–6)	3.33 ± 1.00
Realism (0–6)	2.57 ± 0.65
Overall (mean of sub-scales, 0–6)	3.66 ± 0.70

participants

According to the interpretative scales proposed by Melo et al. [41], the IPQ results for the AR Parkinson's group showed high values for presence but more modest results in involvement and realism. General presence reached a mean of 5.38 ($SD = 1.44$), well above the benchmark of 3.47, reflecting a strong sense of "being there." Spatial presence (M=4.28, SD=1.37) was also above the reference mean of 3.99, suggesting that participants generally felt physically situated in the AR environment.

In contrast, involvement (M=2.69, SD=0.48) was below the benchmark threshold of 3.3, pointing to weaker engagement with the experience. Similarly, realism (M=2.41, SD=1.16) was slightly under the reference value of 2.6, indicating only moderate perceptions of authenticity. The overall presence score (M=3.37, SD=0.49) was just below the benchmark of 3.47, placing this condition within the lower-moderate range of immersion.

Table 5.12: IPQ results for the AR game experience (Parkinson's Group, N=4).

Metric	**Mean ± SD**
General Presence (0–6)	5.38 ± 1.44
Spatial Presence (0–6)	4.28 ± 1.37
Involvement (0–6)	2.69 ± 0.48
Realism (0–6)	2.41 ± 1.16
Overall (mean of sub-scales, 0–6)	3.37 ± 0.49

According to the qualitative scales proposed by Melo et al. [41], the IPQ results for the VR Parkinson's group indicated high levels of presence across all subscales. General presence reached a mean of 5.38 ($SD = 0.75$), well above the benchmark of 3.47, indicating a powerful sense of "being there." Spatial presence (M=4.88, SD=1.13) also exceeded the reference of 3.99, placing it within the strong presence category.

Involvement (M=4.38, SD=0.97) was considerably higher than the benchmark threshold of 3.3, showing that participants were actively engaged and absorbed in the VR experience. Realism (M=3.06, SD=1.12) surpassed the benchmark reference of 2.6, suggesting that the environment was perceived as more authentic compared to AR. The overall presence score (M=4.25, SD=0.80) was well above the benchmark of 3.47, placing the VR condition within the strong presence range.

When compared with the AR Parkinson's group, VR showed higher values in spatial presence, involvement, realism, and overall presence, suggesting that VR provided a more immersive and an engaging experience for participants with Parkinson's disease.

Table 5.13: IPQ results for the VR game experience (Parkinson's Group, N=4).

Metric	**Mean ± SD**
General Presence (0–6)	5.38 ± 0.75
Spatial Presence (0–6)	4.88 ± 1.13
Involvement (0–6)	4.38 ± 0.97
Realism (0–6)	3.06 ± 1.12
Overall (mean of sub-scales, 0–6)	4.25 ± 0.80

Across groups, the results show that VR consistently yielded higher values of presence than AR, both for the control participants and for those with Parkinson's disease. While

AR conditions already achieved moderate levels of presence, particularly in spatial and general presence, VR enhanced these dimensions and also improved involvement and realism. This pattern was especially pronounced in the Parkinson's group, where VR scores were markedly higher than AR, suggesting that VR provided a stronger and more engaging immersive experience overall.

5.1.2.5 Eye tracking data (Cognitive Load)

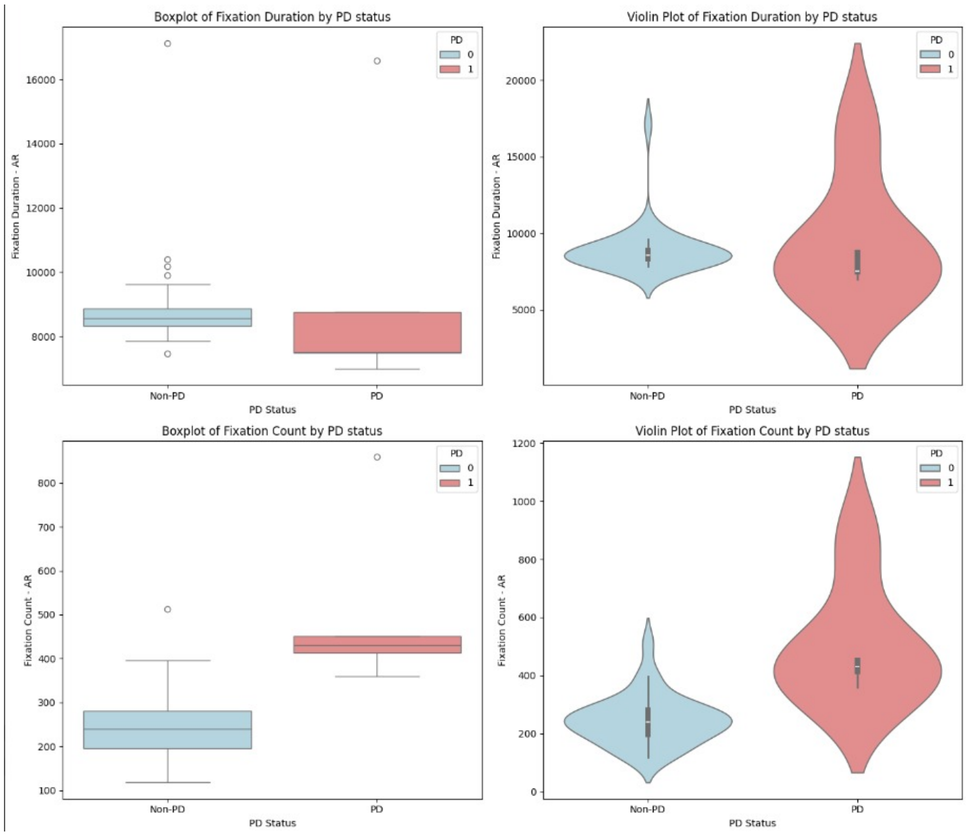
The eye-tracking dataset included multiple parameters related to visual attention and cognitive processing, namely fixation duration, fixation count, average fixation duration (ms), saccade duration, saccade count, and average saccade duration (ms). A comparative analysis was performed between participants with PD and the control group across AR and VR conditions. To evaluate group differences, the non-parametric Mann–Whitney test was applied. As seen in Table 5.14, the results revealed that most of the parameters exhibited statistically significant differences, although the strength and consistency of these differences varied between the VR and AR settings.

Table 5.14: Mann–Whitney test results for eye-tracking metrics comparing PD and non-PD participants. *sig.* indicates statistically significant differences ($p < 0.05$), while *n.s.* indicates no significant difference.

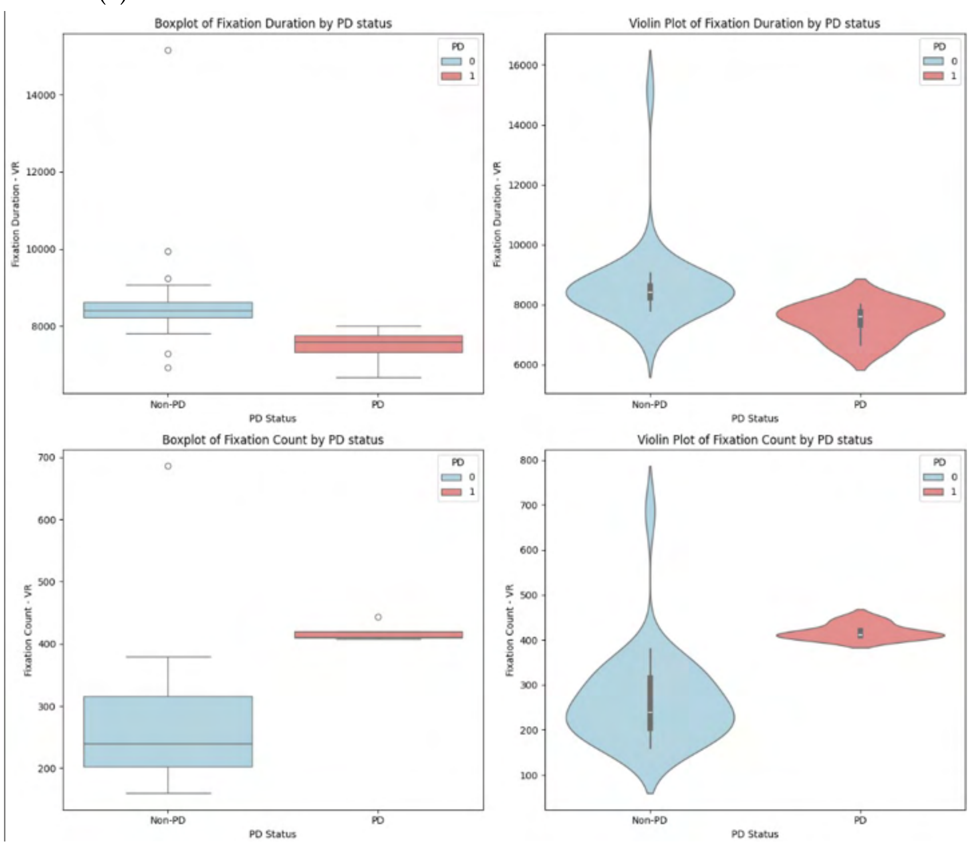
Metric	**VR (p-value)**	**AR (p-value)**
Fixation Duration	0.0020 (sig.)	0.2988 (n.s.)
Fixation Count	0.0029 (sig.)	0.0012 (sig.)
Avg. Fixation Duration (ms)	<0.0001 (sig.)	<0.0001 (sig.)
Saccade Duration	0.0001 (sig.)	<0.0001 (sig.)
Saccade Count	0.0029 (sig.)	0.0006 (sig.)
Avg. Saccade Duration (ms)	0.0002 (sig.)	<0.0001 (sig.)

In the VR condition, clear group differences emerged across all eye-tracking parameters. Statistically significant disparities were found for fixation duration ($p = 0.0020$), fixation count ($p = 0.0029$), average fixation duration ($p < 0.0001$), saccade duration ($p = 0.0001$), saccade count ($p = 0.0029$), and average saccade duration ($p = 0.0002$). These results consistently led to the rejection of the null hypothesis, indicating that PD participants processed visual information in VR differently from the control group.

By contrast, the AR condition showed a more mixed pattern of results. Fixation duration ($p = 0.2988$) did not differ significantly between groups, supporting the retention of the null hypothesis for this metric. However, all other measures revealed significant differences: fixation count ($p = 0.0012$), average fixation duration ($p < 0.0001$), saccade duration ($p < 0.0001$), saccade count ($p = 0.0006$), and average saccade duration ($p < 0.0001$). Thus, while AR preserved comparable fixation durations across groups, it still revealed substantial disparities in attentional shifts and scanning patterns.



(a) Fixation Duration and Fixation Count results for AR condition.



(b) Fixation Duration and Fixation Count results for VR condition.

Figure 5.2: Comparison of cognitive load indicators derived from eye-tracking metrics across AR and VR conditions.

The evaluation of Figures 5.2a and 5.2b highlights distinct differences in fixation behavior between AR and VR scenes for participants with PD. In the AR environment, fixations tended to last longer, reflecting a steadier allocation of attention to individual elements. By contrast, in the VR scene, fixation durations were noticeably shorter, indicating that participants did not maintain their gaze on single points for extended periods. At the same time, the fixation count was higher in VR than in AR, showing that participants shifted their gaze more frequently in the fully virtual setting. In terms of saccade-related measures, no notable differences were observed between AR and VR conditions in the graphs (see Annex I.3 for the rest of the graphs). Taken together, these results suggest that while AR supported longer and more stable fixations, VR elicited a pattern of shorter but more numerous fixations, pointing to a different mode of visual engagement.

5.1.2.6 Parkinson Disease Stages analyses

A statistical analysis was conducted to explore differences in user perceptions across Parkinson's stages, based on the NASA, Paas, PQ, and SUS questionnaires. For the majority of measures, no statistically significant variations were observed, suggesting that perceptions remained relatively stable across different stages of the disease.

Nevertheless, several significant effects were identified. At the $p < 0.05$ level, differences emerged in **NASA2VR** ($p = 0.0198$), related to cognitive load in the VR condition, and in **SUS10AR** ($p = 0.0377$), which pointed to differences in the usability of the AR system.

Even more extreme results were found for **PQ12AR**, **PQ2AR**,and **SUS8VR**, all with $p < 0.01$. While such very low p-values suggest strong differences across stages, they are likely influenced by the small sample size and the uniformity of responses within groups. These values should therefore be interpreted with caution, as they may reflect statistical artifacts rather than consistent effects.

In general, the findings indicate that while most aspects of usability, workload, and presence were consistently perceived throughout Parkinson's stages, some measures - particularly cognitive load in VR, AR usability, and a small set of isolated questionnaire items showed notable differences that may be linked to disease progression.

5.1.3 Discussion

The main objective of this dissertation was to examine whether meaningful differences exist between AR and VR when applied to serious games for rehabilitation in PD. In this first study, the *Fruit Picker XR* prototype was evaluated in two versions, AR and VR, to compare how each environment influences usability, workload, presence, and cognitive load.

The results suggest that AR and VR do not provide identical experiences; instead, they lead to distinct patterns of interaction and perception, particularly when contrasting participants with PD to the control group. This discussion analyses the outcomes of the study in light of the research questions, focusing on the comparative results of AR and VR across the different evaluation metrics. The implications for rehabilitation, the consistency with existing literature, and the limitations of the current study are also addressed.

The NASA-TLX results revealed contrasting trends between the control group and the PD group. For the control group, workload was clearly lower in VR (18.46±11.60) compared to AR (30.38 ± 9.04), suggesting that healthy participants found the VR environment less mentally and physically demanding. This may be explained by the higher degree of familiarity and intuitiveness provided by the immersive VR context, which possibly reduced effort despite the greater sensory stimulation. In contrast, participants with PD experienced similarly high workload in both modalities (AR: 34.72 ± 10.27; VR: 34.72 ± 22.05). However, the considerably larger variance in the VR condition indicates that some individuals reported much higher levels of workload, pointing to greater inconsistency and potentially higher demand in VR overall. Taken together, these findings suggest that VR may reduce workload for healthy individuals but not for those with PD, where the experience is more demanding and less uniform across participants.

The Paas Scale results confirmed that participants with Parkinson's reported higher overall mental effort compared to the control group (PD–AR: 4.50±2.38, PD–VR: 3.50±1.73 vs. Control–AR: 1.87 ± 0.76, Control–VR: 2.03 ± 0.87). Within the PD group, VR was rated as slightly less demanding than AR, although the difference was not large and must be interpreted cautiously, given the small sample size and overlapping variability. This trend contrasts with the NASA-TLX results, where VR showed greater variability and indications of higher workload. A likely explanation lies in the nature of the instruments: the Paas Scale is based on a single overall question about mental effort, whereas NASA-TLX evaluates multiple dimensions of workload, capturing more detailed aspects such as frustration and performance. Taken together, these findings suggest that PD participants consistently perceive both AR and VR as more effortful than controls, while the relative difference between AR and VR within the PD group is small and less conclusive. This underlines the importance of using multiple measures when assessing cognitive load.

The SUS results indicated strong usability across both AR and VR versions of the game, though with clear differences between the control and PD groups. For the control group, overall SUS scores were very high (AR: 82.98; VR: 84.76), placing AR in the "Good" category and VR in the “Excellent” category according to Bangor et al. [5] and corresponding to an "A+" and "A" grade respectively, under the Lewis and Sauro scale [36]. These findings confirm that both AR and VR prototypes offered a highly usable experience for healthy participants. For the PD group, usability remained positive but at a lower level, with scores of 75.62 for AR and 74.38 for VR. These values correspond to “Good” usability for both conditions [5]. In terms of letter grades, both AR and VR map to a B grade under the Lewis and Sauro scale [36]. This suggests that while both environments were usable for participants with PD, AR was perceived as slightly more usable, though the differences remain small. Taken together, the SUS findings show that AR and VR provided similarly high usability for the control group, while for participants with PD, AR appeared marginally more usable. However, both modalities remained within acceptable usability ranges, reinforcing that usability alone is unlikely to explain broader differences in experience between AR and VR.

The IPQ results revealed distinct patterns in presence perception between AR and VR conditions. For the control group, both general and spatial presence reached moderate values (General Presence: AR = 3.79, VR = 4.47; Spatial Presence: AR = 4.05, VR = 4.64), with VR consistently outperforming AR. This outcome was expected, as VR fully replaces the real world with a simulated environment, whereas AR merely augments reality and therefore provides a weaker sense of immersion. Involvement and realism remained comparatively lower in both conditions (Involvement: AR = 2.14, VR = 3.33; Realism: AR = 2.50, VR = 2.57), suggesting that participants did not fully perceive the environments as engaging or authentic, despite VR's immersive qualities. For the PD group, overall presence levels were notably higher than in the control group. Both general and spatial presence exceeded 5 in AR and VR, surpassing the "high presence" threshold reported in recent IPQ benchmarks [41]. This suggests that individuals with PD were more strongly immersed in both environments, potentially due to the novelty of the technology or the therapeutic context enhancing engagement. Involvement was especially elevated in VR (AR = 2.69, VR = 4.38), indicating that VR promoted a deeper attentional focus compared to AR. Realism followed a similar pattern, with higher ratings in VR (3.06) than AR (2.41). In summary, the findings align with expectations: AR, by augmenting the real environment, delivered lower presence scores than VR, while VR offered a more immersive experience. However, the PD group consistently reported stronger presence than the control group, particularly in VR, highlighting the potential of immersive systems as effective tools to capture attention and engagement in therapeutic contexts.

The eye-tracking results showed that the control group experienced lower cognitive load than the PD group. Healthy participants displayed shorter fixations, fewer fixations overall, and less variation in saccade activity, indicating more efficient visual processing. In contrast, PD participants required greater attentional effort, consistent with higher Paas ratings. This difference was obvious in VR, where the immersive complexity appeared to impose greater demands than AR.

The Control Group adopted a more critical perspective on both game versions, likely reflecting their younger demographic, greater gaming experience, and higher familiarity with technology, which raised their expectations. By contrast, the Parkinson's Group, though initially hesitant, showed strong enthusiasm once engaged. Most participants focused less on differences between AR and VR and more on the competitive and enjoyable aspects of play, with many expressing interest in using the system regularly. The therapist also highlighted their positive reactions, noting excitement and active involvement, with some participants preferring the less immersive qualities of AR.

5.2 Second User Study: Comparing Immersion Levels

The second study involved a control group of 18 participants without PD, who served to further validate the system within a broader adult population. The participants in this study ranged in age from 17 to 60 years (mean = 35.5, SD = 15.3). The gender distribution included 12 males and 6 females. Regarding education, 10 participants had completed high school, 8 had a bachelor's degree, and 2 had completed basic education.

Although the game was designed to support five levels of immersion along the virtual continuum, testing all of them in a single test session would have made the protocol excessively long and tiring for participants. Therefore, three representative levels were selected as the most suitable for evaluation in this study:

- **A** — Level 2 (eAR): with virtual baskets.
- **B** — level 4 (AV): room structures (walls, doors, windows, furniture) represented virtually.
- **C** — Level 5 (VR): fully virtual, fictitious environment.

Before recruiting participants, the room was prepared and safety-checked. Using the Meta Quest Pro, the space was manually scanned and mapped, identifying walls, doors, windows, and key furniture to support the level (B), where real structures are represented virtually. This scan was performed a single time as part of the experimental setup.

In this second study, the PLAY platform was used to configure game sessions and apply parameter adjustments, ensuring consistency across participants.

The experimental procedure followed a standardized protocol comprising the following steps:

- **Informed Consent and Identification** – Participants were briefed on the study's purpose and procedures, gave informed consent, and completed an identification questionnaire.
- **Environment Setup** – The testing space was checked to ensure safety and comfort for gameplay.
- **Headset Preparation** – The headset was calibrated and fitted for comfort and stability.
- **Tutorial Session** – A short tutorial (45–60 s) familiarised participants with the game mechanics.
- **Gameplay Session 1** – The first assigned version (A, B, or C) was played for 1:30 while eye-tracking data were collected.
- **Post-Game Questionnaire 1** – Participants completed SUS, IPQ, and NASA-TLX referring to "this version."

- **Gameplay Session 2** – The second version (A, B, or C) was played for 1:30 with data collection.
- **Post-Game Questionnaire 2** – SUS, IPQ, and NASA-TLX were completed again.
- **Gameplay Session 3** – The third version (A, B, or C) was played for 1:30 with data collection.
- **Post-Game Questionnaire 3** – SUS, IPQ, and NASA-TLX were completed once more.
- **Conclusion** – The session ended with equipment shutdown and a thank-you to participants.

To counterbalance the presentation of the three immersion levels, participants were assigned different sequences. For illustration, one complete cycle of ordering was as follows:

Table 5.15: Example of one counterbalancing cycle of immersion levels.

Participant	Order of Levels (1st → 3rd)
P1	A → B → C
P2	C → B → A
P3	B → A → C
P4	A → C → B
P5	B → C → A
P6	C → A → B

5.2.1 Results

This section presents the main findings from the second user study, which compared three levels of immersion along the virtual continuum: AR, AV, and VR. The results are reported for the control group of healthy adults, covering usability, workload, presence, and cognitive load measures.

5.2.1.1 NASA Task Load Index

Table 5.16 presents the NASA-TLX results for the AR immersive level. Perceived workload was generally low. **Mental demand** clustered at the bottom of the scale, with approximately 22% of participants selecting a value of 1 and 50% selecting 2; only a minority reported higher demand (around 17% chose 5, with none at 6 or 7). **Physical demand** showed a similar trend, with 33% of responses at 1 and 44% at 2, and only 11% at 3 and 11% at 4, with no responses above 4. **Temporal demand** was more dispersed: about one third of participants chose 1, 22% chose 2 and 11% chose 3, but roughly one third reported stronger time pressure (28% at 4 and 6% at 5). Perceived **performance** was high, as half of the participants selected the best score (1) and another 34% chose values 2–3, with only small fractions between 4 and 6. **Effort** was mostly low to moderate, with 39% at 1, 28%

at 2, 11% at 3, and 22% at 4, while none selected values of 5 or higher. Finally, **frustration** was minimal: 72% of responses concentrated in value 1, with only 11% each at 2 and 3, and a residual 6% at 5. In line with these distributions, the aggregated **NKScore** was low (18.83 ± 14.31 on a 0–100 scale), confirming that the AR game imposed a relatively low overall workload.

Table 5.16: NASA item response distribution for AR (proportion per Likert option).

Questions	1	2	3	4	5	6	7
NKM: How mentally demanding was the task?	0.22	0.50	0.11	0.00	0.17	0.00	0.00
NKP: How physically demanding was the task?	0.33	0.44	0.11	0.11	0.00	0.00	0.00
NKT: How hurried or rushed was the pace of the task?	0.33	0.22	0.11	0.28	0.06	0.00	0.00
NKO: How successful were you in accomplishing what you were asked to do?	0.50	0.17	0.17	0.06	0.06	0.06	0.00
NKE: How hard did you have to work to accomplish what you were asked to do?	0.39	0.28	0.11	0.22	0.00	0.00	0.00
NKF: How insecure, discouraged, irritated, stressed, and annoyed were you?	0.72	0.11	0.11	0.00	0.06	0.00	0.00
NKScore: Overall Score (0–100)				18.83 ± 14.31			

As shown in Table 5.17, the NASA-TLX results for the AV immersive level indicated that perceived workload remained relatively low, though with a slightly wider spread than in AR. **Mental demand** was modest: 39% of participants chose 1, 22% chose 2, and 28% selected 3, while only a small fraction (11%) reported 4, and none rated higher than 5. **Physical demand** followed a similar pattern, with 28% of responses at 1 and 2, 33% at 3, and only minor proportions at 4 (6%) and 6 (6%). **Temporal demand** was more dispersed, with 22% at 1, 17% at 2, and 33% at 3, while smaller groups indicated stronger time pressure (11% at 4, 6% at 5, and 6% at 6). Perceived **performance** was still high, as one third of participants chose 1, 22% selected 2, and only a small fraction gave ratings above 3 (11% at 4, 11% at 5, and 6% at 6). **Effort** responses were distributed mainly across the lower half of the scale: 33% at 1, 33% at 2, and 11% at 3, with some participants reporting higher effort (17% at 4 and 6% at 5). Finally, **frustration** was minimal, as 89% of participants reported the lowest possible value (1), with only isolated responses across 3 (6%), 4 (6%), and 5 (6%). These distributions are consistent with the aggregated **NKScore** of 22.07 ± 17.58, indicating that the AV condition also imposed a relatively low overall workload.

Table 5.18 summarizes the NASA-TLX results for the VR immersive level. Workload ratings were again low, though slightly more varied across items compared to AR and AV. **Mental demand** showed moderate dispersion: 39% of participants chose 1, 28% selected 2, and 17% rated 3, with smaller proportions at 4 (6%) and 5 (11%), while no responses were above 5. **Physical demand** was generally low, with one third of participants (33%) at 1, 39% at 2, and 6% at 3; higher ratings were rare (11% each at 4 and 5). **Temporal**

Table 5.17: NASA item response distribution for AV (proportion per Likert option).

Questions	1	2	3	4	5	6	7
NKM: How mentally demanding was the task?	0.39	0.22	0.28	0.11	0.00	0.00	0.00
NKP: How physically demanding was the task?	0.28	0.28	0.33	0.06	0.00	0.06	0.00
NKT: How hurried or rushed was the pace of the task?	0.22	0.17	0.33	0.11	0.11	0.06	0.00
NKO: How successful were you in accomplishing what you were asked to do?	0.33	0.22	0.06	0.11	0.11	0.11	0.06
NKE: How hard did you have to work to accomplish what you were asked to do?	0.33	0.33	0.11	0.17	0.06	0.00	0.00
NKF: How insecure, discouraged, irritated, stressed, and annoyed were you?	0.89	0.00	0.06	0.06	0.00	0.00	0.00
NKScore: Overall Score (0–100)				22.07 ± 17.58			

demand indicated more time pressure for some participants: although 11% chose 1 and 22% chose 2, another 22% rated 3, 28% rated 4, and 11% rated 5; none rated 6 or 7. Perceived **performance** remained positive, with 39% of responses at 1 and 33% at 2, while only a minority gave higher values (11% at 5, 17% at 6). **Effort** ratings clustered in the lower half: 33% at 1 and 39% at 2, with smaller fractions spread across 3 (11%), 4 (6%), and 5 (11%). Finally, **frustration** was minimal, with 83% of participants choosing 1 and only a few responses at 2 (11%) and 3 (6%). Overall, the aggregated **NKScore** was 21.30 ± 17.44, confirming that, even under full VR, the task imposed a relatively low workload for most participants.

Table 5.18: NASA item response distribution for VR (proportion per Likert option).

Questions	1	2	3	4	5	6	7
NKM: How mentally demanding was the task?	0.39	0.28	0.17	0.06	0.11	0.00	0.00
NKP: How physically demanding was the task?	0.33	0.39	0.06	0.11	0.11	0.00	0.00
NKT: How hurried or rushed was the pace of the task?	0.11	0.22	0.22	0.28	0.11	0.06	0.00
NKO: How successful were you in accomplishing what you were asked to do?	0.39	0.33	0.00	0.11	0.00	0.17	0.00
NKE: How hard did you have to work to accomplish what you were asked to do?	0.33	0.39	0.11	0.06	0.11	0.00	0.00
NKF: How insecure, discouraged, irritated, stressed, and annoyed were you?	0.83	0.11	0.06	0.00	0.00	0.00	0.00
NKScore: Overall Score (0–100)				21.30 ± 17.44			

5.2.1.2 Paas Scale

Table 5.19 presents the PAAS results across AR, AV, and VR immersive levels.

In the AR immersive level, cognitive load as measured by the PAAS scale was relatively low, with a mean score of 2.44 ± 1.82. This suggests that most participants did not perceive the task as mentally demanding, although the relatively large standard deviation indicates some variability in responses.

For the AV immersive level, the average PAAS score was slightly higher at 2.72 ± 1.84. This still reflects a low cognitive load overall, but with a marginal increase compared to AR, implying that integrating both augmented and virtual elements may have required slightly more mental effort from some participants.

In the VR immersive level, the mean score returned to 2.44 ± 1.58, matching the AR condition in central tendency, though with a slightly smaller variability. This indicates that participants generally experienced the full VR task as no more mentally demanding than AR.

When comparing across conditions, all three mean scores remained close to the lower end of the 1–9 scale, pointing to low cognitive demands throughout. The AV condition showed the highest average, but the differences between conditions were small and within the bounds of measurement variability, suggesting that immersion level did not substantially increase cognitive load.

Table 5.19: PAAS scores across immersion conditions (values are mean ± SD; $N = 18$ per condition).

Metric	AR	AV	VR
PAAS (1–9)	2.44 ± 1.82	2.72 ± 1.84	2.44 ± 1.58

5.2.1.3 System Usability Score

Table 5.20 presents the SUS results for the AR immersive level. The responses indicated generally positive usability. Most participants expressed willingness to use the system frequently (61% in categories 6–7), and they found it easy to use (83% in 6–7). The majority also considered the functions well integrated (83% in 6–7) and believed that most people could learn it quickly (89% in 6–7). Confidence was high (67% in 7), while perceptions of complexity, inconsistency, and cumbersomeness clustered at the low end (39–61% in 1). Some reliance on external support was reported, though responses were spread across the scale. Overall, the AR version was seen as usable, with a few reservations about complexity and learning needs. In the AR condition, the mean SUS score was 82.31 ± 16.00. According to the adjective rating scale proposed by Bangor et al. [5], this falls into the "Good" range. Using the letter-grade conversion introduced by Lewis and Sauro [36], the score corresponds approximately to a grade of "A". This indicates that the AR version was perceived as highly usable, with only minor room for improvement.

As shown in Table 5.21, the SUS results for the AV immersive level also indicated positive usability. Frequent use was endorsed by 50% in categories 6–7, and ease of use was rated even higher (67% in 7). Integration of functions (89% in 6–7) and quick learnability (72% in 7) scored very well. Participants felt confident (78% in 6–7), while ratings of complexity, inconsistency, and cumbersomeness were concentrated at the lowest values (50–56% in 1). As in AR, some responses suggested a perceived need for technical support, but most values remained in the lower half. These distributions reinforce the AV condition

Table 5.20: SUS item response distribution for AR (proportion per Likert option).

Questions	1	2	3	4	5	6	7
SUS1: I think that I would like to use this system frequently.	0.00	0.11	0.06	0.22	0.00	0.28	0.33
SUS2: I found the system unnecessarily complex.	0.39	0.28	0.28	0.00	0.00	0.06	0.00
SUS3: I thought the system was easy to use.	0.00	0.00	0.00	0.11	0.06	0.33	0.50
SUS4: I think that I would need the support of a technical person to be able to use this system.	0.33	0.33	0.00	0.06	0.00	0.11	0.17
SUS5: I found the various functions in this system were well integrated.	0.00	0.00	0.00	0.06	0.11	0.39	0.44
SUS6: I thought there was too much inconsistency in this system.	0.33	0.39	0.06	0.06	0.11	0.06	0.00
SUS7: I would imagine that most people would learn to use this system very quickly.	0.00	0.00	0.00	0.00	0.11	0.28	0.61
SUS8: I found the system very cumbersome to use.	0.61	0.22	0.00	0.06	0.11	0.00	0.00
SUS9: I felt very confident using the system.	0.00	0.00	0.06	0.00	0.06	0.22	0.67
SUS10: I needed to learn a lot of things before I could get going with this system.	0.67	0.11	0.06	0.11	0.00	0.00	0.06
SUS Score (0–100)				82.31 ± 16.00			

as highly usable and consistent. For the AV condition, the average SUS score was slightly higher at 83.43 ± 13.71. This value also lies in the "Good" range of Bangor et al. [5], and similarly maps to a letter grade of "A" under the Lewis and Sauro [36] framework. The results suggest that combining augmented and virtual elements did not negatively impact usability, and may have offered a marginal improvement over the AR version.

Table 5.21: SUS item response distribution for AV (proportion per Likert option).

Questions	1	2	3	4	5	6	7
SUS1: I think that I would like to use this system frequently.	0.00	0.11	0.22	0.06	0.11	0.22	0.28
SUS2: I found the system unnecessarily complex.	0.50	0.17	0.22	0.06	0.06	0.00	0.00
SUS3: I thought the system was easy to use.	0.00	0.00	0.00	0.06	0.11	0.17	0.67
SUS4: I think that I would need the support of a technical person to be able to use this system.	0.39	0.28	0.06	0.11	0.00	0.06	0.11
SUS5: I found the various functions in this system were well integrated.	0.00	0.00	0.00	0.06	0.06	0.39	0.50
SUS6: I thought there was too much inconsistency in this system.	0.39	0.39	0.06	0.17	0.00	0.00	0.00
SUS7: I would imagine that most people would learn to use this system very quickly.	0.00	0.00	0.00	0.06	0.06	0.17	0.72
SUS8: I found the system very cumbersome to use.	0.56	0.22	0.06	0.11	0.00	0.06	0.00
SUS9: I felt very confident using the system.	0.00	0.00	0.00	0.11	0.11	0.28	0.50
SUS10: I needed to learn a lot of things before I could get going with this system.	0.56	0.33	0.06	0.00	0.00	0.00	0.06
SUS Score (0–100)				83.43 ± 13.71			

Table 5.22 summarizes the SUS results for the VR immersive level. Responses were also favourable, though with slightly more variation. Frequent use was rated high (50% in 6–7), and ease of use was very strong (67% in 7). Integration was also positive (78% in 6–7), and quick learnability was endorsed (61% in 7). Confidence was high (67% in 7), while complexity, inconsistency, and cumbersomeness were largely rejected (44–72% in 1). Some responses indicated a need for technical support (28% at 1, 28% at 2), though most still leaned toward independence. Altogether, VR usability was high, but slightly more dispersed across items compared to AR and AV. In the VR condition, the mean SUS score reached 84.26 ± 12.58, the highest of the three. This score remains within the "Excellent" band defined by Bangor et al. [5], and also corresponds to an "A+" grade under the Lewis and Sauro [36] conversion. Thus, the full VR version was perceived as at least as usable as AR and AV, with a slight upward trend.

Table 5.22: SUS item response distribution for VR (proportion per Likert option).

Questions	1	2	3	4	5	6	7
SUS1: I think that I would like to use this system frequently.	0.00	0.11	0.00	0.22	0.17	0.11	0.39
SUS2: I found the system unnecessarily complex.	0.50	0.22	0.17	0.00	0.06	0.06	0.00
SUS3: I thought the system was easy to use.	0.00	0.00	0.00	0.00	0.22	0.11	0.67
SUS4: I think that I would need the support of a technical person to be able to use this system.	0.33	0.28	0.11	0.00	0.11	0.00	0.17
SUS5: I found the various functions in this system were well integrated.	0.06	0.00	0.00	0.11	0.06	0.28	0.50
SUS6: I thought there was too much inconsistency in this system.	0.44	0.33	0.06	0.11	0.06	0.00	0.00
SUS7: I would imagine that most people would learn to use this system very quickly.	0.00	0.00	0.00	0.06	0.00	0.33	0.61
SUS8: I found the system very cumbersome to use.	0.72	0.11	0.11	0.00	0.06	0.00	0.00
SUS9: I felt very confident using the system.	0.00	0.00	0.00	0.00	0.17	0.17	0.67
SUS10: I needed to learn a lot of things before I could get going with this system.	0.67	0.17	0.06	0.11	0.00	0.00	0.00
SUS Score (0–100)				84.26 ± 12.58			

Across all three immersion conditions, SUS scores consistently exceeded the threshold of 80, which Bangor et al. [5] associate with excellent usability. While the differences between conditions are small, the pattern suggests that usability perceptions remained highly positive regardless of immersion level. The conversion to letter grades [36] further supports this interpretation, as all three conditions align with a solid "A" rating, reinforcing the robustness of usability across AR, AV, and VR.

5.2.1.4 IGroup Presence

The presence dimension was assessed using the Igroup Presence Questionnaire (IPQ), which evaluates spatial presence, involvement, and experienced realism. The full set of

IPQ questions, along with their corresponding response ranges, is provided in Annex I.2.1.

Table 5.23 presents the IPQ results for the AR immersive level. The overall IPQ score was 3.18 ± 0.77, which corresponds to a grade of **F** ("Unacceptable") according to the benchmarks by Melo et al. [41]. General Presence was relatively higher at 4.33 ± 2.03, mapping to grade **C/D**, but Involvement remained low (2.71 ± 0.92, grade **F**) and Realism was also weak (2.94 ± 0.82, grade **D**). Spatial Presence reached 3.89 ± 1.12, just below the "Satisfactory" threshold, aligning with grade **D** ("Marginal"). Thus, AR generated a moderate sense of presence in spatial and general dimensions, but realism and involvement limited the overall experience.

Table 5.23: IPQ results for AR condition (values are mean ± SD).

Metric	**Mean ± SD**
Spatial Presence (0–6)	3.89 ± 1.12
Involvement (0–6)	2.71 ± 0.92
Realism (0–6)	2.94 ± 0.82
General Presence (0–6)	4.33 ± 2.03
General IPQ (0–6)	3.18 ± 0.77

As shown in Table 5.24, the IPQ results for the AV immersive level revealed an overall mean of 3.05±0.64, also in the **F** ("Unacceptable") range. General Presence scored 4.44±1.42, which places it in grade **C** ("Satisfactory"), while Spatial Presence (3.98 ± 1.00) remained in the grade **D** ("Marginal"). Involvement (2.58 ± 0.88) was again very low, mapping to **F**, and Realism was modest (2.60 ± 0.54), graded **E** ("Unsatisfactory"). These results suggest that AV provided a somewhat better general sense of being in the environment, but struggled with realism and user

Table 5.24: IPQ results for AV condition (values are mean ± SD).

Metric	**Mean ± SD**
Spatial Presence (0–6)	3.98 ± 1.00
Involvement (0–6)	2.58 ± 0.88
Realism (0–6)	2.60 ± 0.54
General Presence (0–6)	4.44 ± 1.42
General IPQ (0–6)	3.05 ± 0.64

Table 5.25 summarizes the IPQ results for the VR immersive level. The overall IPQ score was highest at 3.29±0.65, but still only achieved grade **F/E** ("Unacceptable/Unsatisfactory"). General Presence was also the highest of the three conditions (4.67±1.33), reaching grade **B** ("Very Good"), while Spatial Presence (4.24±0.84) improved relative to AR and AV, graded as **C/D**. Involvement increased to 3.07 ± 0.91, lifting it into grade **E** ("Unsatisfactory"), though still weak. Realism was the lowest subscale (2.57 ± 0.74), mapping to grade **F**. Overall, VR was most effective in delivering a convincing general sense of presence, though realism and involvement again constrained the total experience.

Across the three scenes, the corrected results confirm that **VR provided the strongest**

Table 5.25: IPQ results for VR condition (values are mean ± SD).

Metric	**Mean ± SD**
Spatial Presence (0–6)	4.24 ± 0.84
Involvement (0–6)	3.07 ± 0.91
Realism (0–6)	2.57 ± 0.74
General Presence (0–6)	4.67 ± 1.33
General IPQ (0–6)	3.29 ± 0.65

presence, particularly in General Presence (grade B) and slightly better involvement. AR and AV, while comparable, were weaker overall, with AV showing slightly higher General Presence but lower realism. The consistent limitation across all conditions was the low scoring in **Involvement and Realism**, which prevented overall IPQ scores from reaching the "Acceptable" range (grades A–C) defined by Melo et al. [41].

5.2.2 Discussion

It is important to highlight that this second study was conducted exclusively with healthy adults and did not include participants with PD. This limits the external validity of the results, since the target clinical population may experience the system differently due to motor and cognitive impairments. Furthermore, although the protocol included eye-tracking as an additional data source, technical issues prevented the collection of gaze metrics, which restricts the analysis to self-report questionnaires and performance logs.

The NASA-TLX results indicated that perceived workload was low across all three conditions, with average overall scores remaining well below the medium threshold. AR and VR conditions produced very similar workload ratings (18.83 ± 14.31 and 21.30 ± 17.44, respectively), while AV was slightly higher (22.07 ± 17.58), though the differences are small. This suggests that the addition of virtual elements in AV may have marginally increased cognitive effort, possibly due to the hybrid nature of the environment requiring participants to reconcile both real and virtual cues. Nevertheless, all values point to low task demands, confirming that the system was not perceived as taxing to operate.

The PAAS scale corroborated the NASA-TLX findings, with scores across AR, AV, and VR clustered around the lower end of the 1–9 scale. AR and VR obtained identical mean values (2.44), while AV was slightly higher (2.72), indicating marginally greater cognitive load. Although the differences are modest, this small increase in AV may again reflect the need to integrate both physical and virtual information. Overall, the results suggest that none of the three immersion levels imposed excessive mental load, supporting the feasibility of the tasks in a rehabilitation context.

Usability perceptions were highly positive across all modalities, with mean SUS scores above 80 for AR (82.31), AV (83.43), and VR (84.26). According to Bangor et al. [5] these values correspond to the "Excellent" range, and to a letter grade of "B" following Lewis and Sauro [36]. The very small differences between conditions suggest that immersion level did not substantially affect usability. This indicates that participants quickly understood the interaction mechanics and felt confident in their use, regardless of whether the environment was augmented, mixed, or fully virtual.

The IPQ results revealed a little more variation across levels of immersion compared to the other questionnaires. Although overall scores remained low relative to the benchmarks of Melo et al. [41], VR consistently outperformed AR and AV in terms of *Spatial Presence* (4.24 vs. 3.89 and 3.98) and *General Presence* (4.67 vs. 4.33 and 4.44). *Involvement* remained weak across all conditions, though VR showed a slight improvement (3.07 vs. 2.71 in AR and 2.58 in AV). *Realism* was similarly low in all modalities, with AR being marginally higher. These findings suggest that immersion primarily enhanced participants' sense of "being there," but improvements in realism and engagement are required to raise presence into an acceptable range. Lower presence scores in AR were expected, since AR augments rather than replaces reality, while AV was theoretically positioned between AR and VR and therefore expected to yield intermediate values.

Participants themselves reported that they were mainly focused on the gameplay, which reduced the extent to which they noticed differences between immersion levels. As a result, the contrasts between AR, AV, and VR were not always strongly reflected in the questionnaire scores, even though some patterns were present. This suggests that the engaging nature of the fruit-catching task may have overshadowed subtle variations in environmental configuration, making the perceived differences across conditions less salient.

5.3 Integrated Discussion of Both Studies

When analyzing the two studies together, some important patterns become clear. First, both studies consistently showed that the system imposed **low workload and cognitive load** on healthy participants, confirming that the task design was not demanding. However, Study 1 revealed that participants with Parkinson's disease perceived higher workload than controls, underlining the need for therapist supervision during clinical use.

Second, **usability remained excellent** across all immersion levels for healthy participants, with SUS scores consistently above 80 in both studies. PD participants in Study 1 rated usability slightly lower, though still acceptable, suggesting that while the interface is robust, minor adjustments may be beneficial for clinical deployment.

Finally, the most notable differences appeared in the **presence results**. In both studies, VR consistently provided the strongest sense of spatial and general presence, while AR was rated higher in realism, as expected given that participants interacted within their real environment. The AV condition occupied an intermediate position but did not always follow the expected gradient, possibly because the participants were strongly focused on gameplay, which reduced the perceived impact of the differences in the scene. Involvement remained weak across all modalities, highlighting a common area for improvement.

In summary, the two studies together confirm the system's feasibility: it is usable, not cognitively demanding, and capable of delivering meaningful levels of presence, particularly in VR. The greatest challenge that emerges from both datasets is the need to enhance realism and involvement to raise presence to acceptable levels, while ensuring that clinical participants can engage safely under therapist guidance.

6

Conclusions and Future Work

This chapter summarizes the main conclusions of the study. This dissertation outlines the course of the research and describes future developments and improvements that It has the potential to yield substantial results.

6.1 Conclusion

The main objective of this dissertation was to explore the virtual continuum in the context of Parkinson's disease rehabilitation, ranging from AR to VR. The framework originally defined and implemented five levels of immersion, but due to logistical and time constraints, only three levels (eAR, AV, and VR) were tested in the user studies. This work was motivated by the potential benefits and challenges of incorporating immersive technologies into therapeutic settings for individuals with Parkinson's disease. To this end, two prototypes were developed and evaluated: an initial set of AR and VR versions based on an existing therapeutic game, followed by a more advanced prototype designed to operate across multiple levels of immersion within the virtual continuum.

The first study compared AR and VR in both healthy adults and a small group of participants with Parkinson's disease. Results showed that healthy participants experienced low workload and high usability in both conditions, with VR providing stronger spatial and general presence. Interestingly, participants with Parkinson's disease reported higher workload but also higher presence, suggesting that immersion may play a particularly engaging role in this population.

The second study extended the analysis to AR, AV, and VR conditions in healthy participants. Across all modalities, workload and cognitive load remained low, and usability was consistently rated as excellent. Presence scores revealed that VR offered the strongest spatial and general presence, while AR scored slightly higher in realism, and AV tended to occupy an intermediate position. However, differences between conditions were modest, likely because participants were strongly focused on the gameplay task. Overall, the results confirm that the system is feasible, well accepted by healthy users, and capable of producing meaningful levels of presence, particularly in VR.

6.2 Contributions

This research makes several contributions to the study of immersive technologies for Parkinson's disease rehabilitation:

- **Immersive Technologies for PD:** The findings highlight the potential of AR, AV, and VR as complementary approaches to rehabilitation. AR was advantageous in terms of realism and ease of use, reducing spatial disorientation by anchoring the player in the real environment. VR, in contrast, maximized spatial and general presence, providing higher engagement and immersion. AV occupied an intermediate position, but differences were subtle, likely due to participants' strong focus on gameplay rather than scene configuration.

- **Methodological Innovations:** This work combined subjective questionnaires with objective measures such as eye-tracking (in the first study) to assess workload and attention. Although technical issues prevented the use of eye-tracking in the second study, its inclusion in the first set a methodological reference for integrating multimodal data to better capture user experience and cognitive load.

- **Adaptability and Customization:** The exploration of the virtual continuum emphasizes the importance of adaptable therapeutic tools. PD manifests with heterogeneous motor and cognitive symptoms, and the results show that different immersion levels can be matched to different patient needs. AR may be more suitable for those with severe motor difficulties, while VR may benefit patients needing higher stimulation and engagement. This adaptability is essential for building personalized rehabilitation strategies.

- **Practical Applications for Healthcare:** A key contribution of this work was the integration of the rehabilitation game with the existing Play platform. It is important to clarify that the Play platform itself was not developed in this dissertation; instead, a dedicated configuration and communication layer was implemented for this game. Each game connected to Play requires its own configuration, and in this case, specific adaptations were made to ensure that therapists could configure sessions and that gameplay data could be transmitted to the platform for monitoring and analysis. This integration demonstrates the practical potential of immersive technologies in clinical contexts, paving the way for interactive, data-driven rehabilitation strategies that improve adherence and therapist oversight.

- **Publications and Dissemination:** This work has also contributed to the scientific community through publications. The first paper was published at the *2025 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)* [15], presenting early results from the 2nd phase game prototype. A second paper, based on the extended study with multiple immersion levels, is under preparation and will be presented at the *15th International Conference on Current and Future Trends of Information and Communication Technologies in Healthcare (ICTH 2025)*, to be held in Istanbul, Türkiye, October 28–30, 2025. These publications confirm the relevance and impact of the research in both immersive technologies and healthcare contexts.

6.3 Limitations

Several limitations must be acknowledged. The recruitment of participants diagnosed with PD was particularly difficult due to the vulnerability of this demographic, leading to a sample that was both small and less diverse. Although the findings provide valuable preliminary insights, expanding the participant base would be necessary to enhance the generalizability of the results. In addition, the evaluation was short-term in nature, focusing primarily on immediate reactions to AR and VR interventions rather than long-term therapeutic effects. The second study was further limited to healthy adults only, which restricts its direct applicability to the clinical population of interest. With respect to data collection, eye-tracking metrics were successfully gathered in the first study but could not be collected in the second study due to technical issues, reducing the opportunity for direct comparison between studies. Another limitation concerns the integration with the Play platform: while the connection between the game and the platform was successfully implemented and used during the second study for session configuration, it was not tested in practice with therapists. As such, the integration cannot yet be considered validated for clinical use. Finally, only three of the five initially defined immersion levels were tested, which constrained the empirical exploration of the full virtual continuum.

6.4 Future Work

The intersection of healthcare and immersive technology offers a wealth of opportunities for advancement and exploration. Although this dissertation lays a foundation for understanding the potential of AR to VR in therapeutic contexts for individuals with Parkinson's disease, several avenues for future research are critical to increase the insight and applicability of this work, whilst addressing the limitations outlined above.

Future research should aim to expand the potential of the system in several directions:

- **Clinical validation:** Conduct larger-scale clinical trials with PD patients, including more diverse cohorts across different stages of the disease. These studies should be carried out under therapist supervision to ensure both safety and therapeutic value.

- **Exploration of the full continuum:** Extend testing to all five originally defined immersion levels, not just AR, AV, and VR. This would allow for a more complete mapping of how incremental changes in immersion affect usability, workload, and presence, and help identify the optimal level for different therapeutic goals.

- **Adaptive and personalized features:** Develop dynamic systems that adjust immersion level, task difficulty, and feedback in real time based on patient performance, fatigue, and therapist input. Machine learning models could be leveraged to tailor sessions to individual needs, enhancing both safety and efficacy.

- **Validation of Play Platform Integration:** Future studies should involve therapists directly in configuring and monitoring sessions through the Play platform. This will allow the evaluation of its usability, workflow integration, and effectiveness in real clinical contexts, moving beyond the researcher-only validation conducted in the second study.

- **Therapeutic Studies:** This work emphasizes the need for longer-term clinical studies to assess the sustained impact of AR to VR interventions on health outcomes, motivation, and adherence to rehabilitation. Monitoring participants over several weeks would make it possible to evaluate effects on motor function, emotional well-being, and overall quality of life, thereby providing a clearer picture of their therapeutic value in PD rehabilitation.

Taken together, these directions highlight how the present dissertation serves as an initial step toward establishing immersive technologies, from AR to VR, as viable therapeutic tools for Parkinson's disease. By addressing the outlined challenges, future work can transform this prototype into a clinically validated, adaptable, and widely applicable system that bridges research and real-world rehabilitation.

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I

Graphs and Tables — Full Results

I.1 First Study

I.1.1 IPQ (Presence)

Table I.1: Control Group Relative Frequency of IPQ answers about the AR game experience

Questions	1	2	3	4	5
PQ1: In the computer generated world I had a sense of "being there".	0.03	0.19	0.35	0.39	0.03
PQ2: Somehow I felt that the virtual world surrounded me.	0.03	0.23	0.29	0.35	0.10
PQ3: I felt like I was just perceiving pictures.	0.39	0.32	0.23	0.03	0.03
PQ4: I did not feel present in the virtual space.	0.10	0.10	0.36	0.26	0.19
PQ5: I had a sense of acting in the virtual space, rather than operating something from outside.	0.03	0.23	0.29	0.29	0.16
PQ6: I felt present in the virtual space.	0.03	0.10	0.32	0.39	0.16
PQ7: How aware were you of the real world surrounding while navigating in the virtual world? (i.e. sounds, room temperature, other people, etc.)	0.23	0.32	0.32	0.06	0.06
PQ8: I was not aware of my real environment.	0.45	0.52	0.03	0.00	0.00
PQ9: I still paid attention to the real environment.	0.00	0.00	0.13	0.51	0.35
PQ10: I was completely captivated by the virtual world.	0.03	0.13	0.48	0.26	0.10
PQ11: How real did the virtual world seem to you?	0.10	0.26	0.32	0.26	0.06
PQ12: How much did your experience in the virtual environment seem consistent with your real world experience?	0.00	0.23	0.48	0.26	0.03
PQ13: How real did the virtual world seem to you?	0.13	0.45	0.35	0.03	0.03
PQ14: The virtual world seemed more realistic than the real world.	0.58	0.39	0.03	0.00	0.00

Table I.2: Control Group Relative Frequency of IPQ answers about the VR game experience

Questions	**1**	**2**	**3**	**4**	**5**
PQ1: In the computer generated world I had a sense of "being there".	0.03	0.10	0.26	0.42	0.19
PQ2: Somehow I felt that the virtual world surrounded me.	0.00	0.16	0.16	0.35	0.32
PQ3: I felt like I was just perceiving pictures.	0.42	0.35	0.19	0.00	0.03
PQ4: I did not feel present in the virtual space.	0.00	0.10	0.29	0.29	0.32
PQ5: I had a sense of acting in the virtual space, rather than operating something from outside.	0.03	0.03	0.29	0.35	0.29
PQ6: I felt present in the virtual space.	0.00	0.03	0.35	0.39	0.23
PQ7: How aware were you of the real world surrounding while navigating in the virtual world? (i.e. sounds, room temperature, other people, etc.)	0.19	0.26	0.35	0.19	0.00
PQ8: I was not aware of my real environment.	0.19	0.39	0.16	0.23	0.03
PQ9: I still paid attention to the real environment.	0.19	0.45	0.26	0.06	0.03
PQ10: I was completely captivated by the virtual world.	0.00	0.19	0.32	0.32	0.16
PQ11: How real did the virtual world seem to you?	0.03	0.39	0.29	0.26	0.03
PQ12: How much did your experience in the virtual environment seem consistent with your real world experience?	0.06	0.10	0.48	0.35	0.00
PQ13: How real did the virtual world seem to you?	0.16	0.35	0.35	0.13	0.00
PQ14: The virtual world seemed more realistic than the real world.	0.68	0.26	0.03	0.06	0.00

Table I.3: Parkinson Group Relative Frequency of IPQ answers about the AR game experience

Questions	1	2	3	4	5
PQ1: In the computer generated world I had a sense of "being there".	0.00	0.00	0.25	0.25	0.50
PQ2: Somehow I felt that the virtual world surrounded me.	0.00	0.00	0.50	0.50	0.00
PQ3: I felt like I was just perceiving pictures.	0.25	0.25	0.25	0.25	0.00
PQ4: I did not feel present in the virtual space.	0.00	0.25	0.25	0.25	0.25
PQ5: I had a sense of acting in the virtual space, rather than operating something from outside.	0.00	0.00	0.50	0.25	0.25
PQ6: I felt present in the virtual space.	0.00	0.00	0.25	0.50	0.25
PQ7: How aware were you of the real world surrounding while navigating in the virtual world? (i.e. sounds, room temperature, other people, etc.)	0.25	0.50	0.25	0.00	0.00
PQ8: I was not aware of my real environment.	0.00	0.75	0.25	0.00	0.00
PQ9: I still paid attention to the real environment.	0.00	0.00	0.50	0.50	0.00
PQ10: I was completely captivated by the virtual world.	0.00	0.00	0.50	0.25	0.25
PQ11: How real did the virtual world seem to you?	0.00	0.25	0.25	0.50	0.00
PQ12: How much did your experience in the virtual environment seem consistent with your real world experience?	0.00	0.50	0.50	0.00	0.00
PQ13: How real did the virtual world seem to you?	0.00	0.25	0.75	0.00	0.00
PQ14: The virtual world seemed more realistic than the real world.	0.75	0.00	0.00	0.25	0.00

Table I.4: Parkinson Group Relative Frequency of IPQ answers about the VR game experience

Questions	**1**	**2**	**3**	**4**	**5**
PQ1: In the computer generated world I had a sense of "being there".	0.00	0.00	0.00	0.75	0.25
PQ2: Somehow I felt that the virtual world surrounded me.	0.00	0.00	0.25	0.50	0.25
PQ3: I felt like I was just perceiving pictures.	0.25	0.25	0.25	0.25	0.00
PQ4: I did not feel present in the virtual space.	0.00	0.00	0.25	0.25	0.50
PQ5: I had a sense of acting in the virtual space, rather than operating something from outside.	0.00	0.00	0.00	0.75	0.25
PQ6: I felt present in the virtual space.	0.00	0.00	0.00	0.75	0.25
PQ7: How aware were you of the real world surrounding while navigating in the virtual world? (i.e. sounds, room temperature, other people, etc.)	0.00	0.25	0.00	0.50	0.25
PQ8: I was not aware of my real environment.	0.25	0.00	0.00	0.75	0.00
PQ9: I still paid attention to the real environment.	0.25	0.75	0.00	0.00	0.00
PQ10: I was completely captivated by the virtual world.	0.00	0.25	0.00	0.50	0.25
PQ11: How real did the virtual world seem to you?	0.00	0.50	0.25	0.25	0.00
PQ12: How much did your experience in the virtual environment seem consistent with your real world experience?	0.00	0.25	0.25	0.25	0.25
PQ13: How real did the virtual world seem to you?	0.00	0.50	0.25	0.25	0.00
PQ14: The virtual world seemed more realistic than the real world.	0.25	0.50	0.25	0.00	0.00

I.2 Second Study

I.2.1 IPQ (Presence)

I.3 Eye-Tracking Plots

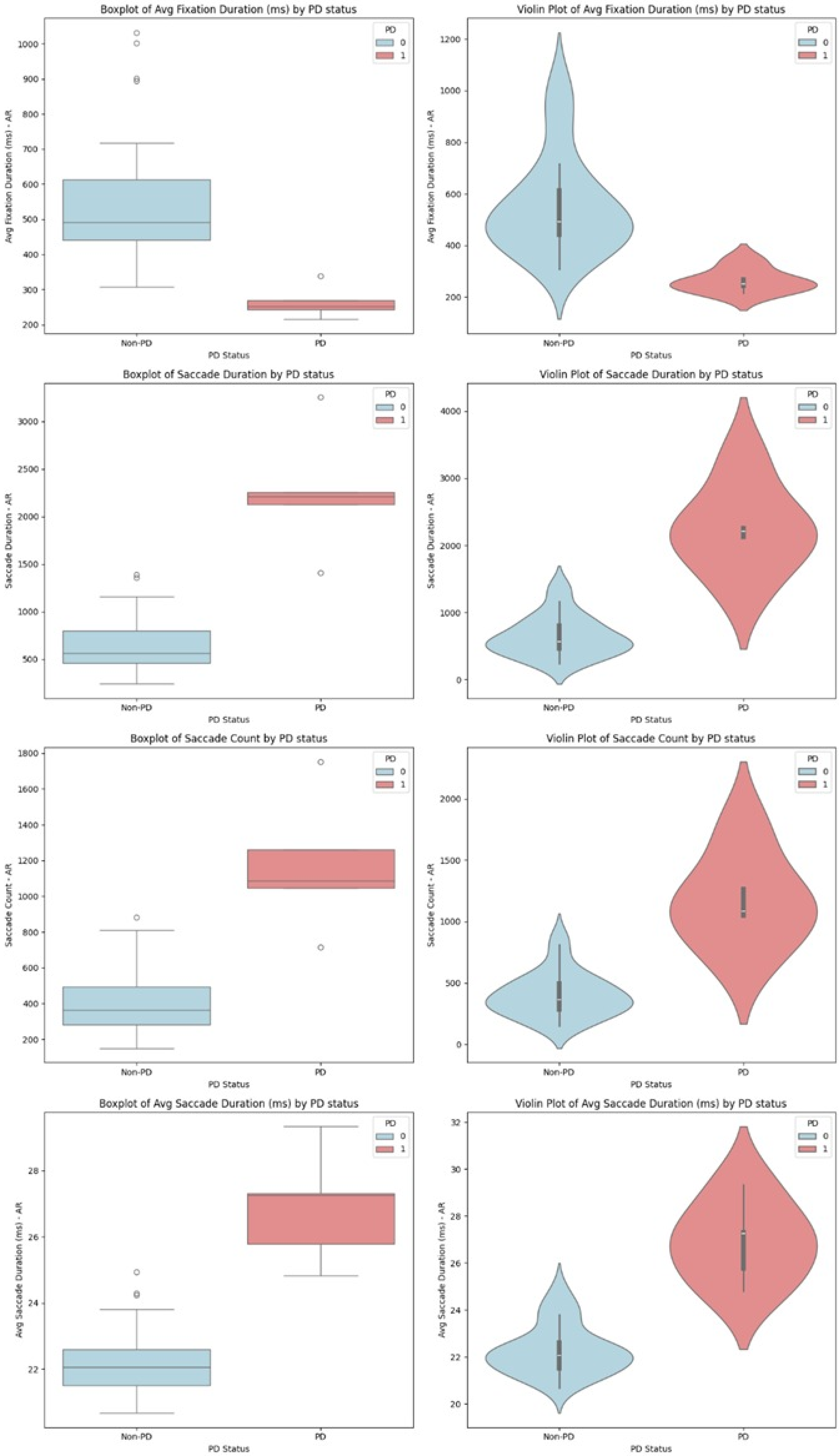

Figure I.1: Eye-tracking metrics in the AR condition (First Study), comparing participants with and without Parkinson's disease.

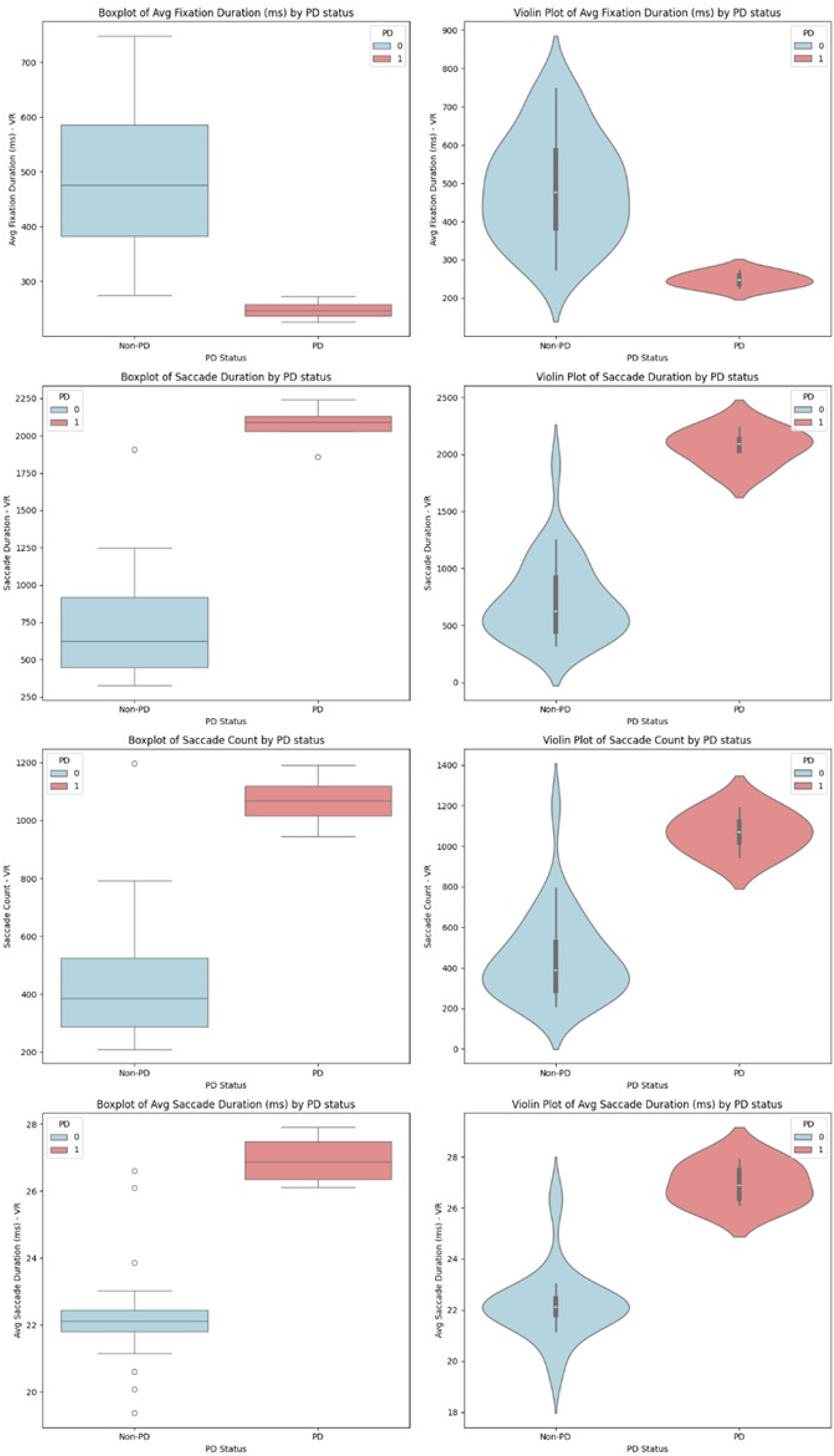

Figure I.2: Eye-tracking metrics in the VR condition (First Study), comparing participants with and without Parkinson's disease.

Table I.5: PQ item response distribution for AR (proportion per Likert option).

Questions	0	1	2	3	4	5	6
PQ1: In the computer generated world I had a sense of “being there”.	0.11	0.00	0.11	0.00	0.17	0.22	0.39
PQ2: Somehow I felt that the virtual world surrounded me.	0.06	0.06	0.11	0.17	0.06	0.17	0.39
PQ3: I felt like I was just perceiving pictures.	0.17	0.28	0.17	0.17	0.11	0.06	0.06
PQ4: I did not feel present in the virtual space.	0.00	0.06	0.06	0.17	0.17	0.17	0.39
PQ5: I had a sense of acting in the virtual space, rather than operating something from outside.	0.00	0.11	0.06	0.28	0.06	0.17	0.33
PQ6: I felt present in the virtual space.	0.00	0.06	0.06	0.17	0.17	0.17	0.39
PQ7: How aware were you of the real world surrounding while navigating in the virtual world? (e.g., sounds, room temperature, other people, etc.)	0.33	0.28	0.11	0.17	0.06	0.06	0.00
PQ8: I was not aware of my real environment.	0.33	0.22	0.11	0.06	0.22	0.00	0.06
PQ9: I still paid attention to the real environment.	0.17	0.06	0.11	0.17	0.17	0.11	0.22
PQ10: I was completely captivated by the virtual world.	0.00	0.11	0.00	0.28	0.17	0.11	0.33
PQ11: How real did the virtual world seem to you?	0.17	0.11	0.11	0.33	0.11	0.17	0.00
PQ12: How much did your experience in the virtual environment seem consistent with your real world experience?	0.00	0.00	0.11	0.28	0.33	0.17	0.11
PQ13: How real did the virtual world seem to you?	0.06	0.28	0.06	0.28	0.11	0.11	0.11
PQ14: The virtual world seemed more realistic than the real world.	0.22	0.22	0.06	0.28	0.00	0.11	0.11

Table I.6: PQ item response distribution for AV (proportion per Likert option).

Questions	0	1	2	3	4	5	6
PQ1: In the computer generated world I had a sense of "being there".	0.00	0.00	0.17	0.06	0.22	0.28	0.28
PQ2: Somehow I felt that the virtual world surrounded me.	0.00	0.06	0.06	0.06	0.22	0.33	0.28
PQ3: I felt like I was just perceiving pictures.	0.44	0.17	0.17	0.06	0.06	0.11	0.00
PQ4: I did not feel present in the virtual space.	0.00	0.00	0.06	0.11	0.28	0.17	0.39
PQ5: I had a sense of acting in the virtual space, rather than operating something from outside.	0.00	0.06	0.06	0.06	0.17	0.39	0.28
PQ6: I felt present in the virtual space.	0.00	0.11	0.06	0.00	0.22	0.22	0.39
PQ7: How aware were you of the real world surrounding while navigating in the virtual world? (e.g., sounds, room temperature, other people, etc.)	0.39	0.28	0.06	0.17	0.11	0.00	0.00
PQ8: I was not aware of my real environment.	0.39	0.17	0.06	0.17	0.11	0.06	0.06
PQ9: I still paid attention to the real environment.	0.22	0.17	0.06	0.11	0.11	0.17	0.17
PQ10: I was completely captivated by the virtual world.	0.00	0.00	0.11	0.17	0.28	0.22	0.22
PQ11: How real did the virtual world seem to you?	0.22	0.06	0.22	0.22	0.22	0.06	0.00
PQ12: How much did your experience in the virtual environment seem consistent with your real world experience?	0.00	0.06	0.00	0.39	0.28	0.11	0.17
PQ13: How real did the virtual world seem to you?	0.17	0.17	0.22	0.22	0.17	0.00	0.06
PQ14: The virtual world seemed more realistic than the real world.	0.28	0.22	0.17	0.11	0.17	0.00	0.06

Table I.7: PQ item response distribution for VR (proportion per Likert option).

Questions	0	1	2	3	4	5	6
PQ1: In the computer generated world I had a sense of "being there".	0.00	0.06	0.00	0.06	0.33	0.22	0.33
PQ2: Somehow I felt that the virtual world surrounded me.	0.00	0.06	0.00	0.06	0.11	0.44	0.33
PQ3: I felt like I was just perceiving pictures.	0.33	0.17	0.22	0.06	0.06	0.11	0.06
PQ4: I did not feel present in the virtual space.	0.00	0.00	0.00	0.06	0.17	0.39	0.39
PQ5: I had a sense of acting in the virtual space, rather than operating something from outside.	0.06	0.06	0.00	0.06	0.22	0.39	0.22
PQ6: I felt present in the virtual space.	0.00	0.06	0.00	0.06	0.11	0.39	0.39
PQ7: How aware were you of the real world surrounding while navigating in the virtual world? (e.g., sounds, room temperature, other people, etc.)	0.28	0.17	0.11	0.11	0.22	0.11	0.00
PQ8: I was not aware of my real environment.	0.17	0.11	0.17	0.06	0.22	0.11	0.17
PQ9: I still paid attention to the real environment.	0.17	0.22	0.22	0.11	0.06	0.06	0.17
PQ10: I was completely captivated by the virtual world.	0.00	0.00	0.06	0.11	0.39	0.11	0.33
PQ11: How real did the virtual world seem to you?	0.22	0.22	0.22	0.22	0.06	0.06	0.00
PQ12: How much did your experience in the virtual environment seem consistent with your real world experience?	0.00	0.11	0.06	0.17	0.28	0.39	0.00
PQ13: How real did the virtual world seem to you?	0.00	0.22	0.28	0.17	0.17	0.11	0.06
PQ14: The virtual world seemed more realistic than the real world.	0.39	0.11	0.11	0.22	0.06	0.06	0.06