# Development of an immersive Virtual Reality game for motor and cognitive rehabilitation in multiple sclerosis

Master's Degree in Computer Engineering

Politecnico di Torino

**Supervisors**
**Prof. Andrea BOTTINO**
**Prof. Fabrizio LAMBERTI**
**Dr. Giacinto BARRESI**

**Candidate**
**Chiara PARENTE**

April 2023

# Abstract

Multiple Sclerosis (MS) is a progressive disease of the central nervous system. Among its symptoms, motor and cognitive impairments (from upper limb tremor to attention deficit) can severely affect the individual capability to perform activities of daily living. Consequently, motor and cognitive rehabilitation procedures constitute a priority for people with MS, and their beneficial effects have been proven. However, the effectiveness of the repetitive exercises adopted in rehabilitation typically depends on factors like the motivation of the patients, leading to difficulties in clinical compliance. Thus, engaging people with MS in performing the expected tasks is a challenge that must be faced for improving the individual adherence to the clinical procedures.

A potential solution to this issue can derive from Virtual Reality (VR), considering how it has gained a lot of interest in the healthcare community. Studies have reported the positive and promising impact of serious games (especially exergames) and gamification in rehabilitation, paving the way for the potential of VR and the related technology, raising motivation and limiting fatigue in MS patients.

Accordingly, this thesis presents the design and the development of an immersive video game that enables rehabilitation exercises in a playful and engaging context. Additionally, this interactive setting is enriched by biofeedback features to calibrate the difficulty of the game in real time to keep the user in a positive mental state. The game involves upper limb rehabilitation and cognitive rehabilitation, with a focus on dual-task. The developed game contains four phases that are played in sequence, each one proposes a particular exergame.

After discussing the system design and development, the thesis focuses on the evaluation of the user experience - especially in terms of engagement - during the rehabilitation game session to obtain important data that can be used in the future to evaluate the effectiveness of the rehabilitation game over time.

# Table of Contents

# Chapter 1

# Introduction

## 1.1 Multiple Sclerosis

Multiple Sclerosis (MS) is a progressive disease of the central nervous system. Among its symptoms, motor and cognitive impairments can severely affect the individual capability to perform activities of daily living and quality of life (QoL).

The main frequent motor impairments include spasticity, bladder problems, disorders of strength, co-ordination and balance impairments, fatigue [1][2], upper limb (UL) dysfunction such as tremor, weakness, sensory deficits and reduced dexterity in one or both hands [3].

MS can also frequently cause cognitive impairments, such as difficulties with perception, attention, awareness, memory, problem solving, reasoning, communication, information processing abilities (including processing speed), and new learning and memory functioning. These impairments can have a harmful effect on an individual's personal, occupational, and social functioning, as well as their overall QoL [4].

MS can develop at a very young age, and there is growing awareness of its occurrence among children and adolescents worldwide. In children the disease preponderantly begins as relapsing-remitting MS (RRMS), with a lower proportion of cases presenting as primary progressive MS (PPMS). [5].

When comparing life expectancy in MS patients to life expectancy in an age-matched population without MS it results only a modest reduction of approximately 5 - 10 years. Because MS typically starts early, has a progressive course, and does not significantly reduce life expectancy, it can often lead to a high prevalence of long-term disabilities [1].

According to a study conducted by the International Journal of MS Care [6], the majority of the 25,728 MS patients polled reported experiencing some level of impairment soon after disease onset. Sensory symptoms and fatigue were particularly widespread, with 85% of patients reporting sensory symptoms and 81% experiencing unexplained fatigue within the first year. Furthermore, over 40% of patients experienced a regression in hand function. Half of the patients (50%) reported minimal or mild cognitive impairment within the first year. Although mobility is typically unaffected during the first decade of the disease, 35% of patients experienced a noticeable decrease in mobility during the first year, and an additional 15% required the occasional use of a mobility device.

Given the significant effect that deficits in cognitive and motor functioning have on the QoL of persons with MS and the high probability of them to appear during the disease, the alleviation of such deficits should be a major goal of MS research and practice [4].

## 1.2 Rehabilitation in MS

Motor and cognitive rehabilitation procedures constitute a priority for people with MS, and their beneficial effects have been proven. Rehabilitation is a process that aims at reducing disability and handicap experienced by someone as a consequence of injury or disease [7]. In the context of MS, the primary goal of rehabilitation is to decrease symptoms and limitations in terms of one's ability to perform daily activities and participate in society. This is accomplished through various interventions that take into account both personal and environmental factors, with the ultimate aim of attaining the greatest possible level of independence and self-management and the highest QoL given the constraints and limits imposed by the disease [1, 2].

### 1.2.1 Neural Plasticity

Research have proven that motor and cognitive rehabilitation in MS induced neural plasticity. The term neural plasticity refers to "the ability of the nervous system to respond to intrinsic and extrinsic stimuli by reorganizing its structure, function, and connections" [8]. The central nervous system structurally and functionally adapts itself in response to external stimuli, environmental changes, or injuries.

Task-oriented motor rehabilitation has been found to induce positive structural changes in white matter and gray matter following high-intensity repetitive training accompanied by visual feedback, such as exergames and visuomotor task training. Conversely, passive rehabilitation has been found to induce maladaptive structural plasticity [9]. Research conducted utilizing neuroimaging techniques have consistently demonstrated significantly increased cerebral activity following cognitive rehabilitation. In particular, computer-based training for attention deficits results in adaptive neural plasticity of the neural network involved in attention [9].

## 1.3 Exergames

Exergames are defined as the combination of interactive video games and physical activity [10]. This dual nature of exergames makes them an extremely powerful tool to make the execution of physical exercise (either for rehabilitation purposes or not) a more enjoyable experience. Several studies claim that the use of exergames also produces relevant psychological benefit on the players, such as an increase in self-esteem and satisfaction [11], positive effects on mood, a reduction of anxiety and depression and a reduction of apathy [12].

The potential of exergames in enhancing cognitive [13] and motor abilities [14, 15] generated a lot of interest in the healthcare community, leading to several studies about the utilization of exergames for rehabilitation.

To not generate stress and to make the player fully enjoy the experience, a well-designed exergame should balance effectiveness of the exercise and attractiveness of the gameplay [16]. In addition, a well-designed exergame should balance the intensity of the exercise and abilities of the player, because an excessive exercise energy expenditure and exercise intensity would have negative psychological effects and reduce enjoyment [17]. For this reason, the development of a successful exergame is an intricate issue that requires a long and meticulous work of finding the correct balance between fun and exercise and between game's challenge and player's abilities.

## 1.4 Virtual Reality

The term Virtual Reality identifies a particular technology where the user interacts with a real-time generated environment through different sensory channels. A VR experience needs a series of devices that manage the immersion of the player in the virtual environment. One of the most common technologies for VR is the use of headsets and controllers, in particular a Head Mounted Display (HMD) is a wearable device that uses stereoscopy to make the user correctly perceive depth.

The illusion of mentally being in the virtual environment (telepresence) increases when the environment correctly responds to the user input, providing plausible feedback, while the illusion of physically being in the virtual environment (immersion), depends on the degree of estrangement from the real world and the responsiveness and effectiveness of the input/output devices (HMD, headphones). [18] Therefore immersion is an objective feature, that refers to technology aspects and used devices [19], whereas presence is a subjective feature, as it refers to psychological and perceptual aspects of the VR experience [20]. Based on immersion, VR can be categorized into three distinct levels [21]:

- non-immersive VR typically involves viewing the virtual environment through a screen, and interacting using a keyboard and mouse. It relies on limited technology such as tablets, smartphones and desktop computers.
- semi-immersive VR utilizes more advanced and expensive technology, such as panoramic displays, to enhance the user's sensory experience. These devices can extend the user's view of the virtual world and occupy a greater portion of their field of view (FOV), resulting in a more immersive experience.
- fully immersive VR involves the use of HMD or CAVE to submerge the users in a completely immersive and interactive virtual environment and to create a clear separation from the real world, facilitating immersion in the virtual world.

The use of semi-immersive and full-immersive Virtual Reality and exergames in addition to the conventional and traditional rehabilitation and physiotherapy has given promising results in the treatment of MS. The use of VR implies a series of advantages that leads to seeing VR as a useful tool for rehabilitation. In particular, VR can rise motivation and participation, it is easy to use, enjoyable and also produces a distraction from the standard and boring training and rehabilitation that patients usually have to perform. [22][23].

Another significant advantage of VR training is the ability to perform home-based rehabilitation, making training more accessible and less expensive. This feature has become increasingly crucial, especially during the COVID-19 pandemic in March 2020, where home-based VR training demonstrated its importance in ensuring the continuation of rehabilitation programs. [24].

## 1.5 Contribution

The exergame designed and developed for this thesis is a full-immersive Virtual Reality exergame for upper-limb and cognitive rehabilitation in persons with multiple sclerosis (PwMS).

The videogame's objective is to disguise a series of different rehabilitation exercises in a fun and entertaining virtual environment ruled by functional game mechanics, with the goal of maximizing engagement and increasing the patient's desire to continue playing and training. The rehabilitation exercises will be centered on upper-limb rehabilitation, with a focus on tremor, and on cognitive rehabilitation, requiring to solve a series of tasks that involve logic, problem solving, high reflexes and spatial attention. The game will also propose a final dual task phase that involves motor abilities, hearing attention and low reaction time.

To correctly and successfully balance the exercise energy expanditure and the exercise intensity, a biofeedback will be used to adjust the exergame difficulty and intensity according to the player's heart rate. Therefore, the difficulty of the game will be changed real-time during the gameplay. Additionally, players must regulate their heart rate by adjusting their breathing rate in order to maintain it below a specific threshold.

This thesis will begin with a state-of-the-art analysis that discusses the current exergames available for people with MS as well as the commonly utilized non-VR-based exercises for rehabilitation. The analysis aims to understand the direction to take for the creation of the video game, identifying any gaps in existing exergames and their strengths.

Next, the game design will be presented and described in detail, including an explanation of the game mechanics and the medical objectives behind each phase of the exergame. Following the game design, the implementation will be summarized, including the technologies involved.

Following implementation, the game's usability will be evaluated by polling a group of 26 subjects. The purpose of this experiment is to assess the effectiveness of incorporating biofeedback in the game to determine its potential for future experiments and development. After the developing the game will be played in two different modalities by the subjects, one modality consists in using the biofeedback system to adjust the game intensity, the other modality instead does not use a biofeedback and keeps the exergame difficulty and intensity fixed during the whole gameplay.

Both the subjective and the objective results of the experiment will be discussed to evaluate the degree of user preference towards biofeedback.

## 1.6 ENACT Project

The thesis project was developed as part of the ENACT (Employing Neuroergonomic solutions to Attenuate the Cerebellar Tremor) project (Figure 1.1) , and its steps were overseen by the ENACT team at the Rehab Technologies Lab in IIT (Istituto Italiano di Tecnologia) in collaboration with AISM (Associazione Italiana Sclerosi Multipla).

The ENACT project is a 3-year research project that started in October 2021. Its objectives are to identify and develop neuro-ergonomic solutions to mitigate the effects of cerebellar tremors in everyday activities for people with multiple sclerosis (PwMS) and to develop exergames and videogames for MS rehabilitation. ENACT is a collaboration between IIT and AISM, with contributions from FISM and other international partners.

**Figure 1.1:** ENACT logo

# Chapter 2

# State-of-the-Art

A preliminary study of the existing rehabilitation procedures for PwMS was conducted. The objective of the first part of the study was to analyze a series of papers in order to identify commonly used non-VR-based rehabilitative exercises for PwMS. In the second part of the study, the objective was to identify and describe the current games and exergames commonly utilized in rehabilitation as a state-of-the-art analysis.

Identifying and studying the conventional rehabilitation exercises and the existing exergames for rehabilitation was extremely important to design and develop a useful and successful exergame for rehabilitation.

## 2.1 Rehabilitation Exercises

The rehabilitation exercises for MS can be grouped in three main categories basing on the intended medical goals, in particular they can be centered on motor rehabilitation, cognitive rehabilitation, or both.

### 2.1.1 Motor rehabilitation

The motor rehabilitation consists in physical activity, the exercises commonly used for PwMS usually involve balance training, upper limb rehabilitation, strength, resistance and fatigue training. The exercises included and analyzed in this study are focused on upper limb rehabilitation, as the objective of the thesis is to develop a rehabilitation exergame for PwMS with upper limb tremor.

The exercises can either be task-oriented and non task-oriented. Non task-oriented exercises include pinching objects, grasping cubes of different sizes and reaching a target positioned in front of the patient. Task oriented exercises are manual exercises with an immediate goal, such as ironing a shirt, sewing, cooking, sweeping, doing patchwork and paper mandala [25].

With upper-limb rehabilitation, the objective is to make the patients perform and repeat a series of specific movements with their arms, that require dexterity, strength and precision. By repeating the movement a large number of time, the resistance of the patient is also exercised.

One interesting exercise, used to evaluate the patients manual dexterity, is the Box and Block test, that consists in grabbing and placing small cubes in a series of different specific positions, with a focus on precision and velocity. The movement is repeated a large number of times [26].

### 2.1.2 Cognitive rehabilitation

The cognitive rehabilitation in PwMS consists in a series of exercises that aims at stimulating different abilities in the patients and at making them learn new techniques that could enhance their memory, their attention and their daily QoL.

One technique to enhance attention, prospective memory and executive function is to give the patients diaries and calendars that they have to use to manage their daily life activities.

The exercises used to rehabilitate short-term and long-term memory in PwMS usually require the patients to memorize some concept, for example by asking them questions after reading a story. Another important exercise is the Story Memory Technique, that works on enhancing the ability to acquire new information into long-term memory, by organizing the information that must be remembered into a story or narrative that is easy to recall.

To improve visuospatial memory, rehabilitation exercises typically involve memorizing a specific pattern and then reproducing it accurately. The 7/24 Spatial-Recall test is a test used to measure and evaluate the visuospatial memory of the patient. It consists in showing to the patient a checkerboard containing a specific pattern of checkers. The checkerboard is placed in front of the patient for 10 seconds. After the initial presentation, the patient has to reproduce the pattern using a blank checkerboard and 10 checkers. The test can use different devices and modalities.

Finally, computer-based training is a common method used to improve memory, cognition, attention, and problem-solving skills [4]. Video games, in particular, are frequently employed for this purpose and will be further explored in section 2.2.

### 2.1.3 Motor and Cognitive rehabilitation

One critical aspect of rehabilitation programs for PwMS is the use of dual-task exercises, which require patients to perform both motor and cognitive tasks simultaneously. Studies have shown the positive effects of dual-task training on PwMS, as well as the challenges they face when attempting to perform these tasks [27, 28].

## 2.2 Videogames and Exergames for Rehabilitation

Twenty articles were studied to describe the State-of-the-Art of videogames and exergames for PwMS rehabilitation. The description of the found games and their characteristics is in Table 2.1. The articles include motor rehabilitation (upper-limb rehabilitation, balance and postural rehabilitation) and cognitive rehabilitation (memory, attention and logic rehabilitation in PwMS in people with Mild Cognitive Impairments (MCI) and in elders).

**Table 2.1:** Videogames and Exergames for Rehabilitation

| Studies | Videogame | VR level of immersion | Target Domain | Description |
|---|---|---|---|---|
| [29, 30] | Khymeia SRL | I | Short-term Motor Learning in PwMS | Desktop-Based. The game includes a collection of cognitive games, including one that displays an object image and prompts the player to spell its name one letter at a time. Another game presents a colored figure and requires the player to select, from a variety of options, a figure with the same color but a different shape. |

| | | | | |
|---|---|---|---|---|
| [31, 32] | Kinect Sports, Kinect Joy Ride, Kinect Adventures | I | Balance and Postural Control in PwMS | Uses Kinect. The games consist in throwing and hitting objects with one hand, receiving and hitting balls with different body parts, overcoming obstacles, dodging objects and imitating specific postures. |
| [33, 34] | RemoviEM | I | Motor rehabilitation in PwMS | Uses Kinect. The game is a serious exergame that consists in helping the patient during the execution of different physical exercises with the use of augmented reality (AR). The exercises consists in making the player move virtual objects or repeat precise movements. |
| [28] | Urban DailyCog | I | Cognitive rehabilitation in PwMS (reaction time, selective attention), Dual Task in MS | Desktop-Based. The game takes place inside a car, in front of a semaphore. In the first part of the game, the player has to press a button when the semaphore turns green. In the second part of the game, the player has to press a button when a particular character exits a shop. In the last part of the game, the player has to press the button if the semaphore turns green and if the character exits the shop. |
| [28] | Driving Simulator Dual Task | I | Cognitive rehabilitation, Dual Task in PwMS | Desktop-Based. The player has to drive in the right lane of the highway and maintain one direction. He has to stay strictly within the lane and maintain a constant speed of 130 km/h. The game is divided in phases. During the last phase, a divided attention task is proposed, where the player has to continue to drive with the same instructions as before and also has to pay attention to the car radio and answer questions about it, such as the number of countries enunciated by the radio program. |
| [35, 36] | BTS-Nirvana | II | Cognitive and motor rehab in PwMS | It reproduces a motivating environment, with interactive stimulation. The interaction with the scenarios, conducted and supported by the therapist, allows improving the motor and cognitive abilities of the patients. In particular, the BTS-Nirvana system consists of two infrared sensors without markers, a projector, a video camera and a large screen. The patient performs the exercises and perceive audio-visual feedback of their interaction with the virtual scenarios, leading to a greater awareness of the movement and the performance. |

| | | | | |
|---|---|---|---|---|
| [37] | Your shape: Light Race, Stack'em up | I | Balance and Falls in PwMS | Kinect-Based. "Your shape" game is a fitness game that contains a series of minigames to improve balance and fitness. In "Light Race" the player has to perform a series of movements according to a luminous circle around their VR figure. In "Stack'em up" the player has to maintain the equilibrium for a long time in a specific position. |
| [38] | Mass Rapid Transit | III | Cognitive impairment in elders | Uses HMD. The game consists in making the player perform the standard procedure of metro transit, from buying a ticket to reaching the desired station. |
| [38] | Looking for a Store | III | Cognitive impairment in elders | Uses HMD. The game consists in finding stores marked on a map within 3 minutes. After two minutes without succeeding, red direction marks would start showing the way to the players. |
| [38] | Kitchen Chef | III | Cognitive impairment in elders | Uses HMD. The game's virtual environment simulates a kitchen equipped with kitchen utensils and appliances such as a flow table, refrigerator, gas stove, etc. The objective of the game is to prepare a meal step-by-step, following the given instructions. The players have to memorize both the recipe and the preparation steps. If the player succeeds, the difficulty of the next dish to prepare will be higher. |
| [38] | Convenience Store Clerk | III | Cognitive impairment in elders | Uses HMD. The objective of the game is to buy a list of item following a shopping list and step-by-step instructions. All the items in the list must be found and then added to the shopping basket in order to complete the checkout. |
| [39] | Rehability | I | Upper-limb rehabilitation in PwMS | Uses Kinect. The game contains a series of minigames with the objective of improving hand-eye coordination, motor coordination, reaction speed and timing and spatial awareness. One of the minigames consists in moving a basket on a table to capture some falling objects and avoiding some others. Another game consists in moving shapes following a trajectory. All the games followed the same principle of moving the arms to manipulate particular objects in different virtual environments. |

| | | | | |
|---|---|---|---|---|
| [40] | | I | Arm and wrist mobility in PwMS | Uses Kinect and linear potentiometers. The game consists in grabbing and manipulating several objects to perform specific tasks, such as grasping cups with two hands and grabbing dishes. The controllers consist in two linear potentiometers that can be manipulated through wrists flexion and extension. |
| [41] | Lumosity: bird watch | I | Visual field in PwMS | Desktop-based. In this game, a letter briefly appears in the center of the screen alongside the shape of a bird and several distractors that appear momentarily in random locations on the screen. The objective is to click on the spot where the bird appeared using the mouse. If the correct spot is selected, a sequence of letters is presented to the player, who must then select the letter that appeared earlier. Correct selections result in the letter being added to a row, spelling out the name of the bird. |
| [41] | Lumosity: Word bubbles | I | Verbal fluency in PwMS | Desktop-Based. The game consists in writing as many words as possible that start with a given syllable. |
| [41] | Lumosity: MonsterGarden | I | Working memory in PwMS | Desktop-Based. In this game, the player must memorize the positions of monsters that appear one at a time on a 4x4 grid and then guide a farmer to avoid them. |
| [41] | Lumosity: ByTheRules | I | Logical reasoning in PwMS | Desktop-Based. In this game, a sequence of shapes of a particular color is presented to the player. The player must determine whether the shapes are correct or incorrect. The objective is to discover the hidden rule that determines whether a shape is correct or not. The rule changes periodically, and the game provides notifications to alert the player of these changes. |
| [41] | Lumosity: PenguinPursuit | I | Spatial Orientation in PwMS | Desktop-Based. In this game, the player must navigate a rotating labyrinth within a given time frame. The buttons to move within the labyrinth also change and rotate, providing additional stimulation to the player's spatial orientation abilities. |

| | | | | |
|---|---|---|---|---|
| [42] | RehaCom | I | Attention and Response Control in chronic stroke patients | Desktop-Based. The game consists in a series of minigames including selecting similar objects and recalling patterns of images and cards. |
| [43] | Dr Kawashima's Brain Training: How Old Is Your Brain? | I | Mathematical abilities, memory and executive functioning in PwMS | Uses Nintendo Switch. The game contains a series of minigames. One of the minigame's objective is to solve, as quickly as possible, 20 to 100 simple mathematical questions that appear on the screen and write the response on the screen. Another minigame's objective is to memorize the position of a series of numbers that appear on the screen for a brief time, then indicate on the screen the position of the numbers starting from the lowest number to the highest. Another minigame's objective is to calculate the time difference between two analog clocks. |
| [44] | Dr Kawashima's Body and Brain Exercises | I | Motor rehabilitation, logic, memory, mathematical abilities and reflexes in PwMS | Uses Kinect. The game contains a series of minigames. The games aim at making the player perform a particular movement or assume a certain pose at a given time. The game "Pizza Catch" consists in remembering the order of pizzas rolling down a conveyor and caching the right ones. The game "Flag Frenzy" consists in rising the correct arm following a voice command. |
| [45] | BioRescue | I | Dual tasking and balance in people with MCI | Desktop-Based. The BioRescue platform contains 1,600 pressure sensors that measure pressure fluctuations in both feet. The games consists in using weight shift to control objects on the screen avoiding obstacles or reaching particular elements. |
| [46] | Juice Making | III | Cognitive and motor rehabilitation in people with MCI | Uses HMD. In this game, the objective is to select a recipe and create a specific juice within a virtual reality environment. The player must memorize a list of fruits, pick them up, and toss them into a container. The container is shaken, and the resulting juice is poured into a cup. |

| | | | | |
|---|---|---|---|---|
| [46] | Fireworks | III | Cognitive and motor rehabilitation in people with MCI | uses HMD. In this game, three numbers are displayed to the player, followed by the same numbers appearing in a random order as fireworks. The objective is for the player to click on the numbers in the same order as they appeared in the fireworks. |
| [46] | Love House | III | Memory rehabilitation in people with MCI | Uses HMD. The game consists in remembering the position of some object inside a house, the objects are then misplaced and the players have to reorganize the object in the correct place. |
| [47] | RAGU | III | Balance, mobility and fatigue rehabilitation in PwMS | Uses HMD. The game is composed by two minigames. The first minigame consists in hitting a ball thrown from different heights with both hand and foot. In the second game, the patients have to avoid a guillotine by bending the body and without moving the feet. |

Most of the articles reviewed utilized non-immersive VR environments and video games. Specifically, the kinect technology was the most commonly used for motor rehabilitation. Out of the 21 games studied, only eight used head-mounted displays and full-immersive VR.

The full-immersive and semi-immersive VR games for upper-limb rehabilitation contained in the review require players to move their arms to reach or manipulate objects. BTS-Nirvana presents a semi-immersive virtual environment that utilizes a projector (Figure 2.1). This system highlights the effects of patients' interactions within the environment. The other games, such as Juice Making and Fireworks, provide players with different objectives to accomplish and different tasks in various environments. It is worth noting that all the full-immersive VR exergames employ graphics aimed at achieving realism, with none utilizing low poly graphics.

To analyze the state-of-the-art of cognitive rehabilitation video games, the research field was expanded to include non-immersive VR systems, and studies that focused on rehabilitating subjects with MCI or elderly populations. This was done because there are limited studies on full-immersive VR games for cognitive rehabilitation in PwMS. The games analyzed in this review consists in making the player memorize patterns and figures, making them solve math questions and recognize similarities and dissimilarities among different objects. Some of the games are centered in stimulating the patients' visual attention and reaction speed.

Several articles included in the review utilized commercial video games, such as Kinect Sport, Kinect Adventures (Figure 2.2) , Kinect Joy Ride, Your Shape, and

**Figure 2.1:** BTS-Nirvana Setup

Dr. Kawashima, for patient rehabilitation. These findings highlight the need for more specialized games to be used in rehabilitation programs. The development of such games is crucial to ensure that patients receive effective and targeted rehabilitation in a gaming context.

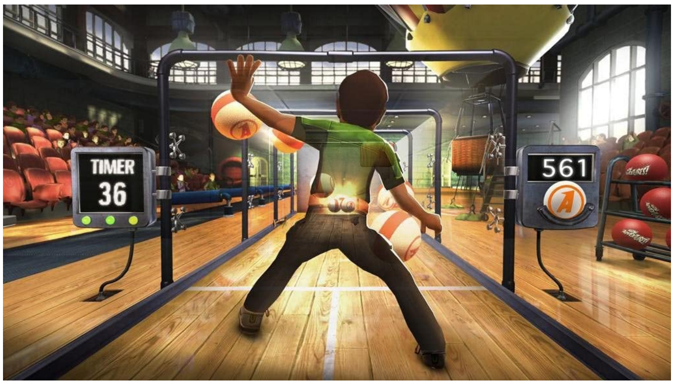


**Figure 2.2:** Kinect Adventures Game

Despite the recognized importance of dual-task rehabilitation, as discussed in subsection 2.1.3, only one study has been found that investigates the use of VR training for dual-task rehabilitation. This study employs two serious games that are desktop-based, namely Urban DailyCog and Driving Simulator Dual Task. The two games use non-immersive VR enviroments.

It is worth noting that the majority of games included in the review were either serious games or simulations. This highlights an opportunity for further development, specifically in transposing the rehabilitative objectives of these games into ones specifically designed for rehabilitation but also with the intention of being played beyond the rehabilitation context. Such an approach aims to create a game that offers a more enjoyable and engaging experience for patients, ultimately enhancing the effectiveness of rehabilitation interventions.

# Chapter 3

# Game design

To create a video-game that could enhance the player's motor and cognitive abilities, while also providing entertainment, a game design process was initiated after reviewing existing video-games used for MS rehabilitation. An effective and well-designed exergame aims at making the game attractive to players, and also effective as a physical exercise.

To reach the flow state of a video game [16], that corresponds to the state of maximum engagement and attractiveness, the game must match the player's abilities and competences. In particular, to reach the flow state, a game should:

- Balance the challenge level to the player's abilities.
- Combine action and awareness.
- Provide clear goals.
- Provide clear feedback.
- Make the player focus on the game's tasks.
- Make the player feel in control over the situation.
- Make the player reduce their feeling of self-consciousness.
- Make the player lose perception of time.
- Be autotelic and give to the player a sense of satisfaction while playing.

Considering exergames, also effectiveness must be taken into accounts, as the balance of intensity of the physical activity required and fitness of the player is crucial for developing an effective exergame [16].

To balance the challenge level to the player's abilities, a biofeedback system was used, that could adapt the difficulty and the challenge of the game in real-time, basing on the player's heart rate value (subsection 3.3.2) [48]. The decision to use heart rate as a measure of exercise intensity and energy expenditure was based on its well-established characteristics as an indirect indicator [17]. The game design process aimed at developing a game that could generate the flow state in the player.

Before proceeding with the actual development of the game using Unity, a storyboard (Figure 3.1, Figure 3.2) was created to outline the game's core features and mechanics.

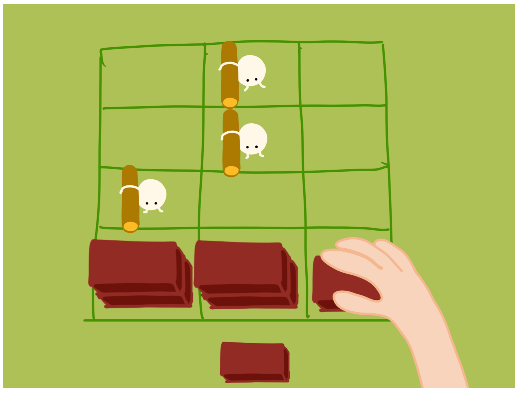

**Figure 3.1:** Phase 1 - Defense Storyboard

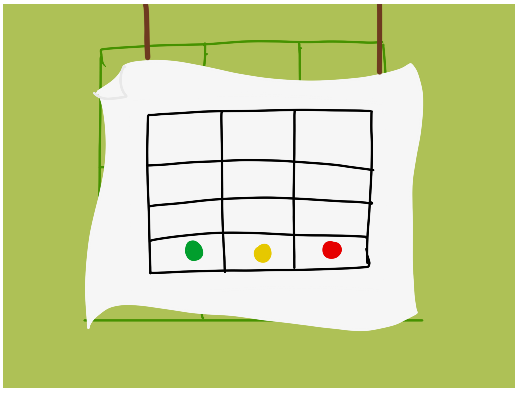

**Figure 3.2:** Phase 3 - Defense Storyboard

## 3.1 Game requirements

To ensure that the video-game was accessible and usable for users with motor impairments, it had to meet several requirements. These include:

- Allowing the player to remain seated during the entire playing session.
- Limiting the allowed actions to pushing buttons and moving the arms in front of the user.

- Allowing the user to take frequent breaks.

In addition to these requirements, the video-game had to meet the aims of the study, which were to:

- Adjust the game difficulty according to the user's biofeedback.
- Challenge the user's cognitive and motor abilities.
- Be entertaining and engaging for the user.

By meeting these requirements, the video-game could be a valuable tool for rehabilitation and improving the quality of life for users with motor impairments.

## 3.2 Game Concept: Castle's Battle VR

The first step in creating the video game involved choosing the appropriate genre that would meet the requirements written above. After careful consideration, the decision was to develop a single-player tower defense game. This type of game requires the player to defend their castle from incoming enemies by strategically placing a set of allies on the battlefield to block their advance. The main action performed by the player is grabbing allies and placing them in the correct position on the battlefield. This gameplay style allows the user to remain seated throughout the session, and there is no need for extensive movement beyond pushing buttons and moving their arms in front of them.

The game is set in a fictional world embroiled in a war, where the player assumes the role of a defender fighting for the attacked side. The player's primary objective is to lead the allies to victory by strategically placing them on the battlefield and issuing commands to troops using the scepter. The title chosen for the game was Castles' Battle VR (Figure 3.3).

## 3.3 Game Mechanics

As a part of the game design process, mechanics were defined as the fundamental building blocks that make up the game. These mechanics were carefully crafted to contribute to the overall gameplay experience and to define the major features of the game.


**Figure 3.3:** Logo of the Game

### 3.3.1 Phases

A crucial game mechanic employed in this game is the division of gameplay into distinct phases. This approach gradually increases the complexity of the game mechanics and allows the player to familiarize themselves with the fundamental movements and logic of the game in a step-by-step fashion. Furthermore, the introduction of multiple phases adds variety to the gameplay and enables a diverse range of rehabilitation exercises at varying difficulty levels. The game comprises four distinct phases, each of which is discussed in detail in section 3.4.

### 3.3.2 Biofeedback-based difficulty

The game mechanics include the ability to adjust the game difficulty based on the player's biofeedback, which is a crucial aspect. To balance the challenge level to the player's abilities, a biofeedback system was used, that could adapt the difficulty and the challenge of the game in real-time, basing on the player's heart rate value. Measuring the heart rate is a good way to produce an indirect indicator of exercise intensity and energy expenditure, that must be balanced to not generate stress and to produce an enjoyable experience [17]. The speed of enemies' advance is the variable that depends on biofeedback and determines the game's difficulty and workload. The enemies move one tile closer to the player each turn, and by adjusting the turn duration, the game automatically becomes more or less difficult. To prevent the player from exploiting this mechanic to keep the game easy, the game pauses if the player's biofeedback level becomes too high. Furthermore, a vignette effect has been implemented to impair vision and motivate the player to achieve a positive state of low biofeedback, resulting in higher difficulty. These changes contribute to the game's balance.

### 3.3.3 Allies placement

One of the fundamental mechanics that constitute the game system and that is present in each phase is the action of grabbing allies and placing them on the battlefield. This action is necessary for the player to defend their castle from the incoming enemies. The allies are initially positioned between the player and the battlefield, and the player is required to pick them up and place them strategically using the game controller. This mechanic serves as a cornerstone of the gameplay as it encourages the player to perform repetitive arm movements to achieve their objectives. Furthermore, this mechanic relies heavily on precision, as the player must place each ally at the exact location on the battlefield.

### 3.3.4 Scepter movement

One of the fundamental game mechanics in the game's action system is the scepter mechanic, which plays a central role in the attack phase of each level. This mechanic involves the player grabbing the scepter and following a precise path, as indicated by a specific arrow displayed in front of them. This mechanism serves to add variety to the gameplay, breaking the monotony of the grabbing action, and encouraging the player to exercise precise control without the pressure of a timer. Moreover, it enables the assessment of the player's accuracy, as the desired path and the executed path can be easily compared.

### 3.3.5 Colors and Shapes

In the pahses 2 and 3 of the game, the allies (Figure 3.4) have two distinct features: their shape and color. This allows for the creation of more complex cognitive exercises.

The feasible shapes for the allies include a circle, square, and triangle while the feasible colors include red, green, blue, and yellow. These features are easily visible and recognizable, making it easy for the player to distinguish between them. This mechanic brings variety to the game and introduces a series of possibilities.

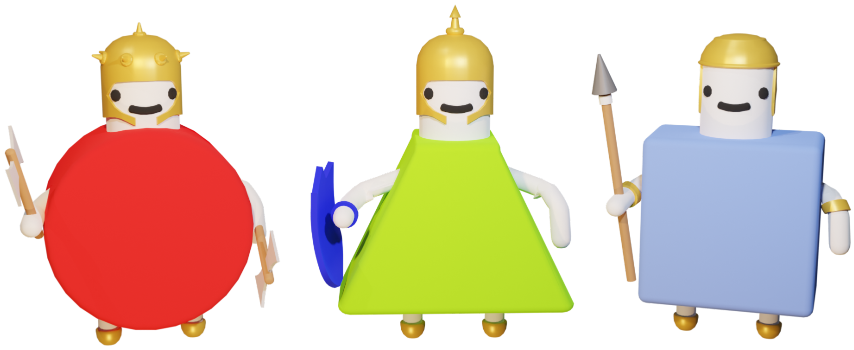

**Figure 3.4:** Allies' models

During phases 2 and 3, the player is required to choose the ally based on different rules. Firstly, they must choose an ally with the same color of the enemy but a different shape. Secondly, they must choose an ally with the same shape of the enemy but a different color. Lastly, in the third phase, the player has to select an ally with both the same shape and color of the enemy. The player must remain focused and concentrated to achieve the objective of the task.

### 3.3.6 Bomb Dropping

The game has a key gameplay element that involves managing the dropping of bombs in phase 4. To introduce a dual task for players, a new version of phase 1 was proposed as a basis for phase 4. Since phase 1 is the easiest and most intuitive phase, it provided a perfect foundation for the new task. The addition to this phase involves a helicopter carrying a color-bomb that flies over the enemy castle. The player must press a button to drop the bomb at the right moment, which requires paying close attention to the audio cues. Specifically, a voice pronounces colors and when the enunciated color matches the color of the bomb, the player must drop the bomb by pressing a button. This mechanic is crucial to the game and adds a new layer of complexity for players to enjoy.

### 3.3.7 Limited and Unlimited Time

The game offers two distinct modes of play: one with a limited time for each phase and another with an unlimited time for each phase. These modes are essential for executing experiments and evaluating the engagement levels of patients as they decide when to end each phase of the game. An implication of this mechanic is that players require visible feedback on the time remaining in the first mode, which will be discussed in the feedback section below (section 3.7) . Additionally, in the second mode, players must have the ability to stop the phases at any time, which is achieved by adding a button to the scene.

### 3.3.8 Scoring System

The game's scoring system is designed to be forgiving and ensure that players can always continue, even if their performance is suboptimal. The game does not have a "losing" condition, and players must complete all four phases to finish the game. The scoring system is based on a four-star rating (Figure 3.5), with each phase contributing to the final score, for a maximum of four stars. The score for each phase is determined by the number of defeated $\mathrm{E_d}$ and the number of total enemies $\mathrm{E_{tot}}$. Specifically:

- if $E_d > E_{tot} * \frac{2}{3}$, then one star is added
- if $E_d > E_{tot} * \frac{1}{3}$, then half star is added
- otherwise the score is zero stars

In addition, at the end of each phase, the player receives feedback from an NPC based on their performance, with different dialogues for varying levels of mistakes. The tone of these conversations is supportive and uplifting to encourage the user to do their best and not feel discouraged.

This scoring system system ensures that the player is never completely defeated, but can always strive to improve their performance in subsequent attempts.

## 3.4 Phases Description

An important design choice made in the game was to divide it into several phases, each with its own unique features and gameplay mechanics. This allows for a


**Figure 3.5:** Game Final Score

variety of rehabilitation exercises to be performed during a single play session. The first, second, and third phases follow the same structure:

- The first part requires the player to defend their castle against incoming enemies.
- A break follows this part.
- The second part requires the player to grab a scepter and move it through the air along a path indicated by a 3D arrow. The player must focus on being precise and not going out of bounds of the arrow. Successfully completing the path with the scepter triggers a special attack (Figure 3.6, Figure 3.7) against the enemy castle.
- Another break follows this part.

In contrast, the final phase of the game focuses on dual-tasking and is structured as follows:

**Figure 3.6:** Phase 1 - Special Attack


**Figure 3.7:** Phase 3 - Special Attack

- A single part requires the player to both defend their castle and attack the enemy castle simultaneously.

- A break follows this part.

By breaking up the gameplay into distinct phases, the game offers a well-rounded rehabilitation experience that challenges players to use a variety of cognitive and motor skills. The inclusion of dual-tasking in the final phase provides an additional layer of challenge for players.

## 3.4.1 Phase 1

### Defense

In the first phase of the game, the main objective is to introduce the player to the mechanics of grabbing and placing allies on the battlefield. The player is tasked with using bricks to build a barrier to protect the castle from incoming enemies (Figure 3.8) . To succeed in this phase, the player must work quickly to stop all the enemies, while also paying attention to which column each enemy is approaching from and placing the bricks in the correct column accordingly.

During each turn, a random number of enemies will spawn on random columns, requiring the player to stay alert and constantly monitor the battlefield to quickly respond with their brick placement.

By emphasizing quick reflexes, strategic thinking, and attention to detail, the first phase of the game sets the foundation for the challenges to come, ensuring that the player is prepared for the increasingly complex tasks that await them.

### Attack

In this phase, the player's objective is to skillfully maneuver a scepter through the air, along a 3D arrow indicating the path to follow. Precise movements are crucial to avoid straying from the designated path. The arrow guides the player horizontally, from left to right (Figure 3.9). Upon successfully completing the path, a visually impressive action takes place, wherein a massive hammer strikes the enemy castle, causing damage.

### Medical objective

The upper-limb rehabilitation program proposed in the defense phase of each game consists of manipulating objects and placing them in specific locations on the battlefield. This task focuses on developing the player's coordination and precision skills. In Phase 1, the defense phase requires the player to perform each movement as quickly as possible to ensure effective defense of their castle.

In the attack phase of each phase, the upper-limb rehabilitation program introduces a different movement requiring the player to perform the task with precision.


**Figure 3.8:** Phase 1 - Defense

**Figure 3.9:** Phase 1 - Attack

### 3.4.2 Phase 2

#### Defense

The second phase introduces to the player a new kind of enemy, which characteristic is to have a particular shape and a particular color.

In the second phase of the game, the battlefield consists of a single column where a random enemy with a unique shape and color appears. The player must select one of five different allies and place it on the battlefield to combat the enemy (Figure 3.10) . The phase is divided into two steps.

During the first step, the player must choose an ally with the same color as the enemy but a different shape. Time is limited, as the enemy slowly advances toward the player. If the player selects the correct ally, the enemy is defeated. However, if the player fails to make the correct choice or takes too long, the enemy will beat the ally or advance further. Once the previous enemy is defeated or has advanced too far, a new enemy will appear.

In the second step, the player must choose an ally with the same shape as the enemy but a different color.

This task requires the player to carefully observe the enemy's shape and color and quickly select the correct ally. By introducing these challenging and dynamic tasks, the second phase adds a layer of complexity and excitement to the game, testing the player's memory, observation, and quick thinking skills.

#### Attack

In this phase, the player is required to grab the scepter and follow a circular arrow (Figure 3.11) , similar to phase 1. The objective is to be precise and avoid going out of bounds of the arrow. Once the player completes the path, a special action is triggered, where a big bomb falls and explodes on the enemy castle, causing damage.

#### Medical Objective

In addition to the upper-limb rehabilitation program, this task incorporates an aspect of cognitive rehabilitation focused on attention and response control. This phase utilizes game mechanics similar to those seen in Rehacom and Kymeia [29, 42], where the player must choose objects based on their visual characteristics and similarity.

### 3.4.3 Phase 3

#### Defense

In the third phase, the battlefield is composed of multiple columns and a big billboard. The billboard shows a specific pattern of shapes and color that the player must follow to place the allies on the battlefield. The player must quickly respond by placing allies on the columns, following the billboard pattern. Each column of the battlefield will display a random enemy with a unique shape and color after a set amount of time. The player must cover all the columns while simultaneously paying attention to the billboard to ensure that the allies are placed correctly (Figure 3.12) .

By introducing this unique challenge, the third phase adds an exciting new dimension to the game, testing the player's agility, strategic thinking, and ability to respond to rapidly changing situations.


**Figure 3.10:** Phase 2 - Defense

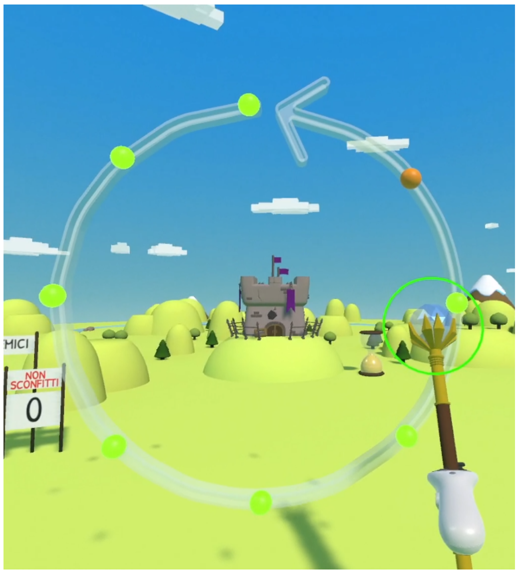


**Figure 3.11:** Phase 2 - Attack

### Attack

During this phase, the player is required to grab the scepter and navigate along a lightning-shaped arrow (Figure 3.13) , following the same concept as in phase 1. Upon completion of the path, a special action is triggered, depicting a massive cloud with a lightning bolt striking the enemy castle, causing damage.

### Medical objective

In addition to the upper-limb rehabilitation program, this task incorporates an aspect of cognitive rehabilitation focused on attention and response control. This phase utilizes game mechanics similar to those seen in Rehacom and Kymeia [29, 42], where the player must choose objects based on their visual characteristics and similarity. By requiring the placement of multiple objects, this phase adds a level of difficulty to the previous phase. Another challenge in this phase is the difference between the shapes shown on the billboard and the 3D allies that the player must select, increasing the complexity level of the task.

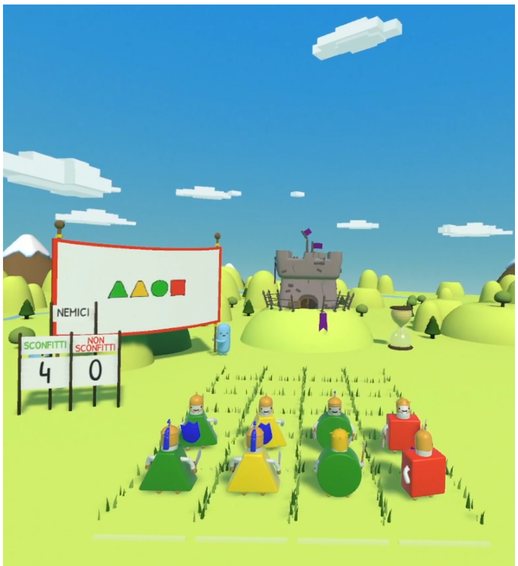


**Figure 3.12:** Phase 3 - Defense

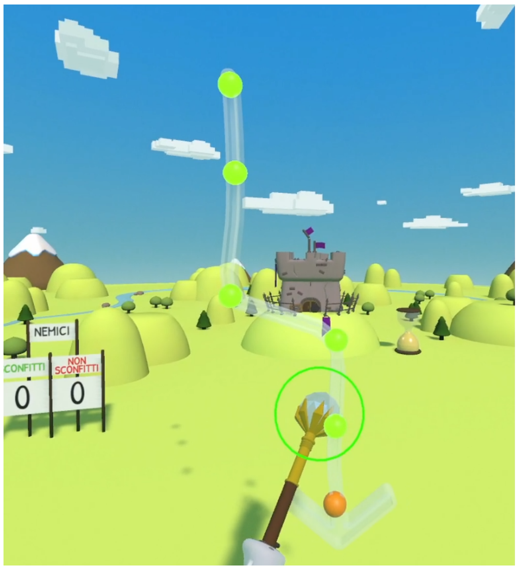


**Figure 3.13:** Phase 3 - Attack

### 3.4.4 Phase 4

#### Defense and Attack

The fourth phase resumes the functioning and the structure of the first one, but introduces an additional task that requires the player's attention in addition to placing bricks in front of enemies. As the player places bricks on the battlefield, a helicopter flies overhead, producing colored bombs that must be dropped on the enemy castle (Figure 3.14) . The player must listen for a voice announcing a specific color and quickly press a button on their controller to drop the bomb at the right moment.

Successfully completing this phase requires the player to maintain focus on both the battlefield and the helicopter, while also being quick and efficient with their brick placement and bomb dropping. This challenge tests the player's multitasking abilities and adds an extra layer of excitement and complexity to the game.

#### Medical Objective

This phase proposes a dual-task exercise, based on the Urban DailyCog game [28]. In particular, this task requires a good reaction time and selective attention as well as motor skills to press the button while placing bricks on the battlefield.

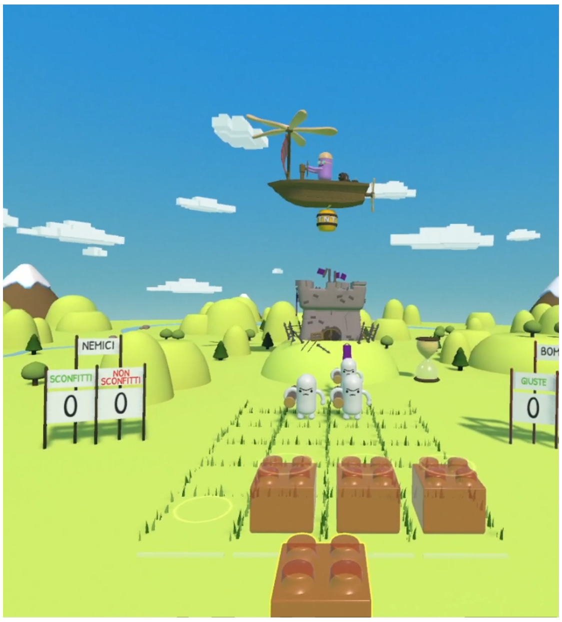


**Figure 3.14:** Phase 4

## 3.5 Game Environment

The game's style is characterized by low-poly graphics and a cartoonish aesthetic (Figure 3.15) . The aim was to create a light-hearted and calming world that would appeal to players. To achieve this, a colorful and cheerful environment was created, with pastel hues dominating the palette. The shapes used in the game are simple and rounded, with the landscape featuring a series of mountains, hills, trees, and a river. The enemy castle is situated in front of the player, while the ally castle is positioned behind, providing an interesting surprise for players who explore the game's environment. In the sky, small clouds rotate slowly around the center of the world, imbuing the scene with a sense of movement.

### 3.5.1 The battle field

The battlefield is arranged in rows and columns, with allies placed on the first row of each column and enemies advancing from the last row of each column. When enemies reach allies, two outcomes are possible: the ally defeats the enemy, or the enemy defeats the ally and moves toward the castle. In the absence of allies, the enemy will advance towards the castle. The battlefield is situated in front of the

**Figure 3.15:** Game environment

player, and the enemy castle is visible in the background.

### 3.5.2 The enemy castle

As players progress through the game, the model of the enemy castle undergoes changes. Specifically, after each scepter phase, a special attack is launched against the enemy castle, causing damage to its structure. Over time, the castle becomes increasingly wrecked, displaying visible signs of the ongoing battle. By the end of the game, the castle is completely destroyed (Figure 3.16) , serving as a clear indication to the player that victory has been achieved.

## 3.6 Characters

All the game characters share a common structure, consisting of a cylindrical and rounded body with long, thin arms and legs, dot eyes, and a simple line for a mouth. While a variety of characters have been modeled and animated, some are purely decorative and do not interact with the gameplay. These characters serve to add variety and fun to the scene.

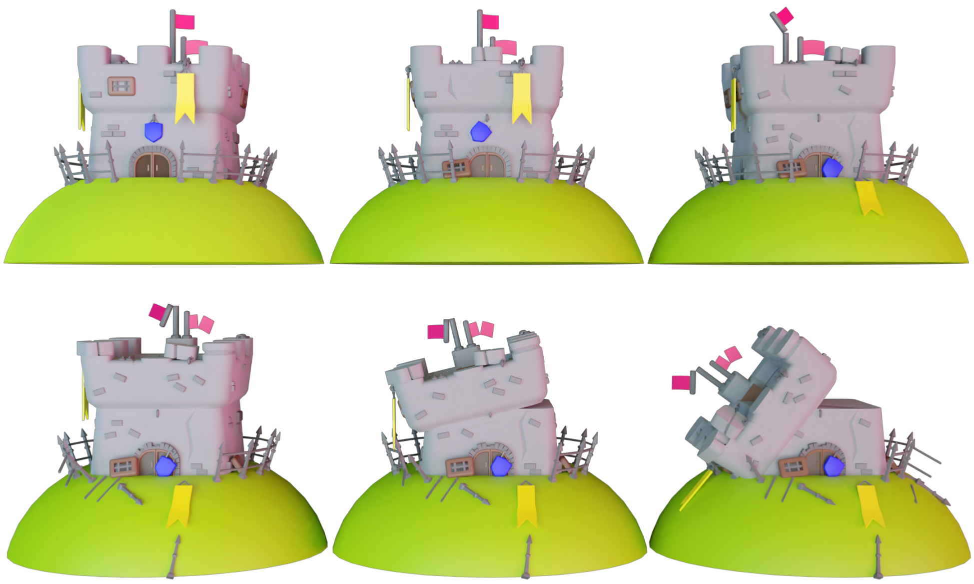

**Figure 3.16:** Castle's 3D Model evolution

In Phase 1, a special hammer attack is executed by a tower of small characters, a pink pilot is in charge of the helicopter (Figure 3.17) , and two characters hold up the billboards.

Undoubtedly, the most significant game characters are those that take part in the battles and the guide NPC. These characters possess distinctive attributes and fulfill specific roles within the game.

### 3.6.1 NPC guide

The Guide (Figure 3.18) is the first NPC to appear in the game and serves the purpose of providing the player with explanations of the various phases, as well as offering vocal feedback on their performance. To help make the instructions clearer, a series of drawings are presented alongside the Guide's speech, visually demonstrating what the player will need to do in the upcoming phase. Once the Guide's speech concludes, the player is presented with the option to either replay the speech or begin playing the game.

**Figure 3.17:** Helicopter NPC 3D model

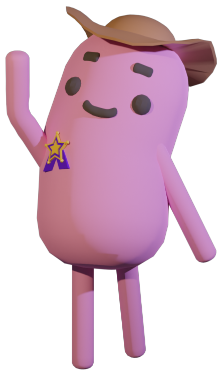

**Figure 3.18:** Guide NPC 3D model

### 3.6.2 Log enemy NPC

The NPCs encountered in the first phase (Figure 3.19) are identified by their use of a log to demolish any bricks that obstruct their path. They are equipped with special animations to swiftly tear down the bricks. Although each NPC can be stopped with just one brick, the brick will also be destroyed in the process.

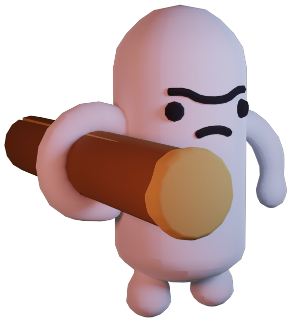

**Figure 3.19:** Log enemy NPC 3D model

### 3.6.3 Shape NPC

The NPCs encountered in phase 2 and 3 possess distinctive body shapes and colors, while also adding variety to the game with their randomly assigned weapons and armor. The weapons include swords (Figure 3.20), axes, spears, and shields. The NPCs have different unique attack animation basing on the equipment they are provided.

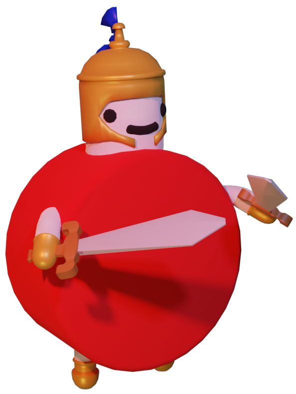

**Figure 3.20:** Shape NPC 3D model

## 3.7 Feedback

The game offers the user immediate and explicit feedback after each action taken, ensuring that the game's status is easily understandable and visible through both visual and auditory cues.

### 3.7.1 Outline

To help the player easily identify the status of the objects, an outline system was implemented in the game.

When the player hovers the controllers over the objects, a yellow outline appears to indicate that they can be grabbed.

After the objects are grabbed, a green outline appears when the player moves them to the designated area where they can be placed on the battlefield.

For the scepter object, the outline system has an additional function. When the scepter is being moved along the path shown by the 3D arrow, the outline will turn green to indicate that it is correctly following the arrow's shape. However, if the scepter moves out of bounds, the outline will turn red to alert the player.

### 3.7.2 Battlefield feedback

Right after each column of the battlefield a semi-transparent bar is placed whose color changes to red when an enemy crosses it (Figure 3.21) . It is used to clearly inform the player that a mistake has been made and that an enemy has not been stopped by an ally. An error sound is reproduced to add importance to what happened.

A glowing yellow circle is used to signal the spots where is possible to release the allies. The circle disappears after an ally is correctly placed on the corresponding spot, to signal that is no longer possible to release other allies on the same spot. In the first and last phase, where is possible to pile bricks on the same spot of the column, the yellow circle simply appears on top on the placed brick, to inform the player that is possible to insert another brick on top of it.

### 3.7.3 Vignette

To ensure that the player is aware of the increasing difficulty level and rising heart rate, a black vignette effect has been incorporated into the game. The intensity of


**Figure 3.21:** Red Bar Feedback

the vignette effect gradually increases as the player's heart rate rises, providing a clear visual cue to the user. This is important because without such feedback, the player may intentionally maintain a high heart rate to keep the game easier, which would not be beneficial for their rehabilitation. By compromising the player's visual field, the vignette effect encourages them to return to a positive state and maintain their progress.

### 3.7.4 Sound feedback

An error sound is reproduced in two cases:

- when an enemy has not been stopped
- when the player presses the button to drop the bomb and the color pronounced by the voice is not the same as the color of the bomb

Other sounds signal when an object is grabbed and when it is released.

## 3.8 Menu

Upon starting the game, a menu (Figure 3.22) appears providing options for the player to customize their game session. Here the player can set de difficulty of the game or proceed to the advanced settings (Figure 3.23) Two game modes are available for the player to choose from: limited time mode, where each game phase automatically ends after a selected amount of time, or infinite time mode, where the player must actively end each phase to progress to the next.

An hourglass appears in the game scene, displaying the time remaining for the current game phase. In infinite time mode, a button is available in the game scene that allows the player to manually end the current phase when pressed.

Additionally, the player can adjust the size of the battlefield by selecting the number of columns for game phases 1, 3, and 4. Increasing the number of columns leads to higher difficulty.

Finally, the player can also customize the frequency with which colors are announced during phase 4 by adjusting the settings in the menu.

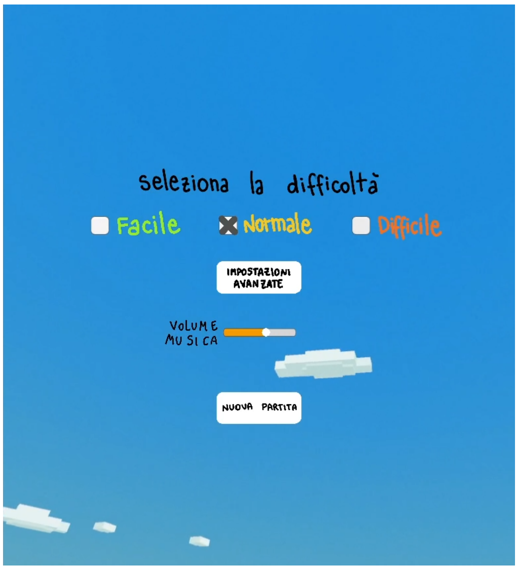


**Figure 3.22:** Menu - Simple

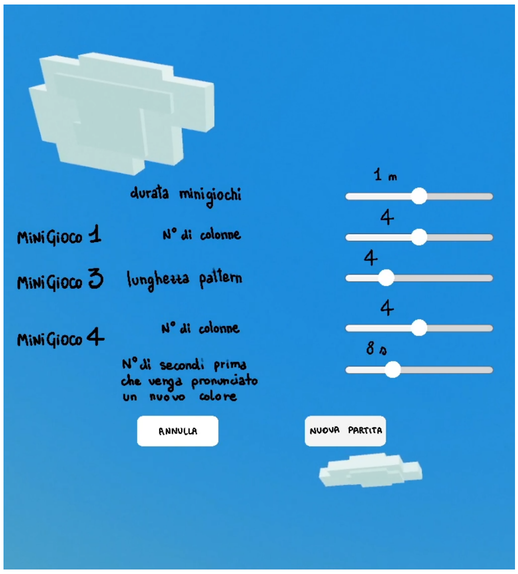


**Figure 3.23:** Menu - Advanced

## 3.9 UI elements

In order to maintain the sense of immersion provided by the HMD and 3D world, the decision was made to completely eliminate the use of non-diegetic UI elements. However, certain information still needed to be conveyed to the player, including the pattern in phase 3, the number of enemies defeated and not defeated for each phase, and the final score. To accomplish this, a series of 3D models, specifically billboards, were utilized to display the relevant information.

Additionally, it was important to display visual aids to explain the various phases and integrate the guide NPC's speech. To achieve this, a 2D image was created to represent a comic cloud that appears above the guide NPC's head, displaying what it is saying (Figure 3.24).

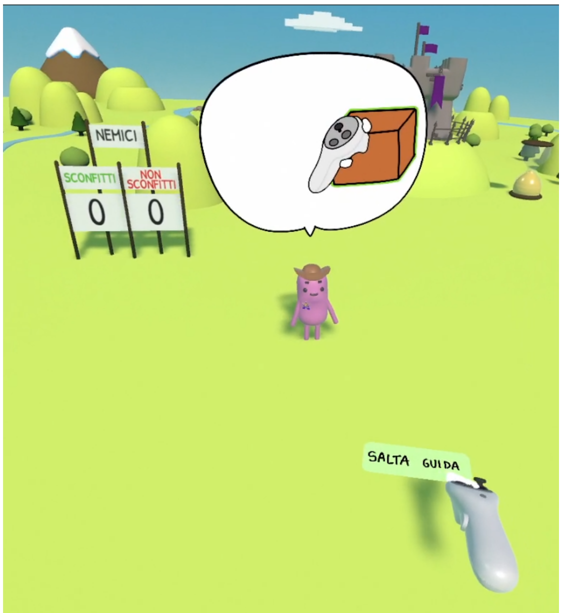


**Figure 3.24:** NPC guide - cloud

## 3.10 Replay value

An important objective of the game was to provide high replay value. For a rehabilitation program, it was crucial to encourage players to engage with the game as much as possible, and to repeat the experience many times over. To achieve this, all battle variables are randomized, including enemy spawns, ensuring that each battle is unique and different from the previous one. Furthermore, to accommodate players as they progress, the features of the battlefield and the phases can be adjusted to add difficulty, as described in the menu section.

## 3.11 Loops and Castle's Battle VR

After developing Castle's Battle VR, another exergame, named Loops, was developed. The decision was to create a second exergame inspired by the scepter phase of Castle's Battle VR.

A series of changes were done to the objects in the environment:

- the scepter was replaced with a sphere.
- the path to follow was replaced with a fixed and semi-transparent torus.

The objective of the game is to maneuver the sphere into the torus and maintain it within the torus's shape by completing a designated number of laps, as indicated on a scoreboard. To succeed in the game, players must carefully maneuver the sphere without colliding with the walls of the torus. When a collision occurs, the controller provides haptic feedback by vibrating, and the sphere changes color to red, providing additional visual feedback.

The game consists of two phases. In the first phase, the size of the ball is controlled through biofeedback. Specifically, when the player's respiratory frequency increases, the size of the ball also increases. Therefore, players must maintain a low respiratory frequency to keep the sphere's diameter small, making it easier to avoid collisions.

In the second phase, the size of the ball changes randomly, simulating the effect of the biofeedback. The players do not know when biofeedback is in use, making it necessary for them to maintain a low respiratory frequency throughout both phases.

# Chapter 4

# Technologies

To model and animate the various game characters, objects and the 3D world, a 3D modelling tool was necessary. All the 3D models used in the game were created and animated in Blender 2.93.0. The game engine used to develop the game was Unity and the coding language was C# for Unity. The Virtual Reality headset chosen for the project was Oculus Quest 2 and to support Oculus Quest 2 and be able to develop a full-immersive VR experience as needed, OpenXR plugin was used. To control the heart rate of the patients and consequentially adapt the game difficulty, a heart rate monitor chest strap Polar H10 was used. To connect the Polar strap and analyze its data to produce a biofeedback the BLE code developed by IIT was integrated inside the game.

## 4.1 Blender

To model the game world, the characters and all the objects in game, Blender 2.93.0 was used (Figure 4.1). Blender is a royalty-free Software for 3D computer graphics, its was first released in 1994 but since 2002 the Blender Foundation decided to release the Blender source code. The software became free and open-source. Blender is also widely used, making it the best choice for the project. Blender's features include 3D modelling, sculpting, animation, rendering, video editing, texturing, digital drawing, rigging, skinning, particle simulation, smoke simulation, fluid simulation, soft body simulation, raster graphics editing, match moving, UV mapping, motion graphics and compositing. Blender's features allow to create and animate professional and detailed 3D models. For the project, UV mapping and texturing were also used. The version used was 2.93 LTS (support until June 2023).

**Figure 4.1:** Blender Logo

## 4.2 Unity

The game engine chosen to develop the game was Unity (Figure 4.2). Unity is a free and powerful game engine developed by Unity Technologies and released in 2005. The engine is cross platform as it supports a variety of console, mobile, desktop and virtual reality platforms. Unity allows developers to create professional and complex 2D and 3D games and other interactive experiences such as simulations, animations and Virtual Reality an Augmented Reality (AR) experiences. Unity supports various programming languages including JavaScript, C#, and Boo. It is a very popular and widely used game engine, its documentation is extremely clear and well-organized. Moreover, its Asset Store allows to find useful tools to simplify the development of new projects. In particular, two packages from Unity Asset Store were imported and used:

- Cartoon FX Remaster Free: for special particle effects and visual effects
- Simple Sky - Cartoon assets: for the skybox

**Figure 4.2:** Unity Logo

## 4.3 OpenXR

To support Oculus Quest 2 and be able to create a VR interactive experience OpenXR plugin (Figure 4.3) was imported and used in the project. OpenXR is an open, royalty-free plugin created by the Khronos Group that provides developers with a unified and easy-to-use interface to support AR and VR platforms and devices. OpenXR supports a wide range of hardware devices, including head-mounted displays (Oculus Quest is supported), motion controllers, and other input devices. To access and interact with these devices, OpenXR provides a consistent set of Application Programming Interfaces (APIs).

**Figure 4.3:** OpenXR Logo

## 4.4 Oculus Quest 2

The game uses Oculus Quest 2 (Figure 4.4) as the headset for the VR experience. The Oculus Quest 2 is a wireless virtual reality (VR) headset developed by Meta Platforms. It was released in 2020 as the successor to the original Oculus Quest. Quest 2 features two built-in OLED displays with a combined resolution of 1832 x 1920 pixels per eye, providing a high level of visual fidelity and detail. It also has a refresh rate of up to 90Hz, which helps to reduce motion blur and improve the overall smoothness of the VR experience.

**Figure 4.4:** Oculus Logo

## 4.5 Biofeedback

The biofeedback system has been implemented using a Polar H10 strap and a BLE system to connect the strap and read the values it produces.

### 4.5.1 Bluetooth Low Energy (BLE)

Bluetooth Low Energy (BLE) is a system that manages the connection and the retrieving of respiratory and cardio feedback from users. The biofeedback was based on the individuals' cardiac autonomic state after a preliminary calibration based on slow breathing (at a rate perceived by the users as "comfortable") [49]. The BLE systems uses a Polar H10 strap to retrieve the necessary information.

### 4.5.2 Polar H10

The Polar H10 (Figure 4.5) is a heart rate monitor released by Polar Electro Oy in 2017. It is commonly used to track heart rate during exercise and other physical activities. It is a chest strap heart rate monitor that uses Bluetooth and ANT+ technology to connect to a wide range of devices, including smartphones, fitness trackers, and gym equipment. The H10 is known for its accuracy and reliability, as it provides precise heart rate data.

**Figure 4.5:** Polar Logo

# Chapter 5

# Implementation

To develop the game, a unified scene was created using Unity. To correctly play the game an external person is required to manage the biofeedback sensors and to set the game variables.Proper gameplay requires the presence of an external individual who can oversee the biofeedback sensors and adjust the game's variables. At the start of the game, the player is required to wear the Polar stripe and an external person must begin the calibration of the biofeedback. The calibration process takes two minutes, after which the game can commence. During calibration, the player is already immersed in the game world and can observe the game logo alongside a percentage indicator that shows the progress of the biofeedback calibration. After completing the calibration process, the external person can proceed to launch the game and configure the settings outlined in section 3.8. Once all the necessary variables have been adjusted, the game can commence in earnest.

## 5.1 Class GameManager

`GameManager` Class is designed to be the core of the program, as it is the class that manages the correct spawn of the various elements in the environment and that stores the status of the game. This script is attached to an empty object in the main scene. It contains a public variable `gamePhase` that indicates what minigame is currently running. The flow of the game consists in a series of actions performed by the `GameManager` class. In particular, for each phase, the class subsequentially performs the following steps:

- The routine to make the guide NPC start their speech about the next phase is called.

- When the player presses the button to start the new minigame, the correct environment is spawned.
- Enemies and allies are spawned.
- If the game modality is timer-based, the timer is started.
- When the timer is over (or when the player presses "stop game" in infinite time game modality), the remaining enemies are killed and the environment is cleared.
- The score for the phase is calculated.

### 5.1.1 Turn management

An important feature of this class is the management of game turns. Each turn, the enemies advance of a tile towards the user. The objects in game must know when they can proceed to the next turn. The management of game turns has been implemented with a public boolean variable `turn` and a variable `turnDuration`. `turnDuration` depends from the BLE biofeedback and defines the duration of each turn. The value of the variable turn changes each `turnDuration` seconds. The objects in the scene check this variable: when the variable changes, they can execute the actions of their turn.

### 5.1.2 Spawn of the environments

Another important feature of the `GameManager` class is the spawn of the battle environment for each phase. Each phase has its own peculiar environment, made up by a defined number of battle field columns, a defined number of places where the allies spawn and other additional objects. For the game phase 1, the game phase 3 and the game phase 4 it is necessary to spawn a battle field whose columns' number is defined with three different variables, one for each phase. `GameManager` class uses a prefab of a single column whose 3D model is designed to be modular: when two prefabs are spawned adjacent, their external borders overlap without interpenetration. It is necessary to spawn the right number of columns and to place them correctly on the ground in a way that the battle field is always centered in the scene. To do so, a function checks if the number of columns to spawn is even or odd and changes the position of the columns accordingly.

For the game phase 2 it is necessary to spawn a single column and a number of allies defined with a variable. For this reason the logic implemented follows the one described above, but applies it to the empties that manage the spawn of the allies.

## 5.2 Spawn of enemies and allies

Allies and enemies spawn in precise positions in the game scene, where different empty objects are placed. The class `SpawnersManager` manages the correct spawn of allies and enemies in the scene. It uses the variable `gamePhase` of `GameManager` class to know what algorithm must be used for the spawn.

### 5.2.1 Spawn of the phase 1 and phase 4 enemies

In the game phase 1 and in the game phase 4 a random number of enemies spawns in alternate turns. The class checks the value of the variable turn in the `GameManager` class and spawns a random number of enemies when the variable becomes true. Calling N the number of enemies to spawn, C the number of columns of the battle field and L the number of enemies left to be spawned:

$$0 < N < \min(C, L)$$

To be sure that N is not zero two times in a row, `SpawnersManager` stores the last value of N and, if zero, sets the lower range limit to 1.

$$1 < N < \min(C, L)$$

Without this logic, it could be possible to have long periods of time without enemies spawning and that must be avoided.

### 5.2.2 Spawn of the phase 2 enemies and allies

For the game phase 2 a single enemy is spawned, choosing its color and shape randomly. It is important to spawn a series of allies that allows the user to win the minigame.

For the first part of the game phase, an ally of same color and different shape of the enemy is spawned (the one to be chosen to win), then an ally of same color and same shape of the enemy, then for the remaining allies random shapes and random colors are chosen. Their order of spawn is also random, for this reason the correct ally is never in the same place.

For the second part of the game phase, an ally of same shape and different color of the enemy is spawned (the one to be chosen to win), then an ally of same color and same shape of the enemy, then for the remaining allies random shapes and random colors are chosen. Their order of spawn is also random, for this reason the correct ally is never in the same place.

### 5.2.3 Spawn of the phase 3 enemies and allies

In phase three, it was essential to generate a pattern of a variable length that did not repeat any objects. This was done to prevent patient confusion and ensure a diverse pattern. To accomplish this, a pattern is generated and displayed on a billboard as a series of sprites. As the enemies advance, the player must correctly place the allies on the battlefield to match the incoming enemies and the pattern.

The shapes and colors of the allies are not random, as they must correspond with the enemies. Instead, they are spawned in a different sequence.

## 5.3 Enemies behaviour

The enemies in the game spawn in a column of the battlefield and move one tile closer to the player each turn. To manage the movement of the enemies a `NavMesh` has been baked and a `NavMesh Agent` component has been added to the enemies' `GameObjects`. Their target destination changes to match the position of the next tile. When the enemies reach the second-to-last tile, the battle with the ally is supposed to commence. For this to happen, allies must be positioned on the last tile of the battlefield, counted from the enemy castle to the player. If an ally has not been placed in the tile, the battle does not initiate, and the enemy continues towards the player before eventually disappearing. However, if an ally has been placed, the battle commences, with the enemy either winning and surviving (if the ally is incorrect) or losing and dying.

The characteristics of shape and color for the shape-type enemies have been controlled through a script named `NPC_type`. This script is also responsible for altering the material color of the body in line with the assigned color. In determining the outcome of a battle, both the ally and the enemy variables for `shape` and `color` are compared.

## 5.4 NavMesh Agents

The game utilizes the `NavMesh Agent` component to control the movement of enemies, guide NPCs, and the helicopter. Two distinct `NavMesh` setups have been created, as the helicopter operates differently from the other objects by flying in the sky instead of moving on the ground.

The guide NPC moves between two different locations. Specifically, it positions itself in front of the player during speeches and returns to a spot adjacent to the battlefield during gameplay phases.

## 5.5 Scepter path

To enable the attack phase of the game, a system was developed to detect when the player's scepter followed the desired path of an arrow. This was accomplished by implementing three `BoxColliders` as triggers: one at the beginning of the arrow, one at the end, and one in the middle. The middle trigger was necessary to prevent the scepter from being able to complete the path by following the arrow in reverse.

Once the scepter crosses all three triggers, a routine is called to check if the path has been completed, and to inform the `GameManager` class that the attack phase has ended. Additionally, to ensure that the scepter remains within the shape of the arrow, another trigger was used that follows the arrow's shape, and which the scepter must remain inside.

## 5.6 Canvases

To generate real-time changing textures for various objects in the scene, a set of canvases were employed. non-diegetic UI elements were avoided by creating 3D models that could visually convey the required information. For instance, a series of billboards were utilized to display the final score, number of enemies defeated and not defeated, and the pattern for phase 3. To accomplish this, a camera capable of producing a render texture was utilized, enabling the content of the billboards to be altered in real-time.

## 5.7 Biofeedback management

To control the game difficulty over time, the decision was to have a variable that could be changed at any time and that could control the speed of advance of the enemies. To do so, the variable `turnDuration` is used. This variable is directly connected to the biofeedback value.

The value of `turnDuration` also affects the intensity of the vignette effect, which is used to signal to the player that the sensor is detecting an increasing respiratory frequency. It is important to alert the player that their heart rate is rising, so they can take action to lower it by relaxing and breathing more deeply and slowly.

The variable `bf` represents the biofeedback value, which is calculated every second and ranges from 0 to 6. To ensure accurate calibration of the system, the BLE code has been adjusted to match the project's specific requirements. The value of `bf` is calculated over a 2-minute calibration period, during which the average heart rate is determined using a sampling rate of one second. To avoid any external influence on the heart rate value, the player is asked to remain seated and silent during the calibration process.

After calibration, the value of `bf` is determined using the player's current heart rate (`hrate`) and the average heart rate (`mHR`), according to the following code line:

```
bf = (int)Mathf.Lerp(6,0,Mathf.InverseLerp((float)(mHR - 15f),
    (float)(mHR + 30f), hrate.Last));
```

This enables the game to quickly detect if the player's heart rate is increasing too much and adjust the game's difficulty accordingly.

A biofeedback value greater than 3 indicates a normal respiratory frequency, but the game only disregards variations in biofeedback when the value is greater than 4. This approach ensures that the game difficulty decreases more smoothly in response to biofeedback. When the biofeedback value falls between 1 and 4, the turn duration variable, represented by the variable `TDuration` in the equation, follows this mathematical rule:

$$\texttt{TDuration} = \texttt{TDuration}_{\texttt{MAX}} - \frac{\texttt{TDuration}_{\texttt{MAX}} - \texttt{TDuration}_{\texttt{MIN}}}{3} \cdot (\texttt{bf} - 1)$$

When the variable `bf` reaches a value of 0, the game halts as it signifies that the player needs to reduce their respiratory frequency and their anxiety levels are escalating. A voice signal to the player that the game has stopped and that it is necessary to breath with a lower frequency and calm down. Therefore, the game completely pauses until the value of `bf` increases once again.

## 5.8 Data Collection

The data collected during gameplay will be analyzed in the future to evaluate player performance and track progress over time. Specifically, four distinct files are generated after each play:

- `ScepterPath.json`: This file contains the trajectory of the scepter during the attack phases.
- `Objects.json`: This file contains information about every object that was grabbed during the game.
- `General.json`: This file contains general information about the game.
- `Bombs,.json`: This file contains information about the last phase of the game, in particular about the dropped bombs.

### 5.8.1 Scepter Path

The `ScepterPath.json` file contains vital information to retrieve the trajectory of the scepter during the attack phases. These phases were specifically designed to evaluate the player's precision in following a predetermined path with their hands. Therefore, it is crucial to have access to the actual trajectory followed by the player and compare it with the desired one.

Every 0.1 seconds, the position and rotation of the scepter are recorded in the file, along with a timestamp, a Boolean value indicating if the scepter was inside the path of the arrow, and a measure of the distance from the desired path (Figure 5.1) .

### 5.8.2 Objects

The `Objects.json` file contains information about every object grabbed by the player during gameplay. For each object, the file records the elapsed time from

```
POS: "( 0,1946102 , 0,4242575 , -1,623091 )"
ROT: "( -0,3967349 , 0,008507095 , -0,1411702 )"
TIME: 590.0952
DISTANCE_FROM_TARGET: 0.009098896
INSIDE_PATH: true
```


**Figure 5.1:** Entry in ScepterPath.json file

when it was grabbed to when it was released, as well as the heart rate value and turn duration at the time of release. Additionally, a boolean is included to indicate whether the object was released within the battlefield. This file is useful for calculating the average time taken by the player to place objects during each phase of the game (Figure 5.2) .


```
NAME_OBJECT: "mattone 1(Clone)"
TOTAL_TIME: 0.930244446
CURRENT_TURN_DURATION: 3.5
CURRENT_HR: 79
PLACED_ON_BATTLEFIELD: true
```


**Figure 5.2:** Entry in Objects.json file

### 5.8.3 General

The `General.json` file contains general information about gameplay and the player's score for each phase. It records the start and finish timestamps for each phase, the timestamps at which the game was paused and unpaused and relative heart rate, it records as well the total number of enemies beaten and not beaten for each phase (Figure 5.3) . This data is useful for evaluating the player's performance and progress throughout the game. Additionally, the file enables calculation of the total time of actual gameplay, which is particularly important for the 'infinite time' modality of the game, as it provides an objective metric for evaluating player engagement.

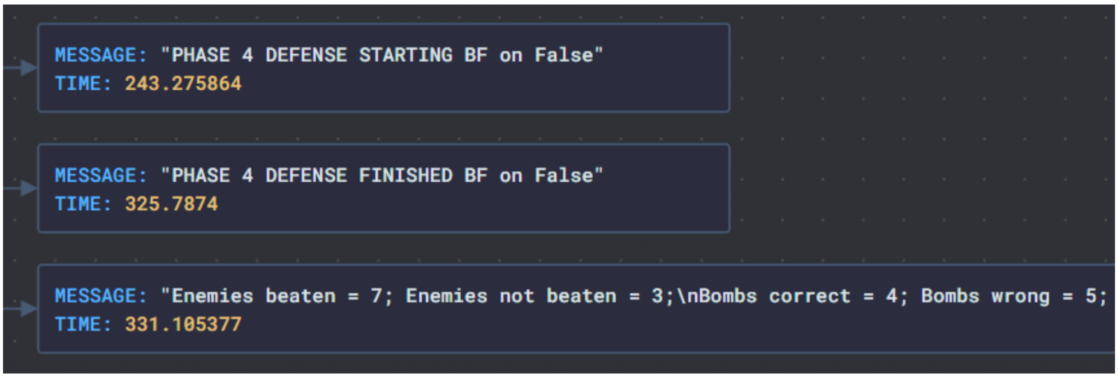


**Figure 5.3:** Entry in General.json file

### 5.8.4 Bombs

The `Bombs.json` file contains information about the final phase of the game. It records the timestamp each time the voice announces a new color and each time the player presses the button to drop a bomb (Figure 5.4) . This data structure enables the calculation of the player's response time and evaluation of their reflexes. Furthermore, it provides insights into the player's ability to multitask and follow instructions, as they must listen to the voice and press the button at the appropriate time.

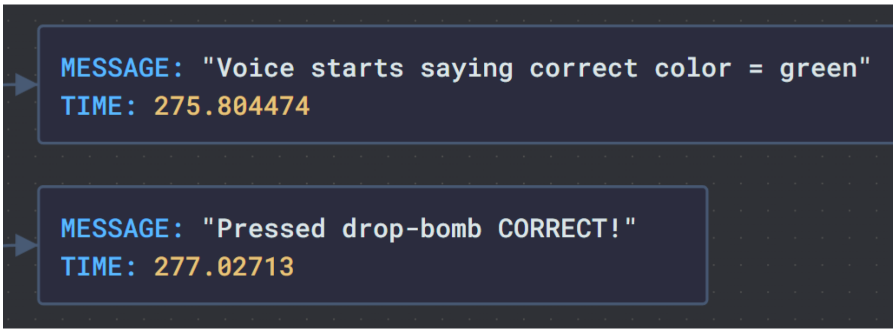


**Figure 5.4:** Entry in Bombs.json file

# Chapter 6

# Experiment

After implementing the game, a series of tests were conducted to evaluate the game's level of engagement and usability and to assess the effectiveness of incorporating biofeedback in the game to determine its potential for future experiments and development.

## 6.1 Sample

The experiment was driven on 24 participants (mean age 28, standard deviation 3.37), gender was balanced in order to avoid effects on the measures. All participants were right-handed and provided their informed consent prior to participating in the study. Out of the 24 participants, one had MS.

## 6.2 Procedure

The experiment (Figure 6.1) involved playing the game under two conditions: with the use of biofeedback and without the use of biofeedback. For each condition, the game was played twice. The first play-through was in limited-time mode, with each mini-game lasting for one minute. The second play-through was in unlimited-time mode, where the player had to actively stop each mini-game to proceed to the next one. After each condition, the player completed a series of questionnaires.

Half of the participants played the condition with the biofeedback on as their first condition, while the other half played it as their second condition. By randomly assigning half of the participants to start with the biofeedback condition and the other half to start with the no-biofeedback condition, any order effects should be equally distributed across the two groups and should not bias the results.

The participants were divided into two homogeneous groups, with the first group being tested a week before the second group. Thirteen participants were recruited for preliminary tests to assess the game's usability and identify any potential issues before the next test.

During the preliminary test, the participants completed the System Usability Scale (SUS) and NASA Task Load Index (NASA-TLX) questionnaires. During the second-group test, the participants completed the SUS, NASA-TLX, and a Post-Test-Questionnaire (PTQ) specifically designed to gather information on the user experience and the overall level of engagement. The questionnaires' items can be found in Table 6.1, Table 6.2, Table 6.5.

Before the experiment, a consent form was compiled by the participants.

**Figure 6.1:** Subject playing the game during the test

## 6.3 Metrics

To evaluate the level of engagement for both the conditions and assess the preference for users to use the biofeedback or not, subjective metrics and objective metrics were used.

### 6.3.1 Subjective Data

The study utilized three different questionnaires to gather subjective data, namely the SUS, NASA-TLX, and PTQ. These questionnaires aimed to evaluate the usability of the system and the perceived workload of the tasks, as well as the engagement level of the participants based on the flow theory (further described in chapter chapter 3). Specifically, the PTQ included ad-hoc questions about the participants' level of focus on the game, level of immersion and presence, willingness to continue playing, satisfaction, and feeling of control over the situation. The questionnaire also assessed if the intensity of the exercise was balanced with the players' abilities by asking them to rate their performance and their level of physical and mental fatigue, all on a 5-point Likert-type scale. In addition, a final question asked about the perceived time, requesting the subjects to report the total playing time.

### 6.3.2 Objective Data

The objective data involved calculating the total playing time during the unlimited-time mode and comparing it with the player's perceived time, asked in the PTQ. An engaging game can cause the player to lose track of time, and this comparison helped determine the level of engagement of the game. Furthermore, a comparison will be made between the amount of playing time in unlimited-time mode for the two conditions: biofeedback on and biofeedback off.

## 6.4 Preliminary tests results

The preliminary tests had the objective of evaluating the usability of the game in order to solve any relevant issue before the actual test. The Table 6.1 contains the mean value (M) and the standard deviation (SD) for each item of the SUS questionnaire.

| N | Questionnaire Items | Biofeedback OFF | | Biofeedback ON | |
|---|---|---|---|---|---|
| | | M | SD | M | SD |
| 1 | I think that I would like to use this system frequently | 3.62 | 1.00 | 3.69 | 0.99 |
| 2 | I found the system unnecessarily complex | 1.08 | 0.27 | 1.00 | 0.00 |
| 3 | I thought the system was easy to use | 4.85 | 0.36 | 4.54 | 0.84 |
| 4 | I think that I would need the support of a technical person to be able to use this system | 1.54 | 0.50 | 1.85 | 0.95 |
| 5 | I found the various functions in this system were well integrated | 4.85 | 0.36 | 4.92 | 0.27 |
| 6 | I thought there was too much inconsistency in this system | 1.08 | 0.27 | 1.00 | 0.00 |
| 7 | I would imagine that most people would learn to use this system very quickly | 4.85 | 0.36 | 4.54 | 0.50 |
| 8 | I found the system very cumbersome to use | 1.08 | 0.27 | 1.15 | 0.36 |
| 9 | I felt very confident using the system | 4.77 | 0.42 | 4.69 | 0.46 |
| 10 | I needed to learn a lot of things before I could get going with this system | 1.15 | 0.36 | 1.08 | 0.27 |

**Table 6.1:** Preliminary test: SUS results

The Table 6.2 contains the mean value (M) and the standard deviation (SD) for each item of the NASA-TLX questionnaire

| N | Questionnaire Items | Biofeedback OFF | | Biofeedback ON | |
|---|---|---|---|---|---|
| | | M | SD | M | SD |
| 1 | How much mental and perceptual activity was required – thinking, deciding, calculating, searching) Was the task easy or demanding, simple or complex, exacting or forgiving? | 6.85 | 3.01 | 6.85 | 3.66 |
| 2 | How much physical activity was required – pushing, pulling, turning? Was the task easy or demanding, slow or brisk, restful or laborious? | 5.77 | 3.42 | 6.92 | 3.34 |
| 3 | How much time pressure did you feel? Was the pace slow and leisurely or rapid and frenetic? | 5.08 | 2.23 | 4.54 | 2.27 |
| 4 | How hard did you work mentally and physically to accomplish your level of performance? | 7.23 | 2.66 | 7.00 | 2.11 |
| 5 | How successful did you feel in accomplishing the goals of the task? How satisfied were you with your performance? | 16.23 | 2.94 | 15.38 | 2.82 |
| 6 | How discouraged, stressed, irritated, and annoyed versus gratified, content, and relaxed did you feel during the task? | 2.08 | 2.53 | 2.38 | 1.78 |

**Table 6.2:** Preliminary test: NASA-TLX results

The SUS questionnaire yielded a total score of 92.52 for the condition without biofeedback and 90.75 for the condition with biofeedback, which is excellent, as a score of 69 is considered above average. The preliminary tests indicated that the game's usability was very high, and its mechanics were well-integrated and user-friendly. Additionally, the NASA-TLX indicated that the workload was not excessive, and the game provided users with a sense of success rather than discouragement or stress.

Given these positive results, no changes were made to the game ahead of the final tests.

## 6.5 Final tests results

The Table 6.3 contains the mean value (M) and the standard deviation (SD) for each item of the SUS questionnaire.

| N | Questionnaire Items | Biofeedback OFF | | Biofeedback ON | |
|---|---|---|---|---|---|
| | | M | SD | M | SD |
| 1 | I think that I would like to use this system frequently | 4.00 | 1.23 | 3.82 | 1.11 |
| 2 | I found the system unnecessarily complex | 1.55 | 0.66 | 1.36 | 0.64 |
| 3 | I thought the system was easy to use | 4.73 | 0.45 | 4.73 | 0.45 |
| 4 | I think that I would need the support of a technical person to be able to use this system | 1.27 | 0.45 | 1.55 | 0.66 |
| 5 | I found the various functions in this system were well integrated | 4.73 | 0.45 | 4.36 | 0.48 |
| 6 | I thought there was too much inconsistency in this system | 1.09 | 0.29 | 1.45 | 0.66 |
| 7 | I would imagine that most people would learn to use this system very quickly | 4.55 | 0.66 | 4.18 | 0.94 |
| 8 | I found the system very cumbersome to use | 1.64 | 0.77 | 2.00 | 0.85 |
| 9 | I felt very confident using the system | 4.64 | 0.48 | 4.27 | 0.62 |
| 10 | I needed to learn a lot of things before I could get going with this system | 1.27 | 0.45 | 1.18 | 0.39 |

**Table 6.3:** Final Test: SUS results

The Table 6.4 contains the mean value (M) and the standard deviation (SD) for each question of the NASA-TLX questionnaire.

| N | Questionnaire Items | Biofeedback OFF | | Biofeedback ON | |
|---|---|---|---|---|---|
| | | **M** | **SD** | **M** | **SD** |
| 1 | How much mental and perceptual activity was required – thinking, deciding, calculating, searching) Was the task easy or demanding, simple or complex, exacting or forgiving? | 7.91 | 4.72 | 8.09 | 4.44 |
| 2 | How much physical activity was required – pushing, pulling, turning? Was the task easy or demanding, slow or brisk, restful or laborious? | 5.18 | 3.76 | 5.18 | 2.33 |
| 3 | How much time pressure did you feel? Was the pace slow and leisurely or rapid and frenetic? | 6.91 | 3.32 | 7.18 | 3.04 |
| 4 | How hard did you work mentally and physically to accomplish your level of performance? | 4.36 | 4.14 | 7.27 | 3.67 |
| 5 | How successful did you feel in accomplishing the goals of the task? How satisfied were you with your performance? | 16.18 | 2.17 | 15.18 | 3.95 |
| 6 | How discouraged, stressed, irritated, and annoyed versus gratified, content, and relaxed did you feel during the task? | 2.91 | 2.43 | 3.45 | 2.68 |

**Table 6.4:** Final Test: NASA-TLX results

The Table 6.5 contains the mean value (M) and the standard deviation (SD) for each item of the PTQ questionnaire.

| N | Questionnaire Items | Biofeedback OFF | | Biofeedback ON | |
|---|---|---|---|---|---|
| | | M | SD | M | SD |
| 1 | How much time did the game last? | 13.09 | 6.13 | 12.00 | 3.91 |
| 2 | How would you rate your performance? | 4.27 | 0.62 | 4.27 | 0.62 |
| 3 | I felt like I lost track of time while playing | 2.91 | 1.38 | 3.18 | 1.11 |
| 4 | I was focused on the game | 4.64 | 0.48 | 4.64 | 0.48 |
| 5 | I felt a strong sense of being in the world of the game to the point that I was unaware of my surroundings | 3.45 | 0.78 | 3.64 | 0.88 |
| 6 | I did not feel a desire to make progress in the game | 1.18 | 0.39 | 1.18 | 0.39 |
| 7 | I did not feel like I wanted to keep playing | 1.64 | 0.77 | 1.45 | 0.66 |
| 8 | I felt that this game provided an enjoyable challenge | 4.18 | 0.72 | 4.18 | 0.57 |
| 9 | I felt that the game was excessively difficult | 1.27 | 0.45 | 1.73 | 0.62 |
| 10 | I felt a sense of accomplishment from playing the game | 4.00 | 0.60 | 3.91 | 0.67 |
| 11 | I felt that the game reacted quickly to my actions | 4.09 | 0.67 | 4.18 | 0.72 |
| 12 | I felt in control of the game | 4.27 | 0.75 | 4.27 | 0.62 |
| 13 | I felt very confident playing the game | 4.64 | 0.48 | 4.27 | 0.62 |
| 14 | I consider playing the game as physical exercise | 2.73 | 1.35 | 2.91 | 1.24 |
| 15 | I felt excited about the physical activities in the game | 3.64 | 0.77 | 3.27 | 0.75 |
| 16 | I felt excited about the mental challenge in the game | 3.64 | 0.64 | 3.73 | 0.86 |

| | | | | | |
|---|---|---|---|---|---|
| 17 | The exercise in this game made me feel good | 4.18 | 0.57 | 4.00 | 0.74 |
| 18 | I would rather not be exercising, even though the exercise was accompanied by game elements | 2.64 | 1.07 | 2.55 | 1.16 |
| 19 | I felt that the physical activity was too intense for me | 1.09 | 0.29 | 1.18 | 0.39 |
| 20 | I felt that the mental effort required was exhausting | 1.18 | 0.39 | 1.36 | 0.48 |
| 21 | I felt that playing the game was beneficial for my physical well-being | 3.55 | 0.78 | 3.18 | 0.94 |
| 22 | I felt that focusing on the game was beneficial for my mental state | 3.64 | 0.88 | 3.27 | 0.96 |
| 23 | I would prefer that this activity was not accompanied by game elements | 1.27 | 0.45 | 1.18 | 0.39 |
| 24 | The mental effort was more intense than the physical effort during the game | 2.18 | 1.03 | 2.83 | 0.94 |
| 25 | I feel that the muscles of my arm need rest | 1.18 | 0.39 | 1.09 | 0.29 |
| 26 | The situation was making me feel the desire to improve my performance | 4.09 | 0.67 | 4.09 | 0.90 |
| 27 | I felt the need to rest or change arm between sessions | 1.18 | 0.39 | 1.27 | 0.45 |
| 28 | I felt that it was more difficult to concentrate as they game progressed | 1.82 | 1.11 | 2.45 | 1.08 |
| 29 | I felt that my performance was decreasing as the game progressed | 1.64 | 0.88 | 1.64 | 0.88 |

| | | | | | |
|---|---|---|---|---|---|
| 30 | I felt that it was difficult to understand how the game works | 1.18 | 0.39 | 1.36 | 0.48 |
| 31 | I felt that it was easy to familiarize myself with different game elements across the sessions | 4.09 | 1.16 | 3.82 | 1.19 |
| 32 | I felt that my pace and performance greatly depended on the game session | 2.91 | 0.90 | 2.64 | 0.88 |
| 33 | I felt that it was easy to avoid the enemies | 3.73 | 1.05 | 4.09 | 0.79 |
| 34 | I prefer a virtual environment without any characters during this exercise | 1.18 | 0.39 | 1.18 | 0.39 |
| 35 | I would prefer this game to have several but shorter sessions | 1.91 | 0.90 | 2.45 | 0.99 |
| 36 | I felt that it was enjoyable to handle and move the scepter in the exercise | 4.09 | 0.79 | 3.91 | 1.00 |
| 37 | I think that the presence of virtual characters can be useful for motivating me during the exercise | 4.18 | 0.83 | 4.09 | 0.90 |
| 38 | How much time did the game last? | 9.64 | 3.91 | 11.36 | 3.84 |
| 39 | How would you rate your performance? | 4.45 | 0.50 | 4.55 | 0.66 |

**Table 6.5:** Final Test: PTQ result

The Table 6.6 contains the mean value (M) and the standard deviation (SD) for the game time in limited-time modality and unlimited-time modality.

| Item | Biofeedback OFF | | Biofeedback ON | |
|---|---|---|---|---|
| | M | SD | M | SD |
| Game time in limited-time modality | 9.64 | 1.82 | 9.73 | 1.48 |
| Perceived time in limited-time modality | 13.09 | 6.13 | 9.64 | 3.91 |
| Game time in unlimited-time modality | 9.36 | 2.27 | 11.64 | 3.47 |
| Perceived time in unlimited-time modality | 12.00 | 3.91 | 11.36 | 3.84 |

**Table 6.6:** Final Test: Game time results

To compare the data of the two conditions, the Wilcoxon signed-rank test was used and the calculated values W and p are derived from this test. The Wilcoxon signed-rank test is a non-parametric test, used to compare data from two different conditions in a within-subject experimental design, where each subject undergoes all conditions in a randomized order.

Statistically significant differences (with $p<0.05$) have been found in the questionnaire just for the item 9 ($W=0.0$ and $p=0.037$) with $M=1.27$ and $SD=0.45$ in the condition without biofeedback, $M=1.73$ and $SD=0.62$ in the condition with biofeedback. Statistically significant differences (with $p<0.05$) have also been found in the post-test spontaneous game time ($W=6.5$ and $p=0.036$) with $M=9.36$ minutes and $SD=2.27$ minutes in the condition without biofeedback, $M=11.64$ minutes and $SD=3.47$ minutes in the condition with biofeedback. Furthermore, the subjective time estimation shows (with $p<0.05$) statistically significant differences too ($W=6.5$ and $p=0.036$) with $M=9.64$ minutes and $SD=3.91$ minutes in the condition without biofeedback, $M=11.34$ minutes and $SD=3.84$ minutes in the condition with biofeedback.

The SUS questionnaire yielded a total score of 89.57 for the condition without biofeedback and 84.55 for the condition with biofeedback

### 6.5.1 Patient Results

The Table 6.7 contains the score given to each item of the SUS questionnaire by the patient.

| N | Questionnaire Items | Biofeedback OFF | Biofeedback ON |
|---|---|---|---|
| 1 | I think that I would like to use this system frequently | 3 | 3 |
| 2 | I found the system unnecessarily complex | 2 | 1 |
| 3 | I thought the system was easy to use | 5 | 4 |
| 4 | I think that I would need the support of a technical person to be able to use this system | 3 | 1 |
| 5 | I found the various functions in this system were well integrated | 3 | 5 |
| 6 | I thought there was too much inconsistency in this system | 2 | 1 |
| 7 | I would imagine that most people would learn to use this system very quickly | 3 | 4 |
| 8 | I found the system very cumbersome to use | 1 | 1 |
| 9 | I felt very confident using the system | 4 | 4 |
| 10 | I needed to learn a lot of things before I could get going with this system | 2 | 1 |

**Table 6.7:** Patient: SUS results

The Table 6.4 contains the score given to each item of the NASA-TLX questionnaire by the patient.

| N | Questionnaire Items | Biofeedback OFF | Biofeedback ON |
|---|---|---|---|
| 1 | How much mental and perceptual activity was required – thinking, deciding, calculating, searching) Was the task easy or demanding, simple or complex, exacting or forgiving? | 11 | 10 |
| 2 | How much physical activity was required – pushing, pulling, turning? Was the task easy or demanding, slow or brisk, restful or laborious? | 5 | 14 |
| 3 | How much time pressure did you feel? Was the pace slow and leisurely or rapid and frenetic? | 8 | 3 |
| 4 | How hard did you work mentally and physically to accomplish your level of performance? | 9 | 10 |
| 5 | How successful did you feel in accomplishing the goals of the task? How satisfied were you with your performance? | 13 | 15 |
| 6 | How discouraged, stressed, irritated, and annoyed versus gratified, content, and relaxed did you feel during the task? | 1 | 1 |

**Table 6.8:** Patient: NASA-TLX results

The Table 6.5 contains the mean value (M) and the standard deviation (SD) for each item of the PTQ questionnaire.

| N | Questionnaire Items | Biofeedback OFF | Biofeedback ON |
|---|---|---|---|
| 1 | How much time did the game last? | 7 | 5 |
| 2 | How would you rate your performance? | 4 | 5 |
| 3 | I felt like I lost track of time while playing | 4 | 4 |
| 4 | I was focused on the game | 4 | 3 |
| 5 | I felt a strong sense of being in the world of the game to the point that I was unaware of my surroundings | 3 | 3 |
| 6 | I did not feel a desire to make progress in the game | 2 | 2 |
| 7 | I did not feel like I wanted to keep playing | 2 | 2 |
| 8 | I felt that this game provided an enjoyable challenge | 3 | 4 |
| 9 | I felt that the game was excessively difficult | 2 | 1 |
| 10 | I felt a sense of accomplishment from playing the game | 4 | 3 |
| 11 | I felt that the game reacted quickly to my actions | 3 | 2 |
| 12 | I felt in control of the game | 3 | 4 |
| 13 | I felt very confident playing the game | 4 | 4 |
| 14 | I consider playing the game as physical exercise | 5 | 3 |
| 15 | I felt excited about the physical activities in the game | 4 | 3 |
| 16 | I felt excited about the mental challenge in the game | 3 | 3 |
| 17 | The exercise in this game made me feel good | 4 | 4 |
| 18 | I would rather not be exercising, even though the exercise was accompanied by game elements | 1 | 3 |

| | | | |
|---|---|---|---|
| 19 | I felt that the physical activity was too intense for me | 1 | 2 |
| 20 | I felt that the mental effort required was exhausting | 3 | 2 |
| 21 | I felt that playing the game was beneficial for my physical well-being | 3 | 3 |
| 22 | I felt that focusing on the game was beneficial for my mental state | 4 | 4 |
| 23 | I would prefer that this activity was not accompanied by game elements | 2 | 2 |
| 24 | The mental effort was more intense than the physical effort during the game | 3 | 4 |
| 25 | I feel that the muscles of my arm need rest | 2 | 3 |
| 26 | The situation was making me feel the desire to improve my performance | 3 | 4 |
| 27 | I felt the need to rest or change arm between sessions | 2 | 2 |
| 28 | I felt that it was more difficult to concentrate as they game progressed | 3 | 4 |
| 29 | I felt that my performance was decreasing as the game progressed | 2 | 3 |
| 30 | I felt that it was difficult to understand how the game works | 2 | 1 |
| 31 | I felt that it was easy to familiarize myself with different game elements across the sessions | 3 | 4 |
| 32 | I felt that my pace and performance greatly depended on the game session | 1 | 1 |
| 33 | I felt that it was easy to avoid the enemies | 3 | 4 |
| 34 | I prefer a virtual environment without any characters during this exercise | 2 | 1 |
| 35 | I would prefer this game to have several but shorter sessions | 1 | 2 |
| 36 | I felt that it was enjoyable to handle and move the scepter in the exercise | 4 | 3 |

| | | | |
|---|---|---|---|
| 37 | I think that the presence of virtual characters can be useful for motivating me during the exercise | 5 | 4 |
| 38 | How much time did the game last? | 20 | 13 |
| 39 | How would you rate your performance? | 4 | 5 |

**Table 6.9:** Patient: PTQ result

The Table 6.10 contains the game time values in limited-time modality and unlimited-time modality.

| Item | Biofeedback OFF | Biofeedback ON |
|---|---|---|
| Game time in limited-time modality | 10 | 11 |
| Perceived time in limited-time modality | 7 | 5 |
| Game time in unlimited-time modality | 43 | 22 |
| Perceived time in unlimited-time modality | 20 | 13 |

**Table 6.10:** Patient: Game time results

## 6.6 Discussion

First of all, the results point at the superiority of the biofeedback condition over the no-biofeedback condition because the first leads to longer spontaneous game time (according to our assumptions, this is a sign of engagement) with a coherent subjective estimation of the duration in this last phase. The sole questionnaire score showing significant differences between the two conditions highlights the higher difficulty of the biofeedback condition. However, pondering the effect on engagement, this issue can be considered as a factor leading to engagement.

As emerged from the SUS questionnaire, Castles' Battle VR proved to be extremely intuitive and easy to use in both conditions. In particular, considering that a score superior than 68 would be considered above average, the score obtained with the tests (89.57 for the condition without biofeedback and 84.55 for the condition with biofeedback) is extremely positive. In Table 6.3, the values closest to the extremes are highlighted in green.

It is noteworthy that Question 6 of the NASA-TLX survey elicited a highly positive mean response in both conditions, indicating that the system does not induce frustration or stress. Additionally, Question 5 generated exceedingly positive results in both conditions, indicating that the game delivers an appropriate level of satisfaction to the player, a critical feature for achieving the flow state. In Table 6.4, values that are closest to the extremes are highlighted in green.

The Post-Test Questionnaire yielded some interesting insights into the game's features. Specifically, the following observations were made:

- Item 4 indicated that players felt very focused on the game in both conditions, which is a key feature for reaching a state of flow.
- Items 6, 7, and 26 suggested that players were motivated to keep playing and making progress in the game, which are also key features for reaching a state of flow.
- Items 8, 9, 19, 20, 25, and 27 pointed out that the game was perceived as excessively easy but enjoyable.
- Items 11, 12, 13, and 30 demonstrated that the game's system was perceived as reactive and responded correctly and quickly to players' inputs, making them feel in control of the situation.

The patient's SUS score yielded a total score of 70 without biofeedback and 87.5 with biofeedback. As 69 is considered above average, this result confirms the usability consideration written above.

The patient's NASA-TLX results indicated that they perceived a higher workload in both conditions compared to other participants, which could have positive implications for the rehabilitation objective of the game.

The results of the PTQ did not show any significant differences from the previously discussed PTQ results.

The most important data obtained from the test can be seen in Table 6.10, which shows the patient's total playing time in the two conditions. Notably, the patient's perception of time was not realistic, as they perceived a much shorter playing time than the actual duration in both conditions. This is a positive result, as it suggests that the patient achieved a state of flow, which is characterized by a distorted perception of time. Additionally, the patient played the game for a much longer time in the unlimited-time mode in both conditions, indicating that the game successfully engaged them and achieved its objective.

# Chapter 7

# Conclusions

This thesis work aimed to design and develop an immersive VR exergame for motor and cognitive rehabilitation in people with MS. The game is a tower defense game with four phases, each focusing on a specific rehabilitation exercise to stimulate cognitive abilities (visual and auditory attention, reflexes, logic) and upper limb movements (precision, velocity). The goal was to create an engaging exergame to make rehabilitation less repetitive and monotonous, while also balancing exercise intensity with the player's abilities.

To achieve this balance, a biofeedback system was used, which can adjust the game's workload in real-time based on the player's heart rate. The sensor monitors the player's heart rate and compares it with their average resting heart rate, generating a biofeedback used to slow down the enemies in-game and reduce the workload required.

Experimental evaluation was conducted to assess the game's usability and engagement, both with and without the use of the sensor, to evaluate its potential for future work. A preliminary experiment on usability was conducted with 13 subjects, followed by a final experiment on usability and engagement with 11 subjects (including one with MS). Both subjective metrics (SUS questionnaire, NASA-TLX questionnaire, PTQ) and objective metrics (duration of play session, difference between perceived and actual duration of play session) were used to evaluate engagement and usability.

As emerged from the questionnaires, Castles' Battle VR proved to be extremely intuitive and easy to use, demonstrating that it could be useful for future work on rehabilitation in PwMS.

Furthermore, the use of a biofeedback to balance the difficulty of the game and the abilities of the player does not negatively affect the general usability of the system and can lead to a higher level of engagement. The biofeedback system is indeed a powerful technology that can help in the development of engaging exergames for rehabilitation, partially solving the problem of finding the right balance between energy expanditure and exercise intensity.

In addition, the questionnaires also revealed that the game may have been too easy for the players. Since none of the subjects had cognitive or upper limb impairments, further testing with PwMS is necessary to gauge the actual level of difficulty perceived by those with such impairments.

## 7.1 Future Work

Castles' Battle VR could be improved with a series of changes with the objective to develop a successful exergame for rehabilitation in PwMS that can be challenging and engaging for the players.

To increase engagement, one of the changes could be to make the minigames more challenging over time. Currently, players are not motivated to keep playing a minigame when using the infinite-time modality because the minigame never changes, leading to a low playing time. Making the game automatically increase its difficulty over time could be an interesting feature to add. The difficulty of the game could be easily increased by augmenting the number of columns of the battlefield. Another interesting feature could be adding bonus attacks when reaching a certain amount of beaten enemies in each phase. For example, every 10 enemies beaten, a bonus attack could be given to the player to break monotony and add an additional purpose for the player to keep playing.

One of the small changes refers to the third phase. Currently, players are not forced to look at the billboard to reproduce the pattern because they can place allies by watching the enemies' shape and color when they appear. To solve this problem, enemies could use a different 3D model without any shape or color. This would force players to follow the pattern shown on the billboard.

To make the game more challenging, one option is to introduce a losing condition. At present, the player cannot lose the game, but incorporating the possibility of losing would add a new level of difficulty.

To enhance the scope of rehabilitation and introduce greater variety to the game, additional phases and mini-games could be incorporated in the future. One possibility is to include a memory phase that focuses on improving short-term memory capacity.

To optimize exercise intensity and align it with energy expenditure, one potential modification could involve utilizing the biofeedback system to maintain the player's heart rate within specific thresholds. This approach would ensure that the game's difficulty level is appropriately matched to the player's abilities. The game could prompt the player to increase their heart rate to a certain threshold and then sustain it at that level, rather than allowing the player to engage in a game that is too easy for their skill level.

# Bibliography


[1] «Rehabilitation interventions in multiple sclerosis: an overview». In: (July 2012). URL: https://doi.org/10.1007/s00415-012-6577-4 (cit. on pp. 1, 2).

[2] «Rehabilitation for people with multiple sclerosis: an overview of Cochrane Reviews (Review)». In: (Jan. 2019). URL: https://doi.org/10.1002/14651858.CD012732.pub2 (cit. on pp. 1, 2).

[3] «Upper limb rehabilitation interventions using virtual reality for people with multiple sclerosis: a systematic review». In: (Oct. 2020). URL: https://doi.org/10.1016/j.msard.2020.102610 (cit. on p. 1).

[4] «Evidenced-Based Cognitive Rehabilitation for Persons With Multiple Sclerosis: A Review of the Literature». In: (Apr. 2008). URL: https://doi.org/10.1016/j.apmr.2007.10.019 (cit. on pp. 1, 2, 9).

[5] «Multiple sclerosis in children: clinical diagnosis, therapeutic strategies, and future directions». In: (Oct. 2007). URL: https://doi.org/10.1016/S1474-4422(07)70242-9 (cit. on p. 1).

[6] «Natural History of Multiple Sclerosis Symptoms». In: (Oct. 2013). URL: https://doi.org/10.7224/1537-2073.2012-053 (cit. on p. 2).

[7] D. T. Wade. «Measurement in neurologic rehabilitation». In: (Oct. 1993). URL: https://doi.org/10.1097/00019052-199310000-00017 (cit. on p. 2).

[8] «Cognitive rehabilitation in multiple sclerosis: the role of plasticity». In: (Apr. 2015). URL: ttps://doi.org/10.3389/fneur.2015.00067 (cit. on p. 3).

[9] «Beyond clinical changes: Rehabilitation-induced neuroplasticity in MS». In: (Aug. 2019). URL: https://doi.org/10.1177/135245851984609 (cit. on p. 3).

[10] «Considerations for the design of exergames». In: (Dec. 2007). URL: https://doi.org/10.1145/1321261.1321313 (cit. on p. 3).

[11] «The Psychological Effects of Exergames for Children and Adolescents with Obesity: A Systematic Review and Meta-Analysis». In: (Nov. 2019). URL: https://doi.org/10.1089/cyber.2019.0341 (cit. on p. 3).

[12] «Impact of Exergames on the Mental Health of Older Adults: A Systematic Review and GRADE Evidence Synthesis». In: (Nov. 2022). URL: https://doi.org/10.1089/g4h.2021.0229 (cit. on p. 3).

[13] «Active exergames to improve cognitive functioning in neurological disabilities: a systematic review and meta-analysis». In: (June 2018). URL: https://doi.org/10.23736/S1973-9087.17.04680-9 (cit. on p. 3).

[14] Heidi Sveistrup. «Motor rehabilitation using virtual reality». In: (Dec. 2004). URL: https://doi.org/10.1186/1743-0003-1-10 (cit. on p. 3).

[15] «The role of exergaming in Parkinson's disease rehabilitation: a systematic review of the evidence». In: (Mar. 2014). URL: https://doi.org/10.1186/1743-0003-11-33 (cit. on p. 3).

[16] Mihaly Csikszentmihalyi. «Beyond boredom and anxiety». In: (1975). URL: https://psycnet.apa.org/record/2000-12701-000 (cit. on pp. 3, 17, 18).

[17] «The Psychological Effects of Playing Exergames: A Systematic Review». In: (Sept. 2017). URL: https://doi.org/10.1089/cyber.2017.0183 (cit. on pp. 3, 18, 20).

[18] «A Call to Unify Definitions of Virtual Reality». In: (June 2019). URL: https://doi.org/10.1016/j.ecns.2019.02.006 (cit. on p. 4).

[19] «A Framework for Immersive Virtual Environments (FIVE): Speculations on the Role of Presence in Virtual Environments». In: (Dec. 1997). URL: https://doi.org/10.1162/pres.1997.6.6.603 (cit. on p. 4).

[20] «Immersion, presence and performance in virtual environments: an experiment with tri-dimensional chess». In: (July 1996). URL: https://doi.org/10.1145/3304181.3304216 (cit. on p. 4).

[21] «Immersion of virtual reality for rehabilitation - Review». In: (May 2018). URL: https://doi.org/10.1016/j.apergo.2018.01.009 (cit. on p. 4).

[22] «The use of gaming technology for rehabilitation in people with multiple sclerosis». In: (Dec. 2014). URL: https://doi.org/10.1177/1352458514563593 (cit. on p. 5).

[23] «Comparison of the effects of two different exergaming systems on balance, functionality, fatigue, and quality of life in people with multiple sclerosis: A randomized controlled trial». In: (Apr. 2020). URL: https://doi.org/10.1016/j.msard.2019.101902 (cit. on p. 5).

[24] «Focus on neglected features of cognitive rehabilitation in MS: Setting and mode of the treatment». In: (Oct. 2020). URL: https://doi.org/10.1177/1352458520966300 (cit. on p. 5).

[25] «Upper limb motor rehabilitation impacts white matter microstructure in multiple sclerosis». In: (Apr. 2014). URL: https://doi.org/10.1016/j.neuroimage.2013.12.025 (cit. on p. 8).

[26] «Adult Norms for the Box and Block Test of Manual Dexterity». In: (June 1985). URL: https://doi.org/10.5014/ajot.39.6.386 (cit. on p. 8).

[27] «Effect of dual-task training on balance in patients with multiple sclerosis: A systematic review and meta-analysis». In: (Apr. 2021). URL: https://doi.org/10.1177/02692155211010372 (cit. on p. 9).

[28] «Cognitive evaluation by tasks in a virtual reality environment in multiple sclerosis». In: (Oct. 2015). URL: https://doi.org/10.1016/j.jns.2015.10.039 (cit. on pp. 9, 10, 30).

[29] «Cognitive recovery in people with relapsing/remitting multiple sclerosis: A randomized clinical trial on virtual reality-based neurorehabilitation». In: (Sept. 2021). URL: https://doi.org/10.1016/j.clineuro.2021.106828 (cit. on pp. 9, 28, 29).

[30] «Impaired Short-term Motor Learning in Multiple Sclerosis: Evidence From Virtual Reality». In: (June 2017). URL: https://doi.org/10.1177/1545968306294913 (cit. on p. 9).

[31] «A Telerehabilitation Program Improves Postural Control in Multiple Sclerosis Patients: A Spanish Preliminary Study». In: (Oct. 2013). URL: https://doi.org/10.3390/ijerph10115697 (cit. on p. 10).

[32] «A telerehabilitation program by virtual reality-video games improves balance and postural control in multiple sclerosis patients». In: (Dec. 2013). URL: https://doi.org/10.3233/NRE-130995 (cit. on p. 10).

[33] «Virtual Rehabilitation for Multiple Sclerosis Using a Kinect-Based System: Randomized Controlled Trial». In: (2014). URL: https://doi.org/10.2196/games.2933 (cit. on p. 10).

[34] «Virtual reality system for multiple sclerosis rehabilitation using KINECT». In: (May 2013). URL: https://doi.org/10.4108/icst.pervasivehealth.2013.252208 (cit. on p. 10).

[35] «Do patients with multiple sclerosis benefit from semi-immersive virtual reality? A randomized clinical trial on cognitive and motor outcomes». In: (Jan. 2020). URL: https://doi.org/10.1080/23279095.2019.1708364 (cit. on p. 10).

[36] «Effects of virtual reality-based training with BTs-Nirvana on functional recovery in stroke patients: preliminary considerations». In: (Oct. 2016). URL: https://doi.org/10.1080/00207454.2017.1403915 (cit. on p. 10).

[37] «Effects of Virtual Reality vs Conventional Balance Training on Balance and Falls in People With Multiple Sclerosis: A Randomized Controlled Trial». In: (Nov. 2020). URL: https://doi.org/10.1016/j.apmr.2020.09.395 (cit. on p. 11).

[38] «Using virtual reality-based training to improve cognitive function, instrumental activities of daily living and neural efficiency in older adults with mild cognitive impairment». In: (Oct. 2019). URL: https://doi.org/10.23736/S1973-9087.19.05899-4 (cit. on p. 11).

[39] «Unilateral arm rehabilitation for persons with multiple sclerosis using serious games in a virtual reality approach: Bilateral treatment effect?» In: (July 2019). URL: https://doi.org/10.1016/j.msard.2019.07.010 (cit. on p. 11).

[40] «Combined virtual reality and physical training improved the bimanual coordination of women with multiple sclerosis». In: (Jan. 2020). URL: https://doi.org/10.1080/09602011.2020.1715231 (cit. on p. 12).

[41] «Computer-assisted cognitive rehabilitation in persons with multiple sclerosis: Results of a multi-site randomized controlled trial with six month follow-up». In: (Feb. 2018). URL: https://doi.org/10.1016/j.dhjo.2018.02.001 (cit. on p. 12).

[42] «Efficacy of RehaCom cognitive rehabilitation software in activities of daily living, attention and response control in chronic stroke patients». In: (Sept. 2019). URL: https://doi.org/10.1016/j.jocn.2019.08.114 (cit. on pp. 13, 28, 29).

[43] «A low-cost cognitive rehabilitation with a commercial video game improves sustained attention and executive functions in multiple sclerosis: a pilot study». In: (Nov. 2014). URL: https://doi.org/10.1177/1545968314554623 (cit. on p. 13).

[44] «Xbox 360 Kinect Cognitive Games Improve Slowness, Complexity of EEG, and Cognitive Functions in Subjects with Mild Cognitive Impairment: A Randomized Control Trial». In: (Apr. 2019). URL: https://doi.org/10.1089/g4h.2018.0029 (cit. on p. 13).

[45] «The effect of cognitive-motor dual task training with the biorescue force platform on cognition, balance and dual task performance in institutionalized older adults: a randomized controlled trial». In: (July 2017). URL: https://doi.org/10.1589/jpts.29.1137 (cit. on p. 13).

[46] «The Effect of a Virtual Reality-Based Intervention Program on Cognition in Older Adults with Mild Cognitive Impairment: A Randomized Control Trial». In: (Apr. 2020). URL: https://doi.org/10.3390/jcm9051283 (cit. on pp. 13, 14).

[47] «Effect of immersive virtual reality on balance, mobility, and fatigue in patients with multiple sclerosis: A single-blinded randomized controlled trial». In: (Apr. 2020). URL: https://doi.org/10.1016/j.eujim.2020.101092 (cit. on p. 14).

[48] «Effects of voluntary heart rate control on user engagement and agency in a virtual reality game». In: (Dec. 2020). URL: https://doi.org/10.1007/s10055-020-00429-7 (cit. on p. 18).

[49] «Spatial Augmented Respiratory Cardiofeedback Design for Prosthetic Embodiment Training: a Pilot Study». In: (Oct. 2022). URL: https://doi.org/10.1109/SMC53654.2022.9945493 (cit. on p. 44).