POLITECNICO DI TORINO

Master's Degree in Computer Engineering

Master Thesis

Motor-Cognitive Rehabilitation in Multiple Sclerosis: A Mixed Reality Game-based Approach

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Summary

Nowadays, rehabilitation procedures for people with multiple sclerosis (MS) are supported by an increasing number of techniques. The aim of this thesis is to empower traditional exercises through recent innovations in mixed reality (combining real and digital elements in the same setting, making the computer-generated items encrusted in the physical setting). This is achieved by developing an interactive environment where rehabilitation tasks are coupled with game-like features with augmentative audio and video cues. The test setting for this thesis focuses on upper limb rehabilitation, with a grid-like structure where the user must place a virtual cube according to a set of rules and constraints requiring the individual capability to control the execution of repetitive actions without violating specific limitations. The effectiveness of this method is initially assessing the performance and experience of users without MS through a series of playtesting sessions as preliminary tests before involving people with MS. The thesis discusses and demonstrates how the engaging features of mixed reality can actively reduce the detrimental effects of repetitive exercises, further improving individual adherence to clinical procedures.

Acknowledgements

To the professors and colleagues I've met at the Politecnico di Torino, the Istituto Italiano di Tecnologia and the Associazione Italiana Sclerosi Multipla, who have encouraged my interest in such a fascinating and delicate subject as multiple sclerosis rehabilitation.

To the support, love and understanding of my girlfriend, family and friends who have been with me on this journey from the first day until the very end.

To mistakes, and the new points of view that emerge from making them.

Thank you.
Antonio

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Acronyms

AI
: Artificial Intelligence

AISM
: Associazione Italiana Sclerosi Multipla

AR
: Augmented Reality

CIS
: Clinically Isolated Syndrome

ENACT
: Employing Neuroergonomic solutions to Attenuate the Cerebellar Tremor

FISM
: Federazione Italiana Sclerosi Multipla

IIT
: Istituto Italiano di Tecnologia

LoR
: Level of Realism

MR
: Mixed Reality

MS
: Multiple Sclerosis

MRTK
: Mixed Reality Toolkit

MRI
: Magnetic Resonance Imaging

PPMS
: Primary Progressive Multiple Sclerosis

PwMS
: Person with Multiple Sclerosis

RIS
: Radiologically Isolated Syndrome

RRMS
: Relapsing-Remitting Multiple Sclerosis

SoP
: Sense of Presence

SPMS
: Secondary Progressive Multiple Sclerosis

TLX
: Task Load Index

VR
: Virtual Reality

Chapter 1

Introduction

Rehabilitation for persons with multiple sclerosis (PwMS) is an ever-evolving field with new techniques being developed to help patients on their path to rehabilitation [1]. A 2020 research supported by Fondazione Italiana Sclerosi Multipla (FISM) showed how clinical and preclinical research on the impact of neurological rehabilitation on MS disabilities is important: further studies are needed to better understand the mechanisms, the best combination of techniques and their optimal timing of application. Over the years, these techniques have been combined with technological advances leading to the spread of "exergames", experiences that combine exercise and play to maintain physical and mental fitness in a fun way, widely used to complement traditional rehabilitation cycles. In addition, recent developments in the virtual reality field are increasingly promising and favoured by an ever more flourishing market. Several studies foresaw an advancement of technology-mediated human communication from today's devices to mixed reality (MR) interfaces, with artificial intelligence (AI) techniques being developed in support of daily tasks [2]. Within this context, the aim is to experiment beyond traditional therapies towards MR, embedding digital elements in a physical domain with the intention of testing the effectiveness of these implementations.

One of these experiences has been developed in this dissertation by combining rehabilitation tasks with gamified features: this involves the inclusion of audiovisual inserts, such as a dynamic music track and a chromatic feedback dictating the pace of the game. The experimental setting for this project focuses on upper limbs: the game is presented as a grid structure where the player must place a virtual pawn according to a set of rules and constraints. The goal is to progress in the game loop by performing repetitive actions, trying to not break any constraints given by the game ruleset. The user will be tested under various stress conditions with the aim to verify the perceived effort with different gameplay elements, searching for a more balanced solution. The effectiveness of the method is verified by assessing the degree of user performance and evaluating the experience under different configurations to demonstrate how mixed reality elements can benefit the execution of repeated tasks, thus verifying their adherence to clinical procedures.

Alongside this gamified experience, a control panel is set up for medical personnel, whose configuration allows access and granular adjustment of game parameters, without the need for any device other than the one used by the patients. The results, which are stored in time and position reports, will be studied to derive analytical data for the dissertation. The experience is put to the test through a series of playtests carried out at the Istituto Italiano di Tecnologia (IIT) by a set of volunteers, with a useful contribution from a PwMS at the Associazione Italiana Sclerosi Multipla (AISM) centre in Genoa.

1.1 Structure of the thesis

The document has the following layout:

- **Chapter 2** (page 4) is devoted to the introduction to virtual reality and its various declinations. The concepts of mixed and augmented reality will be discussed as part of the continuum of this discipline. Then, we will reference multiple sclerosis and the limitations that this pathology imposes on the patient's body. In this context, some case studies of upper limb exercises using virtual reality techniques are presented and compared with more traditional variations.
- **Chapter 3** (page 19) briefly summarises the software and hardware technologies used to realise the MR experience and justifies their use within the project.
- In **Chapter 4** (page 24), the game experience is presented with its features and capabilities, focusing on the elements of the game and the rules that govern them. Finally, a few comments are made on the data collected and the simulation environment used to develop the game, with an overview of

the steps taken to successfully transfer the simulated experience to the device counterpart.

- In **Chapter 5** (page 45), details about the testing phase of the game are shown. Both the content of the questionnaires and the way in which the tests were carried out on the users will be specified. Then, there will be an overview of the results from the experimental phase and a sum up of the information provided by data collecting and user feedback.
- In **Chapter 6** (page 64), the conclusions drawn from the results of the questionnaires and the limitations encountered in project development will be discussed along with possible future iterations of the project.

The source code of this work is available at `https://github.com/VRatPolito/t-iit-motor-cognitive-exergames.git`

Chapter 2

State of the art

2.1 Augmented and mixed reality: a literature analysis

2.1.1 Augmented Reality

In 1994, Milgram and Kishino conceptualized the Virtual-Reality Continuum, defined as a continuous scale between complete virtuality and complete reality: all possible variations and combinations of real and virtual objects are included in the reality-virtuality continuum [3]. The continuum takes into consideration five different systems:

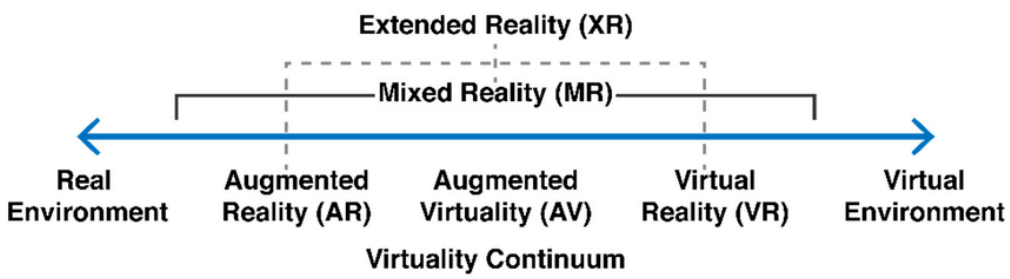


Figure 2.1: A visual representation of the Milgram and Kishino's virtuality continuum [4].

- **Real environment** – The real world without any virtual input. Included in this domain are traditional rehabilitation processes.
- **Augmented Reality (AR)** – Combining the real world with computer generated content. The content can be across a range of sensory modalities, including visual, auditory, haptic, somatosensory and olfactory. The project

conceived in this thesis falls into this category.

- **Augmented Virtuality (AV)** – Augmented virtuality integrates real world objects into a virtual space. Good examples of AV are green screen and video chat backgrounds. This technology supported and enhanced remote working during the COVID-19 pandemic.
- **Virtual Reality (VR)** – A simulated experience that gives users an immersive experience of a virtual world by using pose tracking and 3D near-eye displays.
- **Virtual environment** – A purely digital environment.

In this spectrum, AR defines a system in which virtual objects are added to the real world in real-time during the user's experience. It's a more recent technology compared to Virtual Reality (VR), with an emerging, interdisciplinary framework related to education, and the potential to improve content comprehension and retention. Where VR has struggled to establish a relationship with the real world, AR technology overcomes this by allowing computer-generated content to be placed within the world itself, creating an ”augmented world” where the user can interact with and learn from.

Virtual Fixtures: the first AR experience

The early 1990s saw the start of developments in AR environments. In 1992, at USAF Armstrong Labs at Brooks Air Force Base, San Antonio, Texas, American inventor Louis Rosenberg developed ”Virtual Fixtures”, also known as the first fully immersive augmented reality system. The use case scenario for this idea was for a surgeon who had to make a dangerous incision in the skin: to steady her hand and avoid vital organs, she could use a bulky metal fixture. ”Virtual Fixtures” offered a ground-breaking solution: a virtual fixture that would guide her real scalpel, not just visually, but also physically. Since it's virtual, such a holder would travel through the patient's body and sink into the tissue before a single cut was performed. The military was intrigued by the concept. Not only for in-person tasks such as surgery, but also for remote tasks performed by remote-controlled robots: for example, a technician on Earth could repair a satellite by remotely controlling a robot, assisted by virtual devices superimposed on video images of the real work site.

The system used a unique optical configuration with a pair of binocular magnifying glasses aligned to bring the user's view of the robot arms registered in the exact location of the user's real physical arms. The result was an immersive experience where users could move their arms and see robotic arms where their arms were supposed to be. The system also used computer-generated virtual overlays in the form of simulated physical walls, fields and guides, designed to assist the user in performing real physical tasks [5].

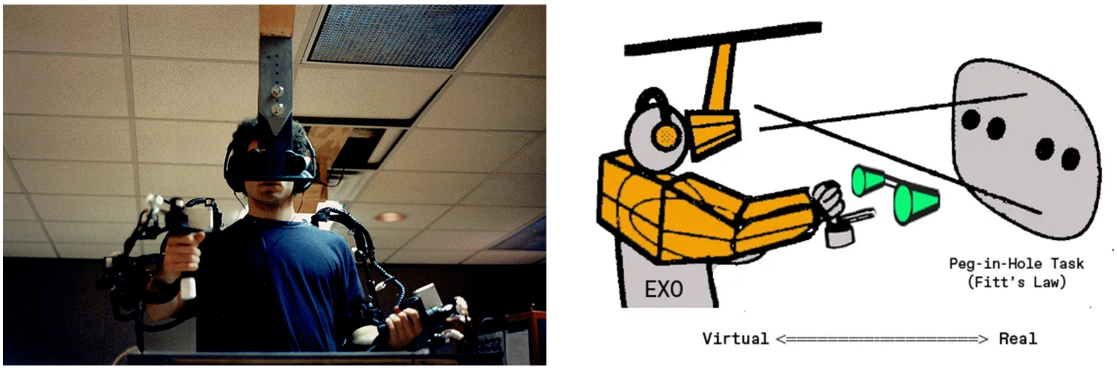


Figure 2.2: "Virtual Fixtures", the first fully immersive augmented reality system. On the right, a drawing by Louis Rosenberg shows a user of the Virtual Fixtures platform wearing a semi exoskeleton, looking at an actual pin board supplemented by virtual conical fixtures [6].

Indicators of the quality of AR experiences

As with VR, the quality of an AR experience can be assessed using quality indicators which are common to both scenarios.

- **Level of realism (LoR)** – A gauge for how realistic your virtual world is. In order to use virtual environments in our daily lives, we should be able to experiment in the virtual world with the confidence that the experience is identical to that of the real world.
- **The sense of presence (SoP)** – The feeling of being present in a virtual environment with so much involvement that it seems to be real, even if it isn't.
- **The degree of reality** – The more real the experience - and the more congruence between what users expect to see and how they interact with the AR environments - the more users will feel like they are in those environments, both in physical and cognitive/emotional terms. Feeling present in both AR and VR environments is important for behaving as you would in reality.

2.1.2 Mixed Reality

Despite its importance, AR is still challenged by the disconnect between real and virtual domain, limiting users' ability to immerse in AR scenarios. This challenge is addressed by the concept of MR, a spectrum that includes VR and AR and implies the ability to actively interact with the virtual/augmented environments and its elements rather than just observe them. As defined by Milgram and Kishino, MR is "a subset of VR-related technologies that involve the merging of real and virtual worlds": the environment creates a window between real and virtual worlds, allowing them to interact and providing the user with practical scenarios [3].

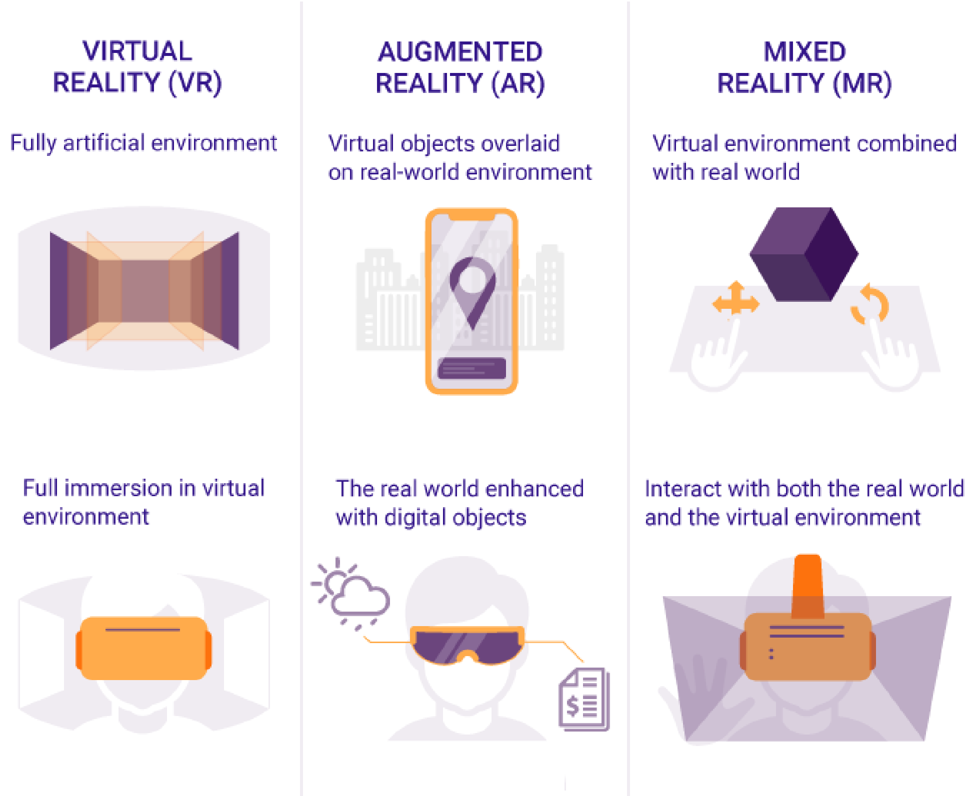


Figure 2.3: A showcase of the main differences between Virtual Reality (VR), Augmented Reality (AR) and Mixed Reality (MR) [7].

MR challenges

Implementing Mixed Reality presents some challenging technological requirements [8]:

- **Display technology** – To provide a sense of immersion, digital objects need to be displayed with high resolution and proper contrast.
- **Accurate position tracking** – The system needs to know the position of relevant physical objects relative to the display system in order to create the illusion that virtual objects are in fixed physical positions or attached to physical objects. Most MR technologies require the system to know the position of the objects being mixed, and their location relative to the display one. In certain cases, the tracking system is physically attached to the screen

so that the person wearing the screen is tracked as well. Both position and orientation of display in all 6 degrees of freedom are required.

2.2 Multiple Sclerosis

This project uses AR and MR technologies to create an exergame - a gaming experience that acts as a form of exercise - to support persons with multiple sclerosis (PwMS). We will now discuss the pathology and its impact on the human body. Multiple sclerosis (MS) is an inflammatory disease of the central nervous system that causes physical or cognitive disability and neurological deficits. The disease is influenced by many factors [9]:

- **Genetic susceptibility** – the risk of developing MS in a person's family members is determined by the amount of genetic information shared between them.
- **Environmental factors** – Environmental factors like exposure to viral and bacterial agents, vitamin insufficiency, and smoking have also been tied to the development of MS. Each of these triggers a cascade of events in the immune system that leads to the loss of nerve cells, the degeneration of nerves and their consequent dysfunction.

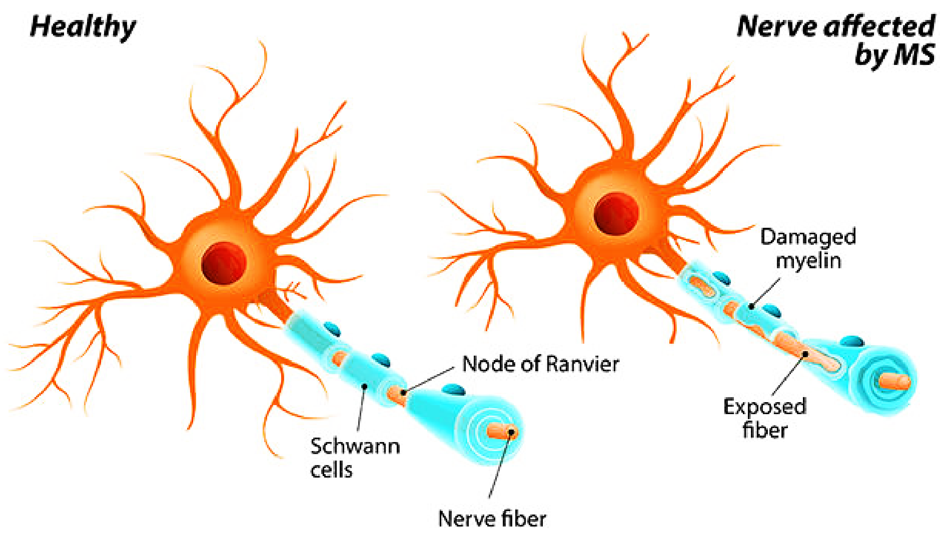


Figure 2.4: A nerve affected by multiple sclerosis. In MS, immune cells invade the brain and spine, attacking both the myelins and the cells which make them. When myelin is destroyed, nerve impulses have a hard time getting through - or can't get through altogether. That's what makes MS symptomatic.

2.2.1 MS in Italy: the AISM barometer

The Multiple Sclerosis Barometer of the AISM (Associazione Italiana Sclerosi Multipla) provides some interesting analytics on the state of multiple sclerosis in Italy [10].

- There are 133,000 people with MS and 3,600 new cases every year in Italy. The prevalence of the disease is estimated at 215 cases per 100,000 inhabitants. Of these, 15% have a progressive form, characterised by persistent disability that gradually worsens over time.
- Multiple sclerosis costs an average of €45,000 per person per year at national level. The cost is much higher, up to €85,000, for the most severe cases.
- Females outnumber males in prevalent cases by about two to one, while there is a 3:1 ratio in incident cases (new cases annually). It typically strikes with an onset of symptoms around the age of 30 and is most often diagnosed between the ages of 20 and 40. It can also be diagnosed in children and young people (in about 5% of cases), as well as in older people.

Region	Centres	Patients
Abruzzo	3	3.622
Basilicata	1	663
Calabria	2	1.677
Campania	10	5.191
EmiliaRomagna	9	5.873
FriuliVenezia Giulia	2	356
Lazio	14	9.130
Liguria	8	3.281
Lombardia	22	12.501
Marche	2	1.718
Molise	1	930
Piemonte	10	3.354
Puglia	7	7.721
Sardegna	3	3.481
Sicilia	10	8.772
Toscana	8	3.081
Umbria	2	576
Veneto	7	3.004
Total	121	74.931

Figure 2.5: Number of MS centres and patients per region. According to the 2022 Barometer, there are 121 active MS centres in Italy. Together, they treat more than 74,000 registered patients [10].

2.2.2 MS categories

Every PwMS undergoes an individual clinical journey, characterised by various relapse and worsening stages. These moments can be summarised in 4 disease courses, as defined by the International Advisory Committee on Clinical Trials of MS in 1996 [11].

Clinically isolated syndrome (CIS)

Clinically isolated syndrome (CIS) is an initial outbreak of neurologic symptoms caused by inflammation and demyelination in the central nervous system. People with CIS may experience different symptoms:

- Vision problems (optic neuritis)
- Vertigo
- Weak arm or leg muscles, with one side of the body affected more than the other
- Loss of sensation in the face
- Loss of control of bodily movements (ataxia)
- Bladder problems

CIS is defined as an episodic event lasting 24 hours or more. While such an episode is typical of MS, not all people with CIS will develop MS. A person with CIS is likely to have a second episode of neurological symptoms and be diagnosed with relapsing-remitting MS if a Magnetic Resonance Imaging (MRI) shows brain lesions similar to MS. The chances of an MS diagnosis are much lower without these lesions.

Relapsing-remitting MS (RRMS)

Relapsing-remitting MS (RRMS) is the most common form of the disease, with well-defined attacks of new or worsening neurological symptoms also referred to as relapses or exacerbations. After these, periods of partial or full recovery or remission may follow. The symptoms can disappear completely or be persistent. However, during these periods, the disease does not appear to be progressing. RRMS is initially diagnosed in about 85% of people with MS. If there is a progression in the course of the disease, it is considered to be secondary progressive MS.

Secondary progressive MS (SPMS)

The initial relapsing-remitting course is followed by secondary progressive MS (SPMS). People who are diagnosed with RRMS eventually go on to have a secondary progressive course, in which there is a gradual worsening of neurological function or an accumulation of disability over time.

Primary progressive MS (PPMS)

In PPMS, there is a worsening of neurological function or accumulation of disability as soon as symptoms appear, with no early relapses or remissions. 15% of people with MS are diagnosed with PPMS.

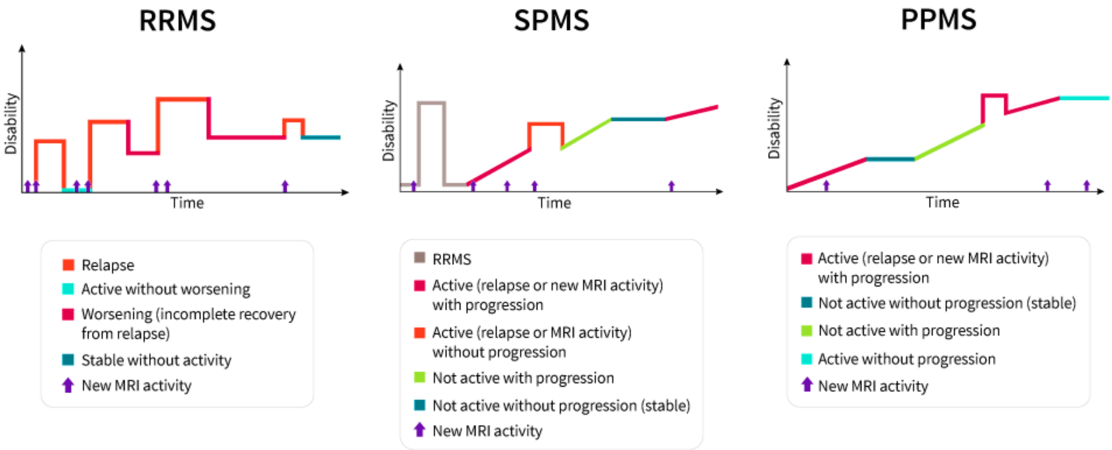


Figure 2.6: Disease activities in RRMS, SPMS and PPMS over time. Each person's experience of MS is individual, so these graphs serve as examples that describe a typical scenario [11].

Radiologically isolated syndrome (RIS)

Radiologically isolated syndrome (RIS) classifies people who have brain or spinal cord lesions that cannot be explained by another diagnosis, are consistent with MS lesions, and have no past or present neurological symptoms or abnormalities on neurological examination. Although not considered to be a course of MS, many of these people had undergone MRI for other symptoms, such as headaches, and the results revealed lesions similar to those seen in MS. Just over half of people with RIS go on to develop MS within 10 years, according to a recent study on the subject [12].

2.2.3 Cerebellar tremor

A cerebellar tremor is a disabling condition that patients with multiple sclerosis experience on a daily basis during the performance of common everyday activities. These types of conditions affect goal-oriented actions, with severe consequences for the motivation to undertake tasks. Specifically, it is manifested as "intention tremor", a dyskinetic disorder characterised by a low-frequency tremor that occurs during the performance of deliberate actions. This leads to dysmeria, i.e., overshooting or undershooting when choosing a target.

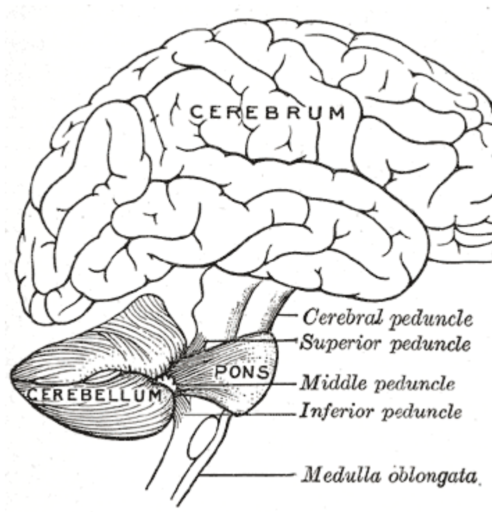


Figure 2.7: Drawing of the human brain, showing cerebellum and pons [13]: lesions in the cerebellum or lesions in the proprioceptive nerves leading to the cerebellum can produce dysmetria, a lack of coordination in respect to a certain physical action.

About the ENACT project

The work carried out in this thesis is part of the **ENACT project** [14] (Employing Neuroergonomic solutions to Attenuate the Cerebellar Tremor), a three-year research project supported by the Istituto Italiano di Tencologia (IIT) and the Associazione Italiana Sclerosi Multipla (AISM), with the support of the Fondazione Italiana Sclerosi Multipla (FISM). This article is part of the data collection planned for the second year of the project (10/2022 - 9/2023), which will focus on data collection in clinical settings, focusing on motor-cognitive rehabilitation.

Figure 2.8: ENACT logo

This project has many aims:

- to study upper limb cerebellar tremors in people with multiple sclerosis;
- to facilitate motor and cognitive rehabilitation exercises for people with multiple sclerosis;
- to develop solutions to alleviate the cerebellar tremor during daily activities.

2.3 MS rehabilitation

Given the unpredictable and fluctuating nature of the disease over time, rehabilitation is a key stage in the treatment of PwMS. It is essential to understand the range of symptoms the patient is experiencing at any given time so the proper treatment can be provided for the current stage of the disease. This approach differs from other neurological conditions such as stroke, brain injury and spinal cord injury, which have fewer variables to consider because they have a ”fixed deficit” and therefore less individualised treatment.

When symptoms begin to interfere with activities of daily living, rehabilitation addresses the problems that may arise by focusing on the pathology and its effects on the human body. There are several rehabilitation paths, focusing on different topics:

- **Physical therapy** – Physical therapy focuses on the body’s ability to perform movement functions properly. Particular attention is paid to the ability to walk, balance, posture and the degree of fatigue experienced by the patient. A large number of exercises are involved in this process with the aim of ensuring the independence of movement of the patient. Such treatment can also help with bladder problems, with physiotherapy focusing on the pelvic floor.
- **Occupational therapy** – Occupational therapy for people with MS helps the individual to carry out daily tasks, such as driving to work, walking and folding laundry. Occupational therapy does not focus on physical abilities per se. Rather, it focuses on the correct performance of general daily functions. It is therefore modelled on the lifestyle of the individual.

- **Speech rehabilitation** – This rehabilitation focuses on issues related to speech or swallowing problems, both of which are caused by central nervous system problems that reduce control of the muscles used in these functions. The aim is therefore to ensure the ease and intelligibility of the communication process.
- **Cognitive rehabilitation** – In all of the above categories, the individual's ability to think, reason, concentrate and remember is also monitored. Professionals are therefore dedicated to ensuring that the patient's ability to perform these functions is maintained and that any changes that occur are recorded.
- **Vocational rehabilitation** – This type of rehabilitation addresses the individual's right to work by providing vocational training, employment support and job transition assistance based on feedback from the individual. It is a fundamental process to empower the patient's employability.

2.3.1 Upper limb rehabilitation

People with multiple sclerosis often experience some degree of upper limb dysfunction such as tremors, sensory deficits, weakness and loss of dexterity in one or both hands. Motion losses can affect people's quality of life, employment status and activities of daily living [15].

A number of studies have provided physiotherapy techniques for the mobility of the upper limbs of people with multiple sclerosis, long before virtual reality was incorporated into the rehabilitation process. Simple exercises can help people with everyday difficulties such as stumbling when walking or difficulty standing for long periods of time [16]. It's important to have advice from a physiotherapist or healthcare professional before starting any exercise programme. Some examples of upper limb rehabilitation exercises include:

- A simple activity in which the user throws and retrieves a tennis ball with one hand and then with the other improves concentration by activating the left and right hemispheres of the brain.
- The simple act of pressing small cork discs with the fingers to simulate a typewriter is an excellent exercise to improve finger agility by developing fine motor skills.
- The dynamic stabilisation of the wrist when holding a half-full bottle of water by lifting the forearm with the elbow resting on the table improves hand dexterity.

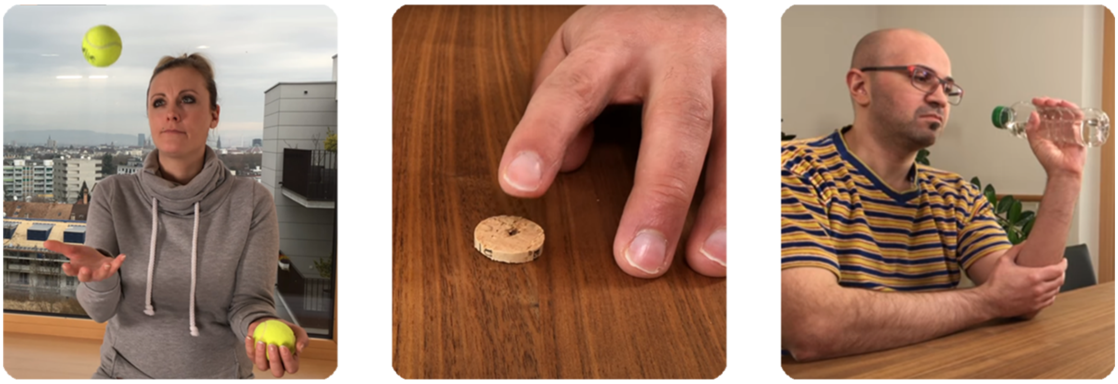


Figure 2.9: Showcasing three exercises designed to rehabilitate the upper limb.

2.4 Case studies

This section features a series of case studies where rehabilitation exercises are combined with augmented reality techniques, discussing their effectiveness and the technologies involved.

2.4.1 Virtual rehabilitation for multiple sclerosis through a kinect-based system: the RemoviEM case study

An interesting example of the use of virtual reality technologies to support patients with multiple sclerosis is given by Microsoft's RemoviEM software [17], where the user interacts with virtual objects through an on-screen projection of his movements. The use of gameplay interludes in conjunction with rehabilitation exercises creates a gaming pretext that engages the user and distracts him from physical exertion. RemoviEM uses VR to help people living with MS perform motor-based rehabilitation exercises. Three different motor exercises are included in the RemoviEM programme:

- **TouchBall** – This first exercise works on balance, weight shifting and lateral trunk movement. It requires a person to "touch" different virtual objects that are displayed on screen.
- **TakeBall** – In this exercise, the MS patient uses both hands to move virtual objects to a specific target, promoting coordination and diagonal movement of the upper extremities.
- **StepBall** – This last exercise requires the MS patient to balance and shift its body weight while performing one-legged lateral movements, stepping over virtual objects that appear to avoid various obstacles.

Figure 2.10: Three exercises from the RemoviEM program.

2.4.2 Augmented Reality for Rehabilitation using Realtime Feedback: the SleeveAR case study

SleeveAR [18] presents a rehabilitation system based on AR technology. It consists of a portable sleeve with embedded sensors that track the movement of the patient's arm, and an AR display that provides real-time feedback to the patient during rehabilitation tasks. SleeveAR addresses the specific scenario of recovering an injured arm by augmenting the surfaces available to the patient, the full arm and the floor, with virtual guidance information.

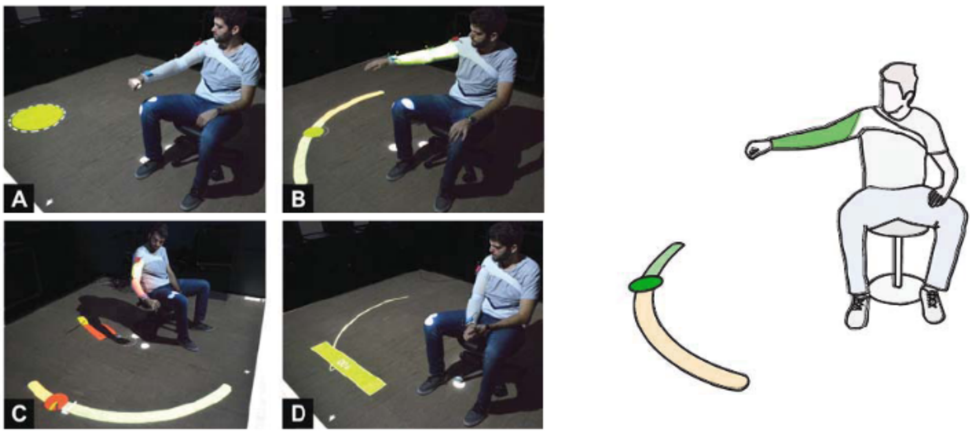


Figure 2.11: SleeveAR provides movement guidance and performance feedback through augmented reality projections on an arm sleeve and on the ground.

Study results suggest that SleeveAR can provide useful feedback to patients during rehabilitation exercises and has the potential to improve rehabilitation effectiveness. Limitations and challenges are also discussed, including further optimization and adaptation to different patient needs, and integration into existing rehabilitation settings. Overall, the paper highlights the potential benefits of providing real-time feedback to patients during rehabilitation exercises and presents a promising approach to the use of AR technology in this regard.

2.4.3 Wearable Augmented Reality Application for Shoulder Rehabilitation: The "Painting Discovery" case study

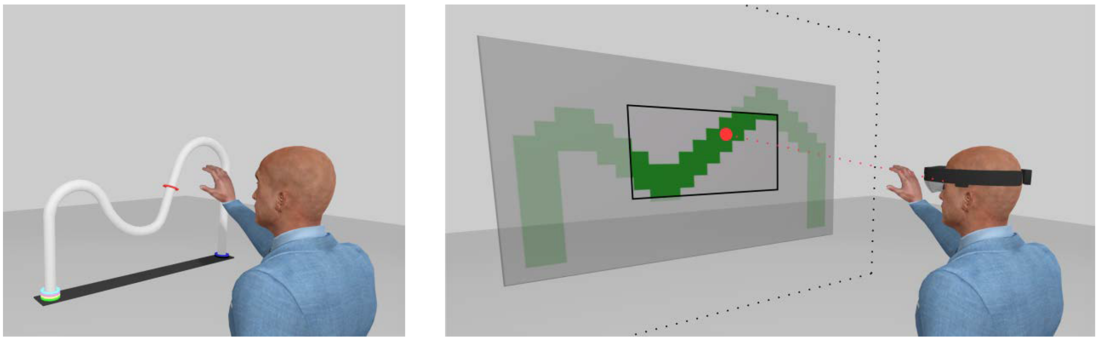
Another interesting case of a serious game designed for upper limb rehabilitation is "Painting Discovery" [19], an AR experience developed at the University of Pisa that uses the same headset from this project - the Microsoft Hololens 2. The Rolyan Graded ROM Arc, a physical therapy activity that helps train upper extremity deficiencies that prevent mobility, was the blueprint for this serious game. It consists of a curved tube with moveable colour tabs that can be moved from one side of the tube to the other.

Figure 2.12: The Rolyan Graded ROM Arc, which inspired the "Painting Discovery" AR experience.

The AR game involves the movement of a virtual cursor, controlled by the user's hand, along a predefined AR trajectory on a semi-transparent panel in front of the user to reveal a painting underneath the grid of tiles. The user controls the cursor by moving their hand, and each touched tile changes as the virtual cursor moves to follow the trajectory.

- If the tile is part of the path, it turns transparent to show the part of the painting underneath.
- If the tile is not part of the path, it turns red to show that a mistake was made in deviating from the path.

Participants in the study, who were interviewed at the end of the game session, agreed on the huge motivational value provided by the experience.



(a) (b)

Figure 2.13: An example of an exercise using the traditional (a) and the AR-based (b) shoulder rehabilitation.

Chapter 3

Tools and Frameworks

In this section, we will review all the tools and frameworks used in the thesis project. We will justify their choice and provide useful documentation on the technological advances that made them possible.

3.1 Microsoft Hololens 2

In the field of augmented reality devices, Hololens 2 is one of the industry benchmarks. As a follow-up to its predecessor, the device improves on its immersion capabilities and ergonomics with a wide range of new features, such as the following:

- **Advanced Eye Tracking** – The Eye Tracking API provides information about what the user is looking at approximately 30 FPS. In order for eye tracking to be accurate, each user must undergo a proper user calibration: this is an automatic process that is activated each time the headset detects a new user. The calibration process takes little more than a minute and allows the technology to be used to its full potential. When calibration is complete, users can pick up where they left off.
- **Full hand tracking control** – Hololens 2 detects users' hands as a left and right skeletal model. Ideally, to implement the idea of direct hand contact with holograms, five colliders could be attached to the fingertips of each hand skeletal model.
- **Spatial audio** – Spatial audio creates sound from any point in the listener's sphere, 360 degrees around the listener. It can be binaural or object-based: Headphones use binaural sound, TVs, radios and speakers use object-based sound.

Figure 3.1: Microsoft Hololens Gen 2 (2019)

Hololens 2 is also a mixed reality device that projects digital elements onto the lens in a real-life setting. Users can enjoy the augmented experience in a familiar environment. This is also made possible by the absence of a hand tracking device: the hands are free to move and virtual objects can be pinched and dragged by simulating the movements of real life.

Improvements on the previous version

- **Field of view** – One of the biggest problems with the Hololens 1 was given by the field of view. People using the headset could only see the holographic image directly so that if there was even the slightest movement of the user's head, the projections would disappear. Users also had to do their best to fit the content into the small square they could see. In Hololens 2, Microsoft increased the mirror angles, doubling the field of view. As a result, the user's perception of the virtual objects is much better. The improvement is significant, but there's still room for improvement: large projections need to be intelligently positioned relative to the user's viewpoint to allow the entire object to be displayed correctly. For the exercise developed for this dissertation, it was necessary to reduce the size of the grid to allow the end user to view it as a whole. Objects are now much closer and more vivid than they were in Hololens 1.
- **Interaction with virtual objects** – Hololens 2 comes with improved gestural control and enhanced sensing capabilities providing a better interaction with virtual objects. In contrast to Hololens 1, which was limited to a few basic gestures, Hololens 2 allows new hand movements such as resizing, scaling, grabbing, dragging, etc. The new iteration of the device can also detect hand gestures and track the user's eyes, allowing them to scroll through windows and text documents by viewing the bottom of the page. A voice assistant that allows you to give directions using voice commands is also integrated.

Figure 3.2: Microsoft Hololens Gen 1 (2016)

3.2 Unity

Unity is a popular game engine enabling developers to create interactive 2D, 3D and VR/AR experiences for multiple platforms including desktop, mobile, console and web. From creating game worlds and characters to scripting gameplay mechanics and implementing advanced visual effects, Unity provides a complete set of tools for designing and building games. Unity also boasts an extensive community of developers creating an enormous range of extensions and assets to enhance games built with the engine. With its ease of use and cross platform integration, it provides an interesting solution for software development dedicated to augmented reality devices: the engine currently supports development for more than 19 different platforms including mobile, desktop, consoles, and VR devices.

Marketability

The game engine has proven itself to be a useful tool in a number of different areas of visual arts. As of 2018, Unity had been used to create half of the mobile games on the market and 60% of augmented reality and virtual reality content [20]. A useful insight is its wide range in the virtual reality market: 90% on emerging augmented reality platforms, such as Microsoft Hololens, and 90% of Samsung Gear VR content [21].

3.2.1 Mixed Reality Toolkit

In spite of its versatility, Unity has shown a lack of availability of features and compatibility when it comes to the world of virtual reality. A great help in this regard is a useful toolkit developed by Microsoft called the Mixed Reality Toolkit (MRTK).

MRTK is both a collection of tools for rapidly creating Mixed Reality (MR) experiences and an application framework. It serves as a bridge to connect the capabilities of a rich set of MR devices, such as the Microsoft Hololens 2, with the

Unity game engine. By exploiting the possibilities of MRTK, a project build can be generated ready to be deployed to the device in a matter of minutes. The ability to take full advantage of the spatial awareness built into the Hololens 2 technology is one of the many features offered by the framework: in mixed reality applications, Spatial Awareness provides awareness of the real world environment.

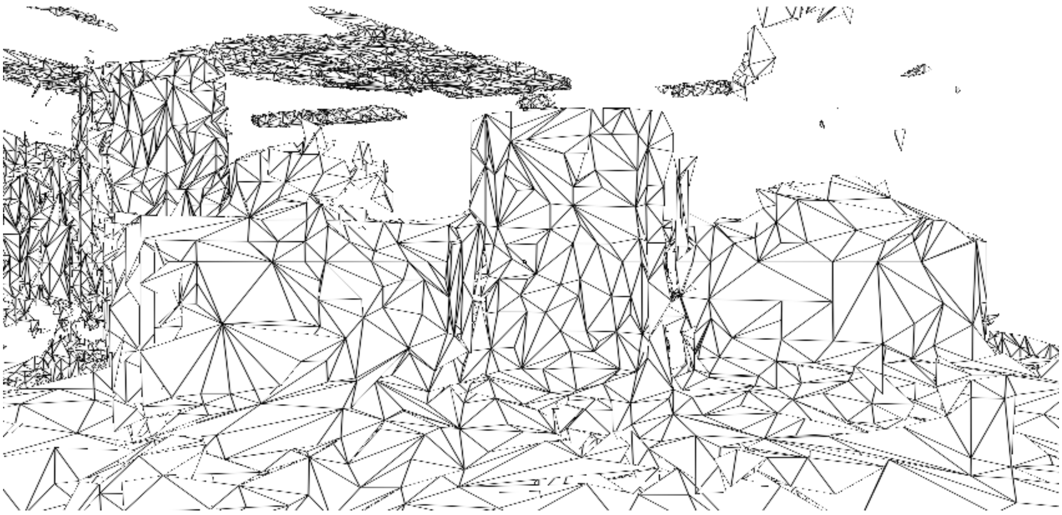


Figure 3.3: A demonstration of the mesh mapping of a room using the MRTK Spatial Awareness tool.

When it was introduced in Microsoft Hololens, Spatial Awareness provided a collection of meshes that represented the geometry of the environment, which allowed for engaging interactions between the holograms and the real world. In the case of the exergame being developed in this thesis, this feature is crucial in allowing the cube to rest realistically on the table during the rest phases, so that it can be recovered naturally at the start of the next section.

3.3 Other software and frameworks

A number of other software and tools were used in the course of the thesis to support the above-mentioned technologies and frameworks. These will not be described further, but are listed here.

- All the graphic components that make up the console's user interface were created using Adobe Photoshop.
- The music production tool FL Studio was used to create the soundtrack and all the audio elements that accompany the game experience. The music

soundtrack is an original work written and exclusive to this dissertation, while many of the sound effects are adaptations of samples taken from Freesound.org [22].

- The elements that make up the game grid were created using Blender, a 3D modelling tool.

Chapter 4

Game design

4.1 The goal

The objective of this thesis is to take an exercise traditionally used in MS upper limb rehabilitation - moving a cube with one hand to different positions on a numbered grid according to predetermined movement sequences - and supplement it with audio-visual and gamified features. This is done to observe, if present, an increase in the user's involvement in the experience.

- In terms of design, the primary goal was to create a clear experience with a compelling look, without any distracting elements which might disadvantage the end user. Specifically, more information was to be provided with fewer elements. As an example, the use of colour as an information medium could improve the rules comprehension.
- The experience had to combine features for users with features for medical staff: it was really important to hide this extra information from the end user to achieve this minimalist feeling. Conversely, the control panel for the medical personnel had to be as intuitive as possible so that parameters could be changed quickly.
- The co-existence of the front-end gameplay and the back-end data being sent in the background during the game was also an important element. Without interfering with the core gameplay, the data had to be presented in a clear and comprehensive manner.
- Another important feature was the immediate storage of data: it is necessary to constantly store data and to properly manage sudden interruptions of the game, with the sub-records being recorded until the pause. This means that it is not necessary to finish a level in order to obtain the data it contains.

4.2 Use case scenarios

Some use case scenarios are considered to better understand a practical use of the exergame.

4.2.1 Supervised by medical personnel

The first of these scenarios implies support by the medical staff involved in the rehabilitation process. The user arrives at the centre with the intention of taking part in a training session: this is done according to a schedule agreed with the staff. When the user first attends this training, he is introduced to the rules of the game. Under the supervision of the personnel, the user is equipped with the headset and participates in the training session. The collected data is then transferred to a computer for further analysis.

4.2.2 Standalone approach

The second scenario implies autonomous use of the device by the user. After being instructed on how to turn on the device and select the application, the user is provided with a device that can be comfortably used in a home scenario. The user completes the exercise and returns the headset to the centre on a weekly/monthly basis according to a schedule agreed with the support staff. The data inside the device is labelled for each session so that it can be exported and easily viewed by the personnel. In this scenario, the user is also introduced to the level selection panel. This allows him to select the preset configuration from the comfort of his own home.

4.3 Game architecture

4.3.1 The cube

The cube is the most important element of the experience: it works as a pawn that can be moved during the mixed reality experience by means of a pinch. The game is played by dragging the pawn into the grid tiles according to a set of rules and restrictions to score points. It is also the only part of the game that has any physical interaction with the user: the user must hold it in order to continue the game. To simulate its physical drag, raycasting is turned off to allow only close-up manipulation. As a simulation of a real object, the cube has a mass and is subject to the force of gravity. Its weight prevents the piece from behaving unexpectedly when it's not pinched: when this happens, the cube simply falls to the table and can be picked up.

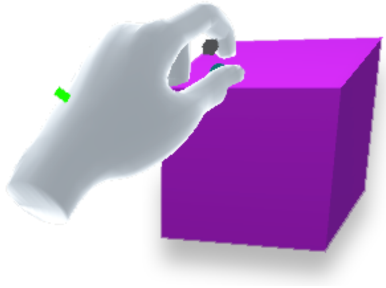


Figure 4.1: The cube, pinched by the user in a simulated environment

4.3.2 The grid

The user is introduced to a grid of 9 tiles, made up of 3 rows and 3 columns. At the beginning of the experience, a randomly selected tile becomes “active” and glows in green colour, rewarding the player with a point as soon as it is crossed with the pawn. When this happens, a new tile is randomly activated from the grid and the previous one becomes inactive: an inactive tile is grey and can be intersected with no consequences. The aim of the game is to try to score as many points as possible in the time available, while avoiding the penalties that can be inflicted by certain actions during the game.

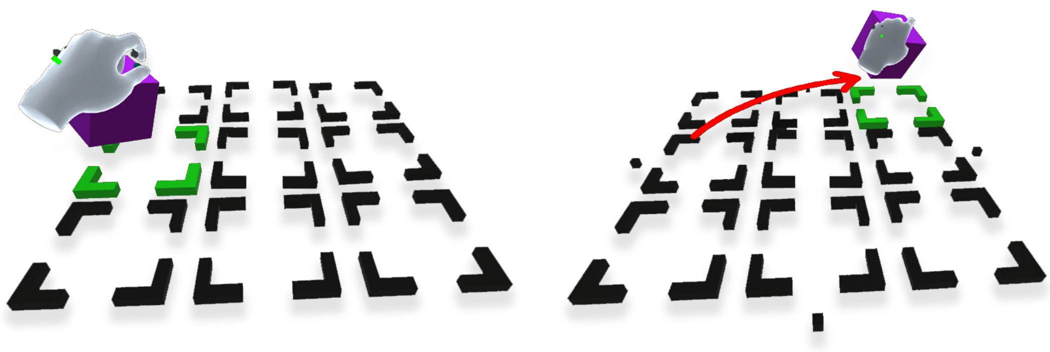


Figure 4.2: Two different stages of the game. On the left, the user is ready to cross the tile in the middle left with the cube. On the right, the tile that has been crossed becomes inactive and the user moves to the top right of the grid to repeat the process with the new, randomly chosen active tile.

4.3.3 Tile types

To add depth to the experience, different types of tiles are provided. These tiles will appear in the game in different proportions and quantities, according to the information provided by the control panel (page 32) before the experience. The aim of these complications is to provide a sense of progress in the gameplay, where a limited range of possibilities still allows for many different combinations. Finding the right balance between these factors is crucial to achieving a compelling gameplay experience. The experimental results (page 45) will show this balance and the effect of its absence in more detail.

- "Active" tiles can be replaced with alternative versions, switching between a "waiting" and an "active" state every 2 seconds. The **"waiting"** state is indicated by a shaky, purple coloured tile: if a tile is crossed while in its "waiting" state, the user is penalized with an error. To score points, you have to time your moves and cross the tile when it is "active".
- Depending on the level settings, an "active" tile can be paired with one or more red glowing **"spiky"** tiles - up to 4 on every grid iteration - that penalize the player by acting as obstacles. They punish the user with an error every time they are crossed by the cube. To avoid unexpected errors or undeserved points, green, red and yellow tiles become "inactive" immediately after being crossed. With each new point or error, the grid tiles are reshuffled and the game resumes.

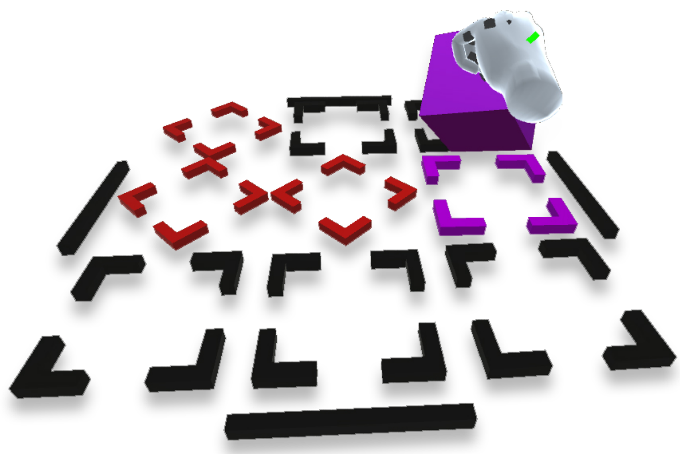


Figure 4.3: A more complex grid formation with three "spiky" tiles and a "waiting" tile. The user must get the timing right and cross the shaky tile when it reaches the "active", green coloured form. To avoid a penalty, he must also try to avoid red tiles.

4.3.4 Levels, sessions, breaks

The different phases of the game, organised according to a well-defined hierarchy, dictate the game and its timing. This hierarchy is crucial to the experience: in addition to the type of tiles involved in each part of the experience, a good balance in the length of each part of the game is the secret of an engaging exercise.

- **Steps** – A single passage from an "active" tile to another. The step is not incremented if an error occurs. The user will have to repeat it with a different tile placement.
- **Levels** – These are a series of movements of the cube within the grid according to common parameters. Each level offers a number of options, including the amount of "spiky" tiles, the number and type of audio channels enabled, and the likelihood of getting a "waiting" tile instead of an "active" one: all these parameters are fully configurable in the control panel (page 32).
- **Sessions** – Several levels form a session. The game experience can consist of several sessions separated by breaks of various lengths.

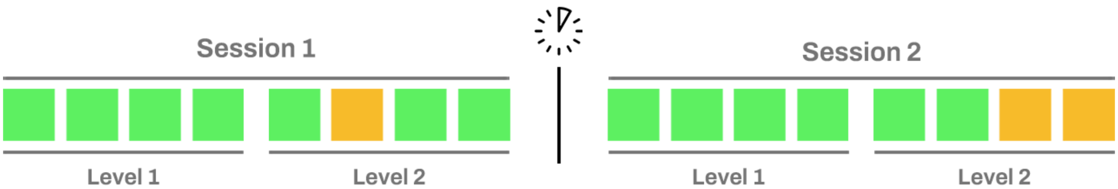


Figure 4.4: A case scenario: the game consists of two sessions of 2 levels each, with 4 steps each and an interval between every session. Each square represents a step in the game, with the ones coloured in yellow indicating the possibility of coming across a "waiting" tile.

4.4 Visual and audio cues

4.4.1 Shrinkable frame

The 3x3 grid of tiles is surrounded by a glowing, shrinkable frame, providing visual clues to the progress of the current session. Since, as will be shown in the experimental phase (page 48), the total duration of the game must be concealed from the user, the frame only provides information about the current session and not about the entire exercise. This information on the progress of the current session is also useful in helping the player understand when there will be a break to rest their hand, a feature that is really helpful in more intensive sessions.

- At the beginning of each session, the frame is absent: as soon as the first "active" tile has been crossed, the frame will be in place and will extend itself each time a step is completed.

- When finished, all four sides are joined together, creating a full frame. If there is a break in the session, each side of the frame will begin to shrink back to its initial size, pulsating in bright yellow. At the end of the break timer, the frame will have reached its minimum length: at this point, a new session will be started together with the frame cycle.

- Colour cues provide feedback to the user. The border lights up green for each new level. A red glow is an indication that the user has made a mistake. A successful step is indicated by a yellow glow.

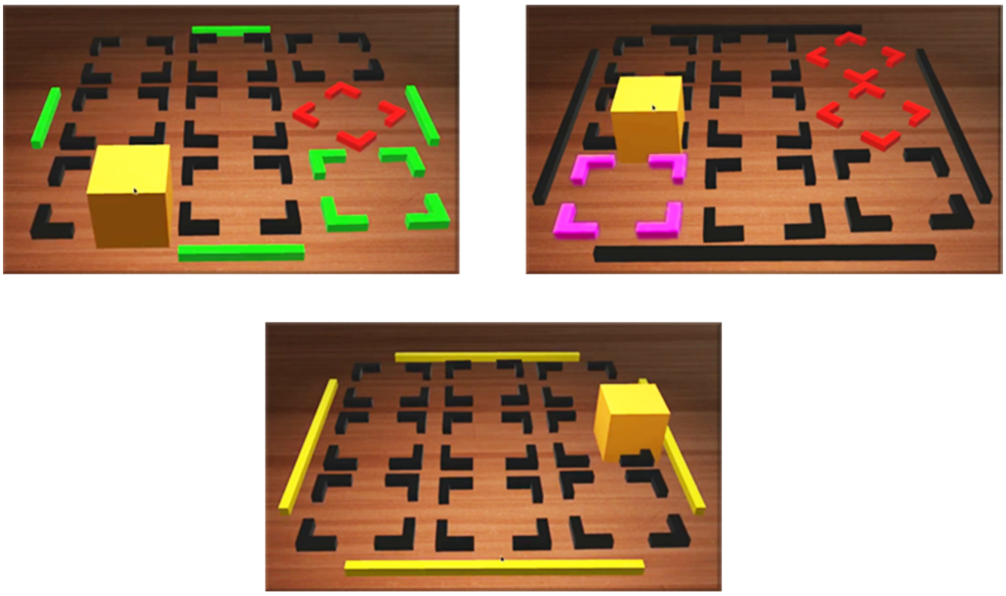


Figure 4.5: Showcasing the frame behaviour. From the left, in the first picture, a green light is shown when a new level has been reached. In the second image, the frame of the game increases in size as the game progresses. During a break, the shrinking frame glows in yellow and the tiles are temporarily disabled.

4.4.2 Music and audio cues

Research and literature have underlined how music, as an essential component of the game's narrative, can be seamlessly incorporated into the nonlinear format of a game [23, 24]. For this reason, the game experience is enhanced with audio elements that follow the user through the exercise, forming an original musical piece composed exclusively for this project and divided into 8 different tracks.

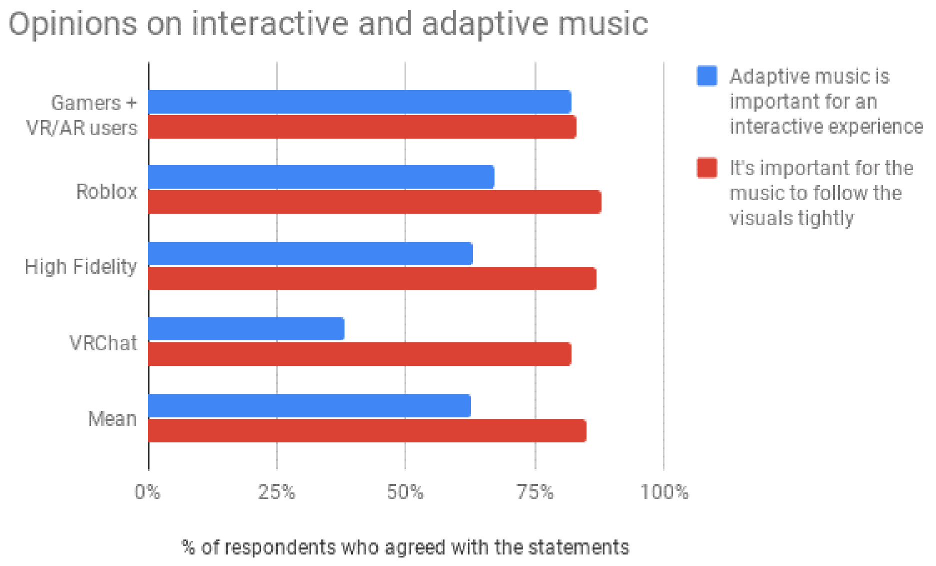


Figure 4.6: Results from a survey [25] conducted by Audiokinetic across different demographics - VR/AR users and traditional video game players, Roblox users, High Fidelity users and VRChat users - that was completed by 179 users. The study showed a rising interest in AR/VR users regarding the use of adaptive music in interactive experiences.

Playing these tracks at specific points throughout the experience gives a sense of progress and rewards the player with a musical progression that resolves after each session. A new instrument is seamlessly added to the track with a small fade in after each level, and fades out in a similar fashion if it's not expected on the next one. The experience can also be played without any music at all by turning it off via the control panel (page 32).

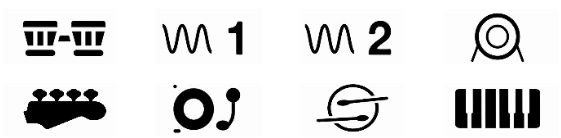


Figure 4.7: The icons of the 8 tracks that make up the piece of music, as they are displayed on the control panel.

The track characteristics are shown below:

- **Track 1** – A percussion tribal rhythm with a small flanger.
- **Track 2** – A moody synth that creates a soft and mellow atmosphere.
- **Track 3** – A companion synth to the previous one, complementing it with low-pitched sounds.
- **Track 4** – An electronic, clean-sounding drum kick.
- **Track 5** – A low frequency bass riff.
- **Track 6** – A synth arpeggio.
- **Track 7** – A clean, punchy snare clap.
- **Track 8** – A short piano piece with a smooth, comforting sound.

The number and type of channels played are adjustable for each level in the control panel. In addition, you can select individual channels for the pause time between the individual tracks, thus ensuring a consistent flow between the individual tracks and avoiding abrupt changes in the music. Cuts are also avoided by writing the pieces of music as endless loops: they play in the background throughout the experience and fade out at the end.

The length of each track is proportional to the average length of the experience: by adding one or more tracks to each level, the user achieves a sense of satisfaction by listening to the entire track at the end of each session. The constant presence of two more intricate tracks, the piano and the synthesiser, prevents repetition.

Apart from the music, smaller audio cues are used as feedback to the player during a session: crossing an active tile plays a different sound depending on the tile type. New levels, sessions or breaks are also introduced with various snippets: coupled with the glowing frame, they update the player with some information about the progress of the current session.

Sound inserts provide feedback when interacting with the various buttons of the GUI, confirming the success of the operation performed.

4.4.3 Ending screen

At the end of a game session, or when time expires, a final display will interrupt the game providing a quick summary. Specifically:

- The total number of tile crossings is shown, as well as a percentage of the ones made correctly versus those made incorrectly.
- The number of seconds remaining is also displayed if the game ends before time runs out.
- In addition to the game data, the name of the folder containing all the reports for the current sitting is displayed.

In the testing phases, a command in the control panel was used to hide most of this information from the end user. The reason for this was to prevent the self-assessment process from being compromised by the pre-display of certain information about the results. The only data that was provided was the location of the stored data to allow the operator to keep track of the location of the files within the device.

Figure 4.8: The ending screen

4.5 Extensions

In addition to the game experience mentioned above, the application allows healthcare professional to configure the parameters and characteristics of the experience without the need for a computer, unless to export the results of an exercise. This is done via a control panel that can be configured using the touch commands offered by the Hololens 2 headset.

4.5.1 Control panel

This feature is designed to help the medical staff tune the experience for the end user. The control panel is divided in two different macro sections: the first contains the "experience setup", and the second the "level setup". By pressing any button on the control panel, the rules are updated and the game is restarted automatically.

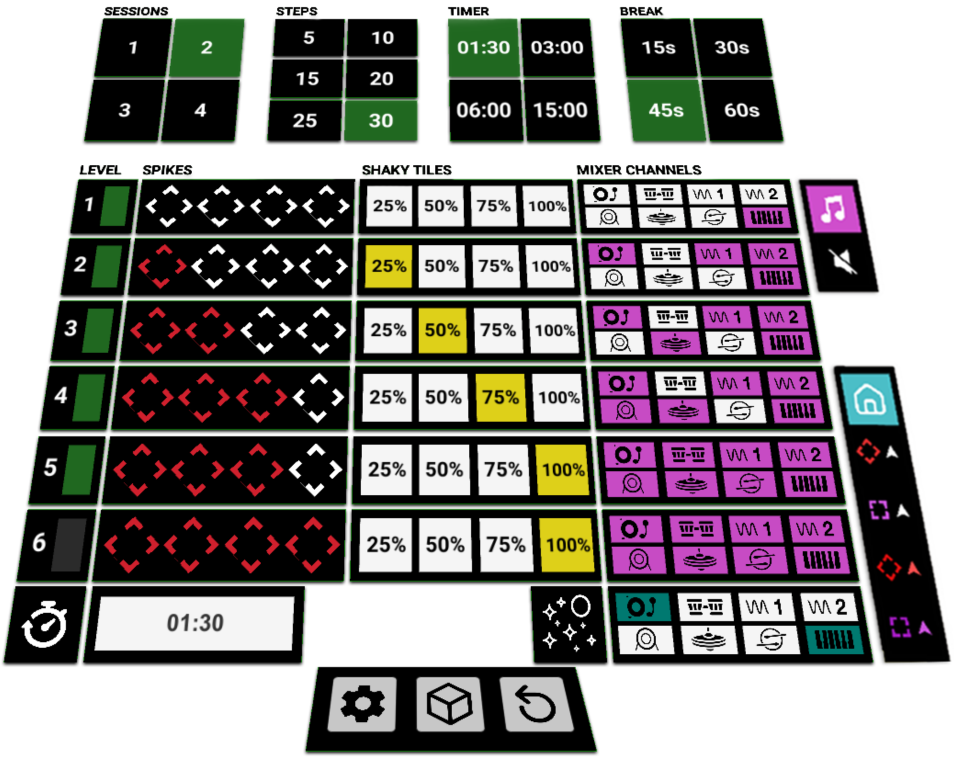


Figure 4.9: The control panel: the top row contains the ”Experience Setup” settings, while the second and following rows contain ”Level Setup” settings. The toolbar appears at the bottom. On the right, there are two vertical menus. These allow you to change a specific preset or mute/unmute the music.

Experience setup

The “Experience setup” settings are listed below:

- **Sessions** – Select the number of sessions (sets of levels separated by a pause) that will be presented to the user during the next session: values between 1 and 4 can be selected.
- **Steps** – Choose the number of steps for each level for the next sitting: from 5 to 30 steps, in multiples of 5 steps.
- **Track** – Select the length of the next sitting. Selectable values include 01:30, 03:00, 06:00 and 15:00 minutes.
- **Break** – Select the length of the break time for the next sitting: from 15 to 60 seconds in multiples of 15 seconds.

Level setup

The “Level setup” settings are listed below:

- **Level** – Select the number of levels per session for the next sitting: pressing any button on the selector will automatically activate the previous ones.
- **Spikes** – Select the number of ”spiky” (red) tiles per level for the next session: from 0 to 4. To reset your selection, press the selected value again. Pressing any button on the selector will automatically activate the previous ones.
- **Shaky tiles** – Choose the probability of finding a “waiting” (purple) tile instead of a green tile in the next sitting: from 0% to 100% in multiples of 25%. To reset your choice, press again on the selected value. By pressing any button on the selector the previous ones are enabled automatically.
- **Mixer channels** – Choose the active audio channels per level. An extra mixer channel is provided to pick the active audio channels during break time.
- **Timer** – During a session, you can open the control panel to see the current time progress of the experience and how much time is left.

Toolbar

While playing, a small toolbar will appear underneath the grid. This toolbar gives you quick access to a number of actions.

- The **“Gear”** button allows the control panel to be opened and closed by pressing it again.
- The **“Cube”** button is useful during a session to reset the cube to its default position if the user loses it. This ensures that the flow of the game is not interrupted every time the cube slips out of the user’s hand due to incorrect calibration of the device, or every time it slides into the void instead of resting on a surface as a result of incorrect room mapping.
- The **“Restart”** button resets the session to its default values. This is useful to avoid having to go through multiple steps to restart the experience.

Throughout the experience, the user is presented with silent hints: whenever the cube moves too far from the grid (for example, if it’s dropped by the user), the ”Cube” button lights up, suggesting a click on it to reposition the cube. At the same time, the restart button lights up at the end of each session.

The handle

The difficulty of re-calibrating the grid position using the Hololens functionality alone became apparent when playing with the device. For this reason, a small handle has been inserted between the grid and the panel. By dragging the handle, you can move the game around to position the experience on the surface you want to use.

This functionality is also very useful in situations where several users need to perform the exercise but are unable to move from their position due to mobility impairments: the grid will be adjusted to the position best suited to their needs by the medical staff momentarily wearing the headset.

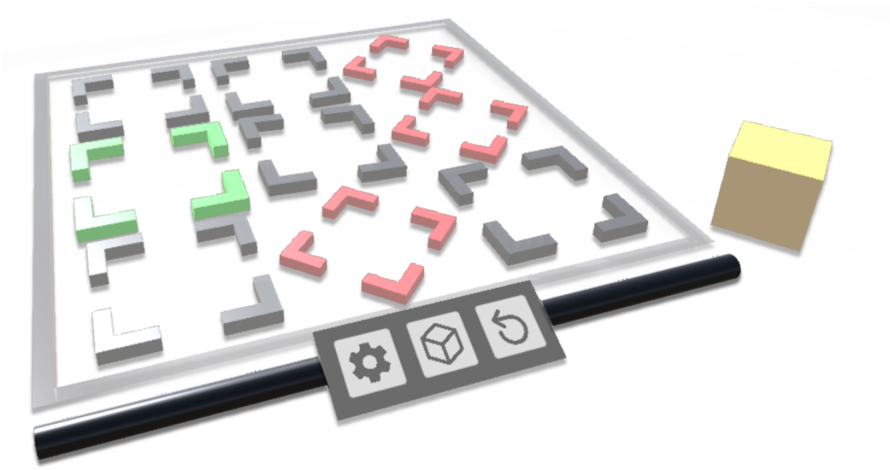


Figure 4.10: The handle

4.6 Game data

4.6.1 Introduction

The MR experience records and locally stores every single game session. This recording is done in real time to avoid losing data in the event of sudden interruptions and starts each time the user hovers the cube over the first active tile. All information about an individual session is stored in the device in a folder renamed with the session timestamp. The timestamp will be displayed to the user at the end of the experience. By providing the timestamp to the medical staff at the end of the session, the game session can be linked to the user. The files contained in each report are listed below and will be described in further detail in the following sections.

- **"times.csv"** - This file contains various temporal information about the game session: in particular, it contains the times taken to perform each section of the game, with the corresponding scores and penalties.

- **"save.txt"** - This file contains a backup of the save file used in the recorded game session. The root savefile in the directory of the game can be replaced with this backup to quickly reset a game session to the parameters used in this iteration.
- **"grid.csv"** - This file contains positional information about the grid.
- **"positions.csv"** - This file contains positional information about the cube, the hands and the eye-gaze.

The last two files are used to perform an analysis of the game using a Python script that takes the coordinates and produces an interactive 3D map of the game. The script can be used to filter only certain parts of the game so that only the parts of interest are displayed.

4.6.2 Time reports: "times.csv"

As the game progresses, rows of data are filled in a .csv file with useful information about the game state, such as:

- An **ID of the current step** that is used to link any time information to the positional one, which is tracked in the related file.
- The **type of tile** being crossed by the dice. There are 4 possible values for this field: "Green" if the cube is in the active state, "Red" if the cube is crossing an obstacle, "Purple (shaky)" if the cube is crossing a "waiting" tile and "Purple (safe)" if the cube is crossing a tile when it has interrupted its "waiting" state and is being crossed at the right time to avoid a penalty.
- The **position of the tile** in the grid that is crossed by the cube. This can be a value ranged from 1 to 9. Tiles are labelled from the top left.
- An **error flag** that is activated whenever the hovered tile is red or purple to indicate a user error.
- The number of the **current session** and the **total number of sessions**.
- The number of the **current level** in the session and the **total number of levels** in the session.
- The **time interval between the last tile hover and the current time**.
- The **time interval between the start of the current level and the current time**.

- The **time interval between the start of the current session and the current time**.
- The **time interval between the start of the game and the current time**.

Step	Tile	State	Tile ID	Session		Level		Delta			
				Current	*Total*	*Current*	*Total*	*Tile*	*Level*	*Session*	*Total*
					(...)						
242	Green	OK	9	2	4	3	6	00.00:997	00.00:997	00.55:238	05.27:262
243	Green	OK	7	2	4	3	6	00.00:761	00.01:759	00.56:000	05.28:024
244	Green	OK	4	2	4	3	6	00.02:700	00.04:460	00.58:701	05.30:725
245	Purple (safe)	ERROR	6	2	4	3	6	00.00:934	00.05:395	00.59:635	05.31:659
246	Green	OK	7	2	4	3	6	00.01:165	00.06:560	01.00:801	05.32:825
247	Green	OK	9	2	4	3	6	00.00:841	00.07:402	01.01:643	05.33:667
248	Green	OK	7	2	4	3	6	00.01:024	00.08:426	01.02:667	05.34:691
249	Green	OK	9	2	4	3	6	00.00:766	00.09:193	01.03:433	05.35:458
250	Green	OK	7	2	4	3	6	00.00:771	00.09:964	01.04:204	05.36:229
251	Green	OK	5	2	4	3	6	00.00:728	00.10:692	01.04:932	05.36:957
252	Green	OK	8	2	4	3	6	00.00:714	00.11:406	01.05:647	05.37:671
253	Green	OK	6	2	4	3	6	00.00:654	00.12:061	01.06:301	05.38:325
254	Green	OK	8	2	4	3	6	00.00:697	00.12:758	01.06:999	05.39:023
255	Green	OK	7	2	4	3	6	00.00:782	00.13:541	01.07:782	05.39:806
256	Purple (safe)	OK	6	2	4	3	6	00.02:651	00.16:192	01.10:433	05.42:457
257	Green	OK	7	2	4	3	6	00.01:549	00.17:742	01.11:982	05.44:007
258	Green	OK	9	2	4	3	6	00.00:752	00.18:494	01.12:735	05.44:759
259	Green	OK	6	2	4	3	6	00.00:732	00.19:227	01.13:468	05.45:492
260	Green	OK	5	2	4	3	6	00.00:739	00.19:966	01.14:207	05.46:231
261	Green	OK	4	2	4	3	6	00.00:792	00.20:759	01.14:999	05.47:023
262	Purple (safe)	OK	9	2	4	3	6	00.02:699	00.23:458	01.17:699	05.49:723
263	Purple (safe)	OK	4	2	4	3	6	00.02:767	00.26:226	01.20:467	05.52:491
264	Purple (safe)	OK	6	2	4	3	6	00.02:532	00.28:759	01.22:999	05.55:023
265	Green	OK	9	2	4	3	6	00.00:983	00.29:742	01.23:983	05.56:007
266	Green	OK	7	2	4	3	6	00.00:615	00.30:358	01.24:599	05.56:623
267	Green	OK	6	2	4	3	6	00.00:709	00.31:067	01.25:308	05.57:332
268	Purple (safe)	OK	8	2	4	3	6	00.02:676	00.33:743	01.27:984	06.00:008
269	Green	OK	6	2	4	3	6	00.00:693	00.34:437	01.28:677	06.00:701
270	Purple (shaky)	ERROR	7	2	4	3	6	00.00:858	00.35:295	01.29:536	06.01:560
271	Green	OK	9	2	4	3	6	00.01:199	00.36:495	01.30:735	06.02:760
272	Green	OK	5	2	4	3	6	00.00:765	00.37:260	01.31:501	06.03:525
273	Purple (safe)	OK	8	2	4	4	6	00.02:697	00.00:000	01.34:198	06.06:222
274	Green	OK	9	2	4	4	6	00.00:834	00.00:834	01.35:032	06.07:057
275	Green	OK	7	2	4	4	6	00.01:147	00.01:981	01.36:179	06.08:204
276	Green	OK	5	2	4	4	6	00.00:718	00.02:699	01.36:898	06.08:922
277	Green	OK	7	2	4	4	6	00.00:910	00.03:610	01.37:808	06.09:833
278	Purple (safe)	OK	5	2	4	4	6	00.02:570	00.06:181	01.40:379	06.12:404
279	Green	OK	2	2	4	4	6	00.00:824	00.07:005	01.41:204	06.13:228
280	Green	OK	6	2	4	4	6	00.00:780	00.07:786	01.41:984	06.14:009
					(...)						

Table 4.1: An extract of a time report from a game session.

4.6.3 Positional data: “positions.csv” and “grid.csv”

Along with the timetable, positional data is also recorded in a separate CSV report containing information about the position and rotation of the cube along with the movement of the hands, as well as positional information about the grid and eye-gaze information taken from the head position and the eye-tracker. Some interesting observations were made using these tracking features, as shown in Section 5.4.3 and in Figure 5.3.

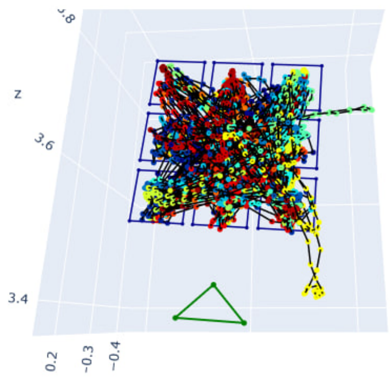


Figure 4.11: A 3-D scatter plot of all the movements of the cube during a single session. Different steps are represented by different colours. The cloud can be filtered to show only the most interesting clumps.

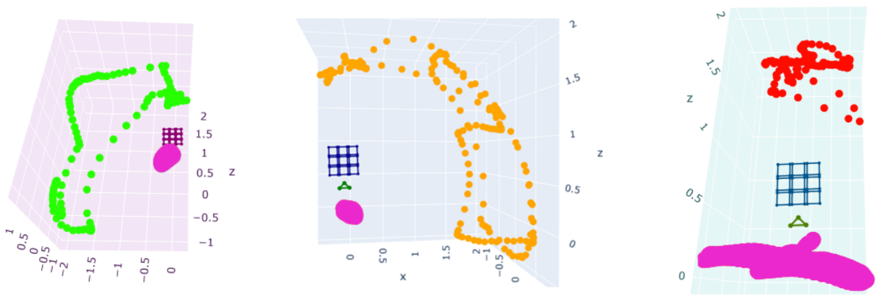


Figure 4.12: Eye-tracking tests to check the accuracy of measurements on the game grid: the purpose of these tests is to simulate moments of distraction during the game. Head positions are indicated by purple dots. On the left: looking to the left without looking at the grid. Middle: looking to the right without looking at the grid. On the right: generic head movement test.

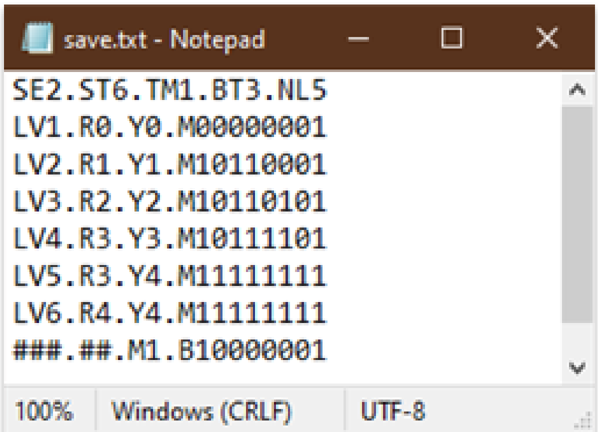
Information on the position of the head, eyes, dice and hands is stored every

10Hz and is associated with the millisecond value of the current session duration, along with the ID of the current step. The need not to overload the device during a game session dictates the choice of this level of detail. In support of this, positional information is initially stored locally and only written into the file each time a tile in the grid is crossed, thus avoiding an excessive number of simultaneous file writes. The 3D data is then visualised in a graph using a small script written in Python: this can be useful to get an initial overview of the data before undertaking more detailed analysis.

4.6.4 Savefile: "save.txt"

The game supports a save system that parses a text file at the beginning of the experience and uses it to extract the default values that the medical staff will find already set at the start of the session. This savefile is a standard text file that gets parsed at startup and can be edited on-the-fly. Conversely, this file is automatically modified during the experience with each change from the control panel. This means that the changes made during the last session are saved without having to restore all the settings each time the program is opened.

The intention is to provide a system for loading/saving values: if different patients are assumed, a save file will be associated with each one, which can be loaded via the interface and saved elsewhere. In a similar way, once an optimal set of functionalities has been found, a save file can be created to be re-used at a later stage.




```
SE2.ST6.TM1.BT3.NL5
LV1.R0.Y0.M00000001
LV2.R1.Y1.M10110001
LV3.R2.Y2.M10110101
LV4.R3.Y3.M10111101
LV5.R3.Y4.M11111111
LV6.R4.Y4.M11111111
###.##.M1.B10000001
```

Figure 4.13: Savefile details: the information is displayed in a similar order to its control panel counterpart.

This function is the base for a control panel tool, the "Preset" function. Using this feature, the user can set 5 different presets and quickly switch between them using a panel on the toolbar. Any change made on the control panel is then reflected in the active preset.

Default presets

The medical staff is free to change the presets according to their needs: however, the default presets are installed after the first start of the software. There are 5 different presets, listed below:

- **Home** – A default setting with a few general values, with no focus on any particular element of the game. Each level is a linear progression, and the addition of new complications is incremental.
- **Soft spikes** – During each part of the experience, the configuration is heavy on spikes presence. This challenges the user, forcing them to hold the cube more precisely when moving from one active tile to another.
- **Soft shakes** – Throughout each part of the experience, the configuration is heavy on the presence of purple tiles. This is a challenge for the user, as they are forced to wait for the tile to return to its green state almost every time a new active tile is presented.
- **Heavy spikes / Heavy shakes** – Two configurations mirroring the “soft spikes” and “soft shakes” parameters, but with longer sessions where the game cannot be finished before time runs out. It works as an endurance test.

4.7 Mixed reality integration

4.7.1 Mixed Reality Toolkit (MRTK)

After playtesting - which addressed some issues with the game logic - it was time to convert the experience into a format suitable for mixed reality devices. During the first part of development, when access to a mixed-reality headset was not available, a Unity plugin called Mixed Reality Toolkit (MRTK) came to the rescue. MRTK-Unity is a Microsoft-led project that provides a broad set of components and features to accelerate the development of cross-platform MR applications in Unity. It provides the cross-platform input system and building blocks for spatial interactions and UI, prototyping games through an in-editor simulation that allows you to see changes immediately.

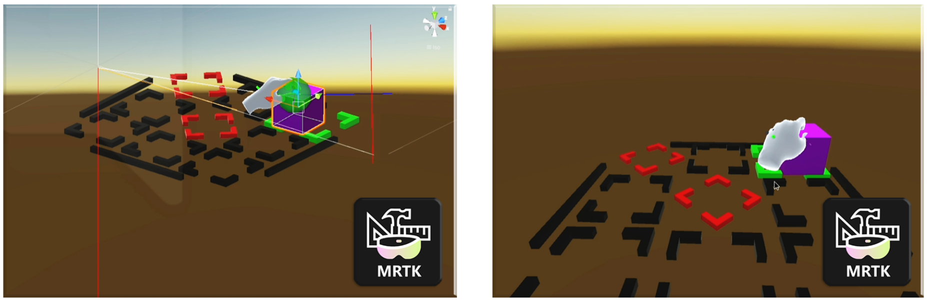


Figure 4.14: Testing the experience using the MRTK simulated MR environment

One of the key features of this toolkit is the Spatial Awareness system, which provides real-world environmental awareness in mixed reality applications. This tool provides a collection of meshes that represent an environment's geometry, allowing collisions and interactions between the experience and the surrounding world. This is important for the development of the experience because even though the grid is floating above the table, the pawn that the user moves has its own weight and mass. If it falls, it has to react in an appropriate way to get a realistic experience.

MRTK paved the way for a new phase of game testing, using a mouse and keyboard to simulate the hand movements and its drag and pinch gestures. The game was unchanged in its features but some of them were recalibrated to provide a more accessible experience.

- The grid was scaled proportionally to the cube, which is now about the size of a human hand.
- The cube was allowed to move freely along the 3 axes, rotating on itself according to the movement of the hand holding it. The cube also got its own gravity.
- At the start of the game, an invisible floor was inserted underneath the cube, preventing it from falling out of the room: this was a safety measure to ensure that the cube didn't load before the spatial awareness rendering of the room's depth, falling into an infinite void.

Despite its usefulness for verifying the correct implementation of most functions, this type of testing was insufficient to replicate the hands-on experience. Mouse/keyboard movements were often clumsy and unnatural, resulting in incorrect interface usage: as an example, the buttons on the control panel were very difficult to press by simulating the corresponding real life gesture with the virtual hand.

4.7.2 Testing on a Hololens 2 emulator

After this stage of development, it was finally time to test the actual functionality of the program within a simulated environment. This was possible by taking advantage of the Hololens 2 device emulator provided by Microsoft, which served as a testing bridge before getting access to the device itself.

A huge downside associated with the use of this system is the enormous computational cost required to simulate the device's operating system: huge input lags and general low fps during the simulations provided a subpar experience, still offering a preliminary hands-on on the headset interface.

However, this system was still helpful in demonstrating how it was possible to store report files locally on the device and access them later using the wireless syncing capabilities offered by Windows Device Portal.

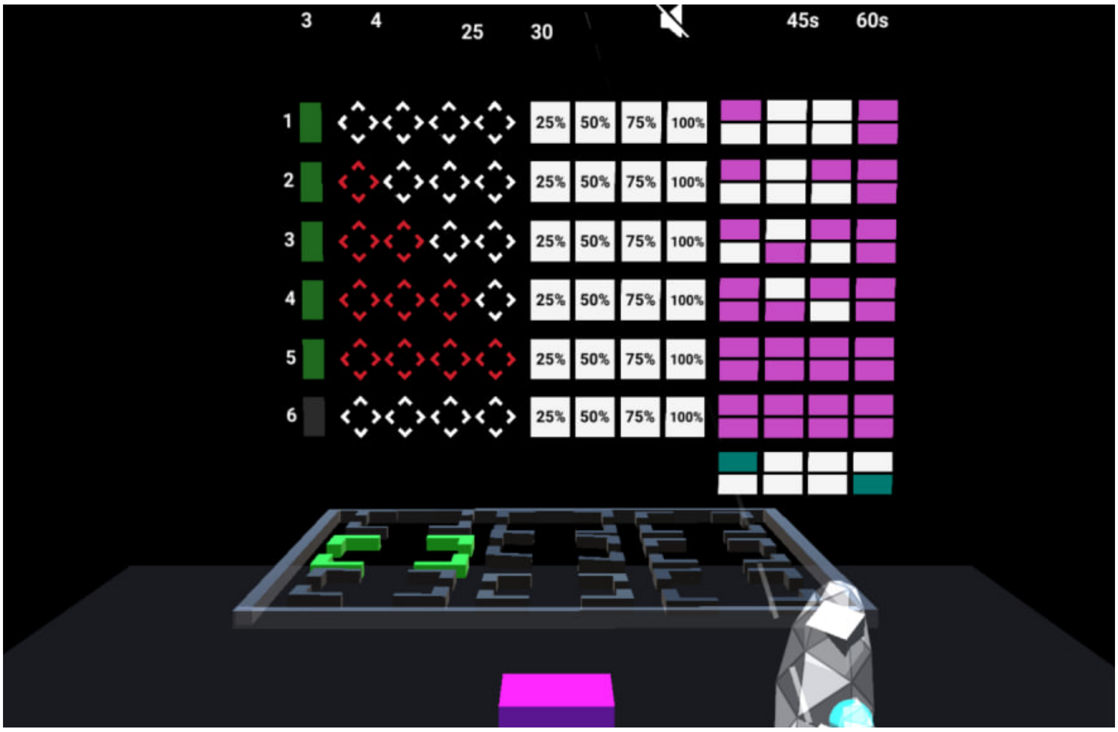


Figure 4.15: A preview of an early version of game that was tested on the Hololens 2 emulator: the lack of background is caused by the test environment, which is purely virtual. Stutters and long loading times, as well as input lags made this testing environment almost unusable.

4.7.3 Testing on a Hololens 2 device

In the final phase of development, with all the main features of the software in place, it was time to test the device on the screen using the ARM64 build, taking advantage of the compatibility offered by MRTK. Testing the device allowed to make a number of corrections otherwise impossible to achieve in a purely simulated environment.

Among them:

- Improving usability, the size of the grid and cube was slightly reduced.
- For ease of use, the size of the control panel has been increased.
- Reflecting light sources have been added to make the grid render more realistic.
- Some game colours have been changed to make them more visible and easier to distinguish from other ones: for example, green and yellow were very similar on the screen of the device.

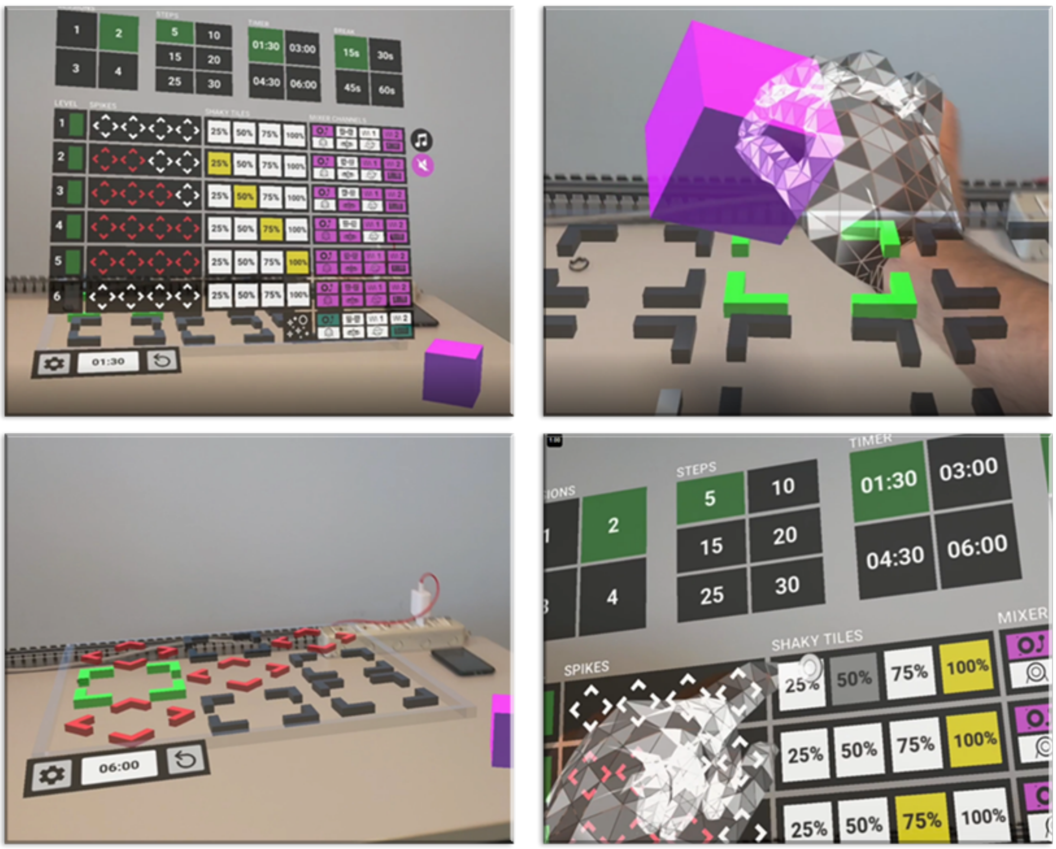


Figure 4.16: Playtesting an early version of the game using the Hololens 2 device.

The hands-on tests highlighted the importance of playing the experience in an appropriate environment to get the most out of the device. A good rule of thumb for avoiding tracking errors during a session is to play in a room with plenty of light. In addition, playing the game on an empty table rather than an overcrowded table helps to improve spatial awareness calculation, which in turn reduces stuttering during the game.

Chapter 5

Experiments

The experiments were conducted during the second half of March 2023, in a series of separate sessions. The first part of the test involved 17 (9 male, 8 female) healthy volunteers without MS from the Istituto Italiano di Tecnologia (IIT) in Genoa. They had the following age information:

$$Age_M = 27.76 y.o.$$

$$Age_{SD} = 2.56$$

Subsequently, a male patient with MS volunteered to make a symbolic contribution at the Associazione Italiana Sclerosi Multipla (AISM) centre in Genoa. For each subject, the experiment lasted between fifty minutes and one hour, depending on the duration of "Heavy spikes" and "Heavy shakes" configurations, which will be discussed in section 5.2.

Figure 5.1: Subjects involved in the playtesting phase.

5.1 Questionnaires

Questionnaires to be administered to the user at the end of each stage of the experience were designed and selected prior to the testing phase: we will now focus on their content. The full items of these questionnaires can be found at page 47.

5.1.1 Post test questionnaire

The first end-of-exercise questionnaire contains a series of statements about the exercise just completed, and has been written in collaboration with the IIT.

- After each configuration of the experiment, users were always asked to give an estimate of the length of the game session just completed.
- With every new configuration tested, users were asked to rate several characteristics of the game experience on a scale of 1 to 5, where 1 meant "very low" and 5 meant "very high". These included items about physical and mental effort as well general feedbacks about the gameplay elements of the experience and their success in engaging the user.
- At the end of every "Heavy" game session, users had to rate the effort they perceived during the longer gameplay session.

5.1.2 NASA Task Load Index (TLX)

The NASA Task Load Index [26], a subjective, multi-dimensional assessment tool that evaluates perceived workload along with other aspects of performance, was completed at the end of each post-test questionnaire. At the moment this paper is written, the TLX has been cited in over 14,000 studies in Google Scholar, which is a testament to the impact the NASA TLX has had on human factors research. It is used in many fields, including aviation, health care and other complex socio-technical fields. Questionnaires were completed on a scale of 1 to 20.

ID	Item
Q2	How would you rate your performance?
Q3	I felt like I lost track of time while playing.
Q4	I was focused on the game.
Q5	I felt a strong sense of being in the world of the game to the point that I was unaware of my surrondings.
Q6	I did not feel a desire to make progress in the game.
Q7	I did not feel like I wanted to keep playing.
Q8	I felt that this game provided an enjoyable challenge.
Q9	I felt that the game was excessively difficult.
Q10	I felt a sense of accomplishment from playing the game.
Q11	I felt that the game reacted quickly to my actions.
Q12	I felt in control of the game.
Q13	I felt very confident playing the game.
Q29	I consider playing the game as physical exercise.
Q30	I felt excited about the physical activities in the game.
Q16	I felt excited about the mental challenge in the game.
Q17	The exercise in the game made me feel good.
Q18	I would rather not be exercising, even though the exercise was accompained by game elements.
Q19	I felt that the activity was too intense for me.
Q20	I felt that the mental effort required was exhausting.
Q21	I felt that playing the game was beneficial for my physical well-being,
Q22	I felt that focusing on the game was beneficial for my mental state.
Q23	I would prefer that this activity was not accompained by game elements.
Q24	The mental effort was more intense than the physical effort during the game.
Q25	I feel that the muscles of my arm need rest.
Q26	I noticed that my movements became slower as the game progressed.
Q27	I felt the need to rest or change arm between sessions.
Q28	I felt that it was more difficult to concentrate as the game progressed.
Q29	I felt that my performance was decreasing as the game progressed.
Q30	I felt that it was difficult to understand how the game works.
Q31	I felt that it was easy to familiarize myself with different game elements across the sessions.
Q32	I felt that my pace and performance greatly depended on the game session.
Q33	I felt that it was easy to avoid the red tiles.
Q34	I felt that it was exhausting to wait for the tiles to become green.
Q35	I would prefer this game to have several but shorter sessions.
Q36	I felt that it was more enjoyable to avoid the red tiles than waiting for the purple tiles to become green.
Q37	I felt that it was harder to avoid the red tiles than waiting for the purple tiles to become green.
PQ2	How would you rate your performance?

Table 5.1: Post test questionnaire

ID	Scale	Question
N1	Mental Demand	How mentally demanding was the task?
N2	Physical demand	How physically demanding was the task?
N3	Temporal Demand	How hurried or rushed was the pace of the task?
N4	Performance	How successful were you in accomplishing what you were asked to do?
N5	Effort	How hard did you have to work to accomplish your level of performance?
N6	Frustration	How insecure, discouraged, irritated, stressed and annoyed were you?

Table 5.2: NASA Task Load Index (TLX)

5.2 The experiment

5.2.1 First contact

The subject is seated in a chair and, after the signing of a consent form, is introduced to the game and its main rules. The grid and the colours of its different pieces are introduced to the player. The subject is free to test the cube by moving it around with their hands and is asked to test the "recovery" mechanism of the cube in order to preserve the flow of the game if they lose it during the experiment: this is made by throwing away the cube and pressing the "Cube" button to retrieve it.

Then, the subject is asked to select a hand preference to use throughout the session. Typically, the subject will select the left hand if left-handed and the right hand if left-handed. Once the patient has become familiar with the game along with its rules and controls, he can start the experiment: moving the dice on the first green block formally starts the first of the 4 configurations, starting the timer along with the tracking process.

5.2.2 Configuration 1 - Soft spikes

Level 1	2 obstacles	0% chance of purple tiles
Level 2	3 obstacles	0% chance of purple tiles
Level 3	3 obstacles	25% chance of purple tiles
Level 4	4 obstacles	25% chance of purple tiles
Level 5	4 obstacles	25% chance of purple tiles
Level 6	4 obstacles	50% chance of purple tiles

Sessions	Max 2 sessions
Break	15 seconds between each session
Steps	15 steps per level
Time	03:00 minutes (+ break time)

Table 5.3: Configuration 1 - Soft spikes

The first exercise involves the configuration shown in Table 5.3. It consists of 6 levels where, from the very start of the game, the number of red tiles to avoid is high. These obstacles increase in number until they have reached their maximum number before the break. In this configuration, the probability of coming across a purple tile is limited: it is zero at the beginning. Then, in the last stages of each session, the probability of coming across a purple tile increases up to 50% at the very last level.

This favours a game with a quick transition between the green tiles. The total session lasts 3 minutes, at the end of which a warning indicates that the first phase of the experiment has ended. It should be noted that at this stage the user is unaware of the total duration of the exercise; they are only informed that a warning will stop them during the experience.

Each time the user successfully reaches the end of a session, he is rewarded with a 15-second pause in which he can rest his hand briefly before continuing. During this pause, the timer is momentarily interrupted. The 3-minute duration generally allows for a single break in this first part.

Questionnaire 1 - First part

At the end of the first phase, the user removes the headset and is asked to fill in the first section of the questionnaire. Given the effort that the exercise may require, it is useful to complete the questionnaire at this stage to allow the user to rest the arm and the hand during the transition from one phase to the next.

5.2.3 Configuration 2 - Heavy spikes

Level 1	2 obstacles	0% chance of purple tiles
Level 2	3 obstacles	0% chance of purple tiles
Level 3	3 obstacles	25% chance of purple tiles
Level 4	4 obstacles	25% chance of purple tiles
Level 5	4 obstacles	25% chance of purple tiles
Level 6	4 obstacles	50% chance of purple tiles

Sessions	Max 4 sessions
Break	15 seconds between each session
Steps	30 steps per level
Time	Max 15:00 minutes (+ break time)

Table 5.4: Configuration 2 - Heavy spikes

The second exercise has the same configuration as the previous one, with two simple variations. The first of these is the number of steps: each level is twice as long, so that twice as much time is needed to reach the pause in the game, which lasts 15 seconds. The second and more important change is to the overall duration of the experience: the user is informed that the session is infinite, and so there is no end warning as there was before. It will be the user himself who will have to indicate his intention to interrupt the game session if he is tired, sore or simply bored by the experience.

Questionnaire 1 - Second part

At the end of this phase, the user will remove the device again and will be asked to fill in the questionnaire that was started earlier. This is followed by a short break before the second phase of the experiment is carried out.

5.2.4 Configuration 3 - Soft shakes

Level 1	1 obstacles	50% chance of purple tiles
Level 2	1 obstacles	50% chance of purple tiles
Level 3	1 obstacles	75% chance of purple tiles
Level 4	2 obstacles	75% chance of purple tiles
Level 5	2 obstacles	100% chance of purple tiles
Level 6	2 obstacles	100% chance of purple tiles

Sessions	Max 2 sessions
Break	15 seconds between each session
Steps	15 steps per level
Time	03:00 minutes (+ break time)

Table 5.5: Configuration 3 - Soft shakes

In this part of the exercise, the user is asked to start a new configuration which, unbeknown to him, contains some variations in the game ruleset. The number of red tiles is reduced (never more than two per round) and the probability of coming across purple tiles is increased (reaching 100% in the final stages of the game). This style of play involves a slower transition between tiles with frequent waiting times.

Before starting, the user will be asked to play with the same rules regarding the tile colours as in the previous games and will be warned that the game will end autonomously as in the first experiment. However, there is no guarantee that the duration of the session will be the same as the duration of the first session.

Questionnaire 2 - First part

At the end of the third exercise, the participant will be asked to fill in a new copy of the questionnaires with the same items as in Configuration 1 to record any changes in the perception of the experience based on the changes entered, whether they were experienced and with what intensity.

5.2.5 Configuration 4 - Heavy shakes

Level 1	1 obstacles	50% chance of purple tiles
Level 2	1 obstacles	50% chance of purple tiles
Level 3	1 obstacles	75% chance of purple tiles
Level 4	2 obstacles	75% chance of purple tiles
Level 5	2 obstacles	100% chance of purple tiles
Level 6	2 obstacles	100% chance of purple tiles

Sessions	Max 4 sessions
Break	15 seconds between each session
Steps	30 steps per level
Time	Max 15:00 minutes (+ break time)

Table 5.6: Exercise 4 - Heavy shakes

The fourth and final exercise shows the same variation in timing as the transition between the first and second configuration: the game has the same ruleset but double the duration and unchanged pause time.

Questionnaire 2 - First part

When this last phase is completed, the user will remove the device for the last time and will be asked to complete the questionnaire they started earlier. This concludes the experiment.

5.2.6 About exercises administration

The tests are designed to avoid the possibility of bias due to the order in which the different configurations are presented to the user. Therefore, the user will randomly start the experiment with “Soft spikes” followed by “Heavy spikes” or, conversely, with “Soft shakes” followed by “Heavy shakes”. The “Spikes” and “Shakes” configurations are always performed consecutively. Thus, the completion of the questionnaires serves the dual purpose of gathering information about the experience and allowing the user to rest during the transition from one exercise to another.

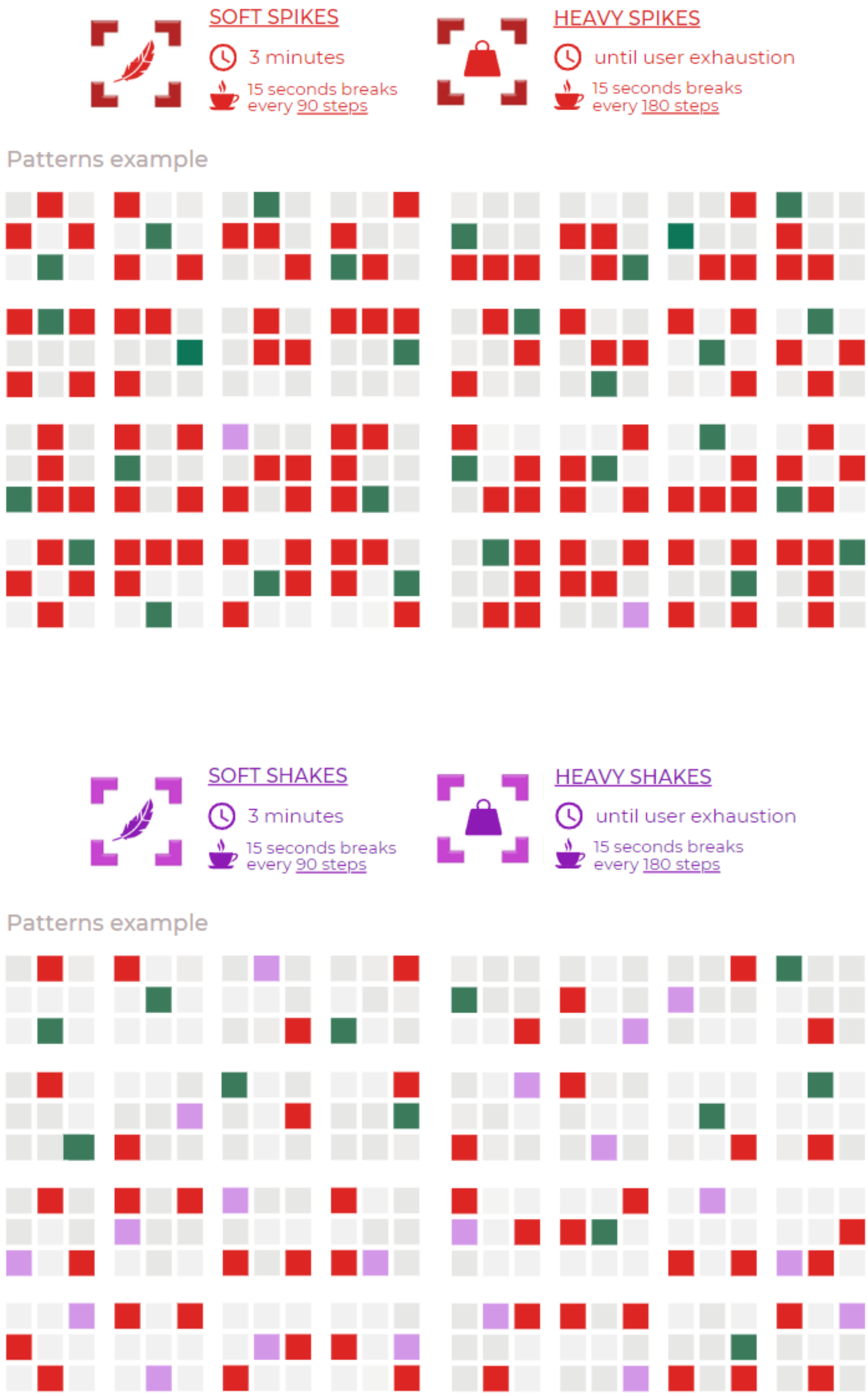


Figure 5.2: Showing the 4 testing configurations with a simulation of pattern occurrences.

5.3 Results

We will now focus on the results of the questionnaires. By reviewing the questionnaire scores, we will try to identify some interesting trends in the measurements and better understand their meaning. The experimental design is within-subject and the statistical test used for analysis is the Wilcoxon signed-rank test, as non-parametric tests are suggested for discrete scales.

5.3.1 Goals

The objectives of these analyses are manifold:

- It is important to discover how users really engage with the experience through play. In fact, it is necessary to check whether the audiovisual enhancements can be an effective support for the end user.
- Independently of the engagement with the game, another aspect to be considered is the usability of the experience. In particular, it is necessary to check that the gameplay and the rules of the game are clear and that there are no disruptive elements that could contaminate the flow of a gaming session.
- Another aspect to be considered concerns the balance of the game sessions and their impact on the physical and psychological stress of the user involved. In this regard, balanced solutions and more strenuous modes will be both tested.

	Heavy Shakes		Heavy Spikes		
Item	**M**	**SD**	**M**	**SD**	
Q2	4.29	0.66	4.41	0.49	
Q3	2.82	1.1	3.12	1.28	
Q4	4.47	0.7	4.82	0.38	*
Q5	2.82	1.25	3.24	1.11	
Q6	1.65	0.76	1.47	0.7	
Q7	2.35	1.13	1.71	0.82	*
Q8	3.65	0.48	3.82	0.86	
Q9	1.35	0.59	1.12	0.32	
Q10	3.65	0.84	3.71	0.67	
Q11	4.59	0.69	4.65	0.84	
Q12	4.35	1.13	4.35	1.08	
Q13	4.59	0.6	4.65	0.48	
Q29	3.65	1.03	3.18	1.15	
Q30	2.88	1.13	3.35	1.23	
Q16	2.76	0.89	3.18	0.86	
Q17	3.41	0.69	3.71	1.07	
Q18	2	0.84	2.24	0.94	
Q19	1.82	0.98	1.59	0.84	
Q20	1.47	0.61	1.35	0.59	
Q21	3.12	1.13	3.06	0.80	
Q22	3.24	0.94	3.41	0.84	
Q23	1.65	1.08	1.47	0.92	
Q24	2	1.19	2.29	1.32	
Q25	2.94	1.47	3	1.28	
Q26	2.71	1.23	1.71	1.02	
Q27	3	1.37	2.71	1.23	*
Q28	2.18	1.25	1.47	0.7	
Q29	2.18	1.04	1.59	0.91	*
Q30	1.06	0.24	1	0	**
Q31	3.71	1.36	3.53	1.42	
Q32	3.06	1.16	2.47	1.04	
Q33	4.29	1.13	4.18	1.1	*
Q34	2.94	1.21	2	0.91	
Q35	3	1.08	2.65	0.97	*
Q36	3.47	1.29	3.12	1.02	
Q37	1.76	0.73	1.71	0.57	

	Long Shakes		Long Spikes	
Item	**M**	**SD**	**M**	**SD**
PQ2	3.76	0.81	4.12	0.47

Table 5.7: Post Test Questionnaire results: items with $p < 0.05$ have been marked with (*), items with $p < 0.01$ have been marked with (**). Full items are listed at page 47.

5.3.2 Statistically significant differences

The values calculated in the following results (W being the sum of signed ranks and p being the p-value, an indicator of the results significance) are derived from the Wilcoxon signed-rank test. This test is used to compare data in two conditions according to a within-subjects experimental design in which the conditions are tested by the subject in random order. Statistically significant differences have been found for the following questionnaire items (with $p < 0.05$). In the following sections, we will discuss what these indicators suggest and contextualise them with the experimental results. We will cross-reference these parameters with the most interesting results from the user questionnaires.

- **Item 04** ($W = 0.0$ and $p = 0.048$) with $M = 4.29$ and $SD = 0.67$ in "Soft shakes" condition, $M = 4.41$ and $SD = 0.49$ in "Soft spikes" condition;
- **Item 06** ($W = 55.0$ and $p = 0.005$) with $M = 2.71$ and $SD = 1.23$ in "Soft shakes" condition, $M = 1.71$ and $SD = 1.02$ in "Soft spikes" condition;
- **Item 27** ($W = 55.0$ and $p = 0.005$) with $M = 2.71$ and $SD = 1.23$ in "Soft shakes" condition, $M = 1.71$ and $SD = 1.02$ in "Soft spikes" condition;
- **Item 28** ($W = 33.5$ and $p = 0.033$) with $M = 2.18$ and $SD = 1.25$ in "Soft shakes" condition, $M = 1.47$ and $SD = 0.7$ in "Soft spikes" condition;
- **Item 29** ($W = 45.0$ and $p = 0.005$) with $M = 2.18$ and $SD = 1.04$ in "Soft shakes" condition, $M = 1.59$ and $SD = 0.91$ in "Soft spikes" condition;
- **Item 32** ($W = 41.5$ and $p = 0.023$) with $M = 3.06$ and $SD = 1.16$ in "Soft shakes" condition, $M = 2.47$ and $SD = 1.04$ in "Soft spikes" condition;
- **Item 34** ($W = 83.0$ and $p = 0.024$) with $M = 2.94$ and $SD = 1.21$ in "Soft shakes" condition, $M = 2$ and $SD = 0.09$ in "Soft spikes" condition;
- **Item N5** ($W = 125.5$ and $p = 0.003$) with $M = 9.24$ and $SD = 5.02$ in "Soft shakes" condition, $M = 5.12$ and $SD = 3.04$ in "Soft spikes" condition.

5.3.3 Performance

Subjects participating in the experiment rated their performance. During "Heavy" variants of the configurations, users felt that their performance was declining. The variant with more purple tiles showed the most significant decrease, with a reduction of more than half a point between short and long sessions. The results are consistent with the analysis of match results from the savedata collected.

Soft spikes	Heavy spikes	Soft shakes	Heavy shakes
4.41 | 5.00	4.12 | 5.00	4.29 | 5.00	3.76 | 5.00

Table 5.10: $Q2/PQ2_M$: "How would you rate your performance?"

Item	Heavy Shakes M	Heavy Shakes SD	Heavy Spikes M	Heavy Spikes SD	
N1	6.88	4.86	6.94	4.68	
N2	11.35	5.18	9.24	5	
N3	7.53	3.99	7.35	4.3	
N4	4.12	3.4	3.18	2.92	
N5	9.24	5.02	5.12	3.03	**
N6	4.12	4.75	2.82	3.15	

Table 5.8: NASA Task Load Index (TLX) results: items with p<0.05 have been marked with (*), items with $p < 0.01$ have been marked with (**). Full items are listed at page 47.

	Soft Shakes Perceived	Soft Shakes Real	Soft Spikes Perceived	Soft Spikes Real
M	398.82	195	360	195
SD	219.68	-	160.73	-

	Heavy Shakes Perceived	Heavy Shakes Real	Heavy Spikes Perceived	Heavy Spikes Real
M	497.65	375.53	596.47	471.12
SD	278.22	134.55	272.61	176.69

Table 5.9: Time tracking results (s)

5.3.4 Game elements

Overall, users were in favour of the inclusion of gaming elements in the experience. The simplicity of the rules and the flow of the game received positive evaluation. A positive feedback came from the music elements: almost all users appreciated the soundtrack and the sense of culmination brought by the introduction of new tracks after each level with only two exceptions who preferred the game to be played without this feature.

Soft spikes	Soft shakes
2.24 | 5.00	2.00 | 5.00

Table 5.11: $Q18_M$: "I would rather not be exercising, even though the exercise was accompained by game elements"

Soft spikes	Soft shakes
1.47 | 5.00	1.65 | 5.00

Table 5.12: $Q23_M$: "I would prefer this activity was not accompained by game elements"

5.3.5 Focus and motivation

The results of the research questionnaires were positive in terms of ease of use of the game and overall performance. The game reacted well to players' actions and there was generally positive feedback regarding the gaming experience and the interactive features involved. A significant level of concentration during the game was confirmed by the playtesters. In particular, the variant with more red tiles showed slightly higher scores.

Soft spikes	Soft shakes
4.65 | 5.00	4.59 | 5.00

Table 5.13: $Q11_M$: "I felt that the game reacted quickly to my actions"

Soft spikes	Soft shakes
4.65 | 5.00	4.59 | 5.00

Table 5.14: $Q13_M$: "I felt very confident playing the game"

Soft spikes	Soft shakes
4.35 | 5.00	4.35 | 5.00

Table 5.15: $Q12_M$: "I felt in control of the game"

Soft spikes	Soft shakes
4.82 | 5.00	4.47 | 5.00

Table 5.16: $Q4_M$: "I was focused on the game"

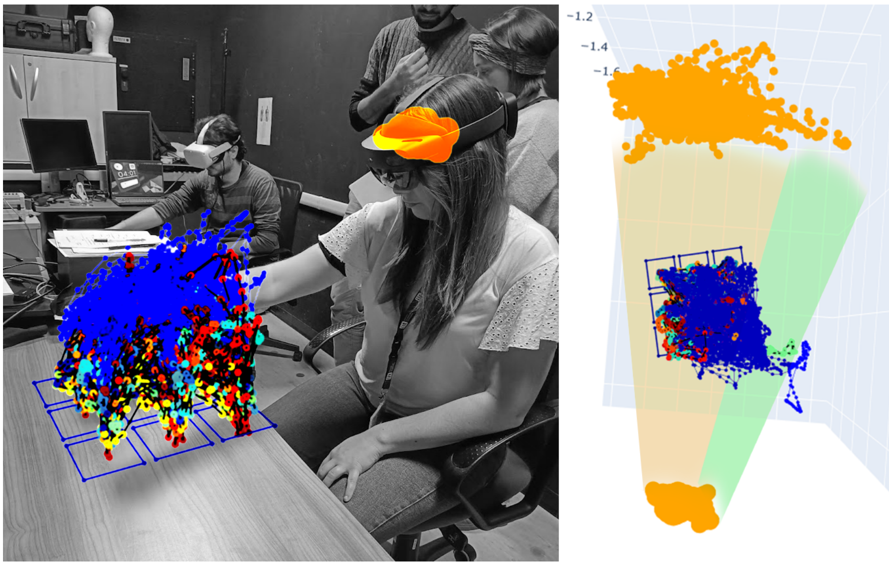


Figure 5.3: On the left, a photo of the experience overlaid on the 3D map generated by the gaming session. In the graph on the right, the orange glow indicates the user's field of view during the experience. The green glow, slightly offset from the grid position, shows the user's field of view during breaks, when the cube is placed on the surface to relax the arm.

5.3.6 Engagement

User involvement in the game experience showed a significant reduction when a higher number of purple tiles was involved. This happened due to a deliberate disproportion in the occurrence of different tiles during the experimental phase, done to assess the perceived difference between the two configurations. One solution aimed at increasing engagement is to use more balanced sessions, with rule sets changing between levels to keep the user engaged. Furthermore, the results of the Wilcoxon signed-rank test on Items $Q26$, $Q28$, $Q29$, $Q34$ [5.3.2] underline signs of fatigue in "shakes" condition alongside higher effort, a thesis which is further highlighted by the item $N5$ from the NASA TLX. Items $Q14$ and $Q7$ [5.3.2] point at the superiority of the "spikes" condition over the "shakes" condition because the first lead to higher focus and motivation to play more. This hypothesis is further supported by Item $Q32$ pointing at a stronger burden of the pace in purple condition: subjects were asked to discuss this choice at the end of the experiment and, despite the randomised order in which the configurations were administered, the collected feedback remained consistent. In longer sessions ("Heavy spikes", "Heavy shakes"), both verbal feedback and postural cues [5.3.7] suggested higher levels of fatigue in the "Heavy shakes" condition.

- **"Soft spikes"** and **"Heavy spikes"** configurations led to fast gameplay sections without break moments, in which the scarce presence of purple tiles brought to faster gameplay. The analysis of the scores showed that most of the mistakes were made when purple tiles appeared after long sections of green tiles: the user automatically crossed them with the cube, caught up in the game loop and used to a series of normal tiles. Such an approach to gameplay could be disfavoured with stronger penalties.
- On the other hand, **"Soft shakes"** and **"Heavy shakes"** forced a more tedious gameplay with a monotonous distribution of purple tiles and a reduction in the number of obstacles to be avoided.

Soft spikes	Soft shakes
3.35 | 5.00	2.88 | 5.00

Table 5.17: $Q15_M$: "I felt excited about the physical activities in the game"

Soft spikes	Soft shakes
3.18 | 5.00	2.76 | 5.00

Table 5.18: $Q16_M$: "I felt excited about the mental challenge in the game"

Soft spikes	Soft shakes
3.71 | 5.00	3.41 | 5.00

Table 5.19: $Q17_M$: "The exercise in the game made me feel good"

5.3.7 Fatigue

We will now focus on the questionnaire scores related to the user's perceived fatigue during gaming sessions. The data shows that despite the forced unbalanced configurations, the effort never leads to significant discomfort. On a mental level, the game has simple rules that help reduce the perceived mental load.

Soft spikes	Soft shakes
1.59 | 5.00	1.82 | 5.00

Table 5.20: $Q19_M$: "I felt that the physical activity was too intense for me"

Soft spikes	Soft shakes
1.35 | 5.00	1.47 | 5.00

Table 5.21: $Q20_M$: "I felt that the mental effort required was exhausting"

Still, users manifested a general sense of fatigue in some of the gaming sessions presented. This was enhanced by the constraint imposed by the experiment to always use the same arm during the entire course of the various configurations. Fatigue depends very much on the physical condition of the player's arm during the test, a parameter that fluctuates throughout the experimental sessions.

Soft spikes	Soft shakes
3.00 | 5.00	2.94 | 5.00

Table 5.22: $Q25_M$: "I felt that the muscles of my arm needed rest"

Soft spikes	Soft shakes
1.71 | 5.00	2.71 | 5.00

Table 5.23: $Q26_M$: "I noticed that my movement became slower as the game progressed"

5.4 Observations

The following is a list of some observations made during the game sessions that may be helpful for understanding users' approach to the proposed experience.

5.4.1 Reaching further tiles

In terms of muscle tension, user feedback during the experience revealed that movements towards the upper parts of the grid (Fig. 5.4, right) were more fatiguing than those towards the middle and lower rows (Fig. 5.4, left). This suggests that, especially in configurations that emphasise the use of the purple tiles with longer waiting times in a still position, the tension of the outstretched arm is an element of fatigue to be considered when evaluating the equilibrium of game elements during a session configuration.

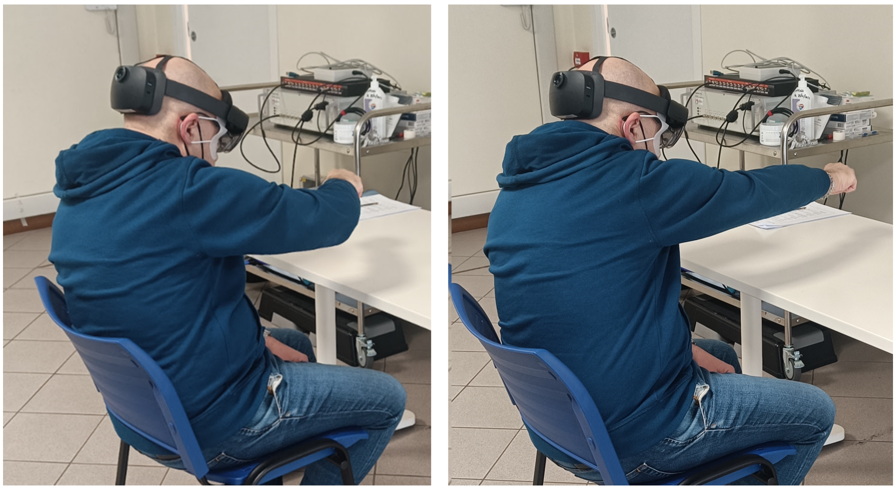


Figure 5.4: Showing various arm strechings

5.4.2 Avoiding muscular tension

A number of experiments on healthy volunteers revealed some peculiar ways in which the volunteers tried to alleviate the fatigue caused by long gaming sessions. Three subjects (as shown in figure 5.5), rested their arm on their body up to the elbow in order to alleviate the discomfort caused by muscular tension, which becomes more pronounced during the third and fourth exercises, where purple tiles are insistently handled. Another test person (shown in figure 5.6) adopted a peculiar technique which consisted in holding the elbow with the other hand during the course of the exercise. There was no penalty for this kind of shortcuts in terms of game points.

Figure 5.5: In some instances of the game, users tried to mask their fatigue by resting their arm on their body (right figure), thrusting their centre of gravity forward to select higher positioned grid elements. A correct configuration requires the arm to operate independently and unaided (left figure).

Figure 5.6: Sometimes users tried to mask their fatigue by resting their arm on their elbow (figure right) and using it instead of the arm to move the cube on the grid. As before, a correct configuration requires the arm to work independently and without any support (figure left).

5.4.3 Confidence in holding the cube

It is also interesting to note the way in which users interact with the cube: most users handled it with a claw-like grip and moved it confidently between the tiles. This was the approach suggested to the user at the very start of the experience: to provide a comparison, the user is asked to think of the cube as a cookie and the grid tiles as cups of milk. A subset of users, on the other hand, approached the cube with a less confident grip, clutching the cube tightly with their fists for fear of losing it, despite being advised otherwise. It was clear from the interviews and questionnaires that such a grip was a kind of effort multiplier, as evidenced by higher predictions of time and physical effort indicators when confronted with users who simply pinched the virtual pawn.

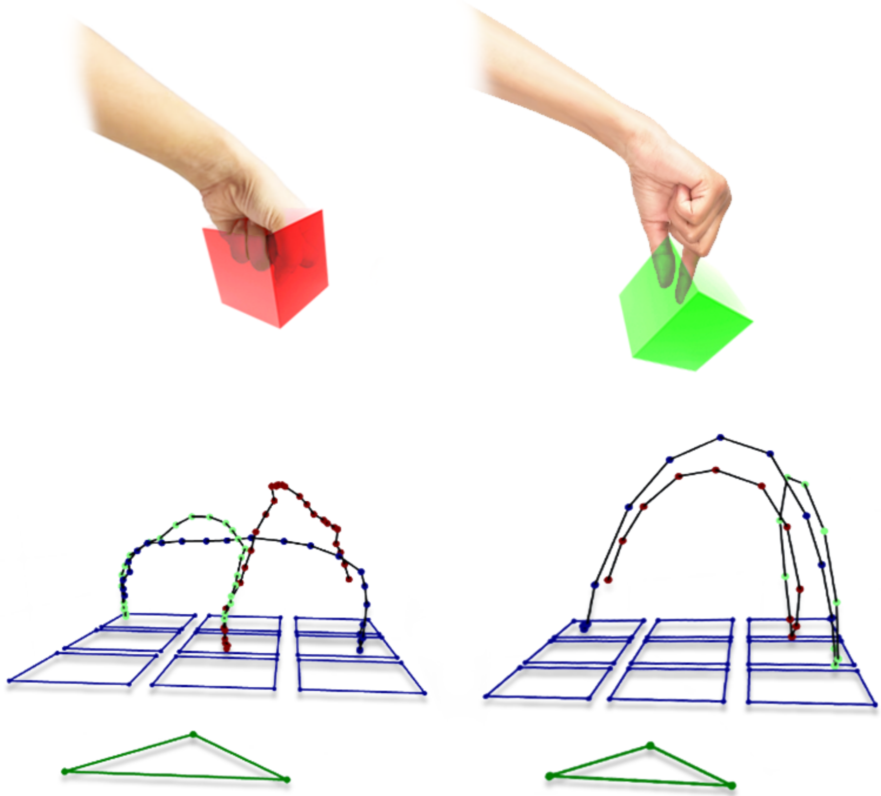


Figure 5.7: During the experiments, some of the users moved the cube by holding it in their fist (top left). This often resulted in a more tense, slow and irregular movement between tiles (bottom left), due to fear of losing the cube. The pincer grip (top right), on the other hand, favoured a more precise and versatile style of play (bottom right) and was the preferred choice of most players.

Chapter 6

Conclusions

The aim of this project was to demonstrate the actual usefulness of gamification elements within a rehabilitation context, exploiting AR/MR technologies, in order to lighten the psycho-physical load related to the repetitive tasks that these exercises often entail. In pursuit of this goal, we translated a traditional rehabilitation exercise into AR/MR language, exploiting some interesting insights from previous attempts described in the literature and searching for new approaches to test in this iteration.

With regard to the experimental results, the post-test questionnaires showed positive feedback regarding the game elements and the level of concentration that these entail, demonstrating its potential in the treatment of PwMS who are already using similar exercises without enhanced features. The results related to involvement showed that including these elements, although positive, was necessary but not sufficient to achieve real reductions in perceived workload, as results from the Wilcoxon Signed Rank Test showed interesting shifts in the "fatigue" related statements depending on the various configurations tested. In fact, the load becomes more considerable in prolonged sessions, especially in configurations that make more intensive use of purple tiles, thus forcing long arm suspensions. The solution to these results is therefore not to have an exclusive preference for configurations that do not have purple tiles, but rather to introduce such game elements at a frequency that is not so invasive as to affect the game loop.

In terms of computational load, the device was able to withstand the prolonged workload imposed by the intense experimental sessions. Occasionally, it registered slight stuttering, but this did not affect the test phases. The tracking system recorded all sessions correctly and the granularity of the position data collection process (one scan every 10 Hz) was sufficient to make interesting observations about the subjects.

6.1 Limitations

Some of the limitations encountered in the design of the experience will now be presented, with suggestions for possible future workarounds where these are available.

6.1.1 Projection surface

One of the major limitations imposed is due to the device used in the experiment: the Microsoft Hololens 2 proved to be a very good device capable of withstanding the computational load imposed by the game logic, but less capable of comprehensively displaying all the information on the screen at the same time. This is due to limited projection surface which required a reduction of grid size to display all nine tiles properly. Larger tiles and wider upper limb movements could be achieved by using a device with a larger projection surface, allowing a different set of movements.

6.1.2 Initial price

The price of augmented reality devices has also been an obstacle to the project's aims, as they remain beyond the reach of most people. A realistic hypothesis, especially taking into account the advanced age of many patients who are familiar with the exercise but cannot afford to own it, is that of a MS specialized centre offering spaces to use the equipment or the possibility of renting it. However, buying the device may reduce the overall cost of rehabilitation, since the physical therapist does not need to monitor and instruct the patient during rehabilitation, except for the initial setup and data processing phases.

6.1.3 Lack of elderly subjects

A limitation of the present study was the lack of elderly subjects, limiting the generalisability of the survey results. However, it is reasonable to assume that the proposed technology could be used to rehabilitate young to middle-aged people.

6.2 Future work

The exergame's design and subsequent testing phase allowed only part of the project's potential to be explored. This section is an outline of some of the ideas that could be of interest for further development of the game. Many of these proposals delve deeper into the game language introduced by the program designed with the purpose of diversifying the gaming versatility.

6.2.1 Experimenting with musical tracks

The music track is certainly an area that could be expanded within the project. Overall, users were in favour of the inclusion of gaming elements in the experience. As we stated in the previous chapter, users mainly appreciated the soundtrack and its sense of culmination and flow. However, in the experiments carried out for this thesis, a single track with a neutral style was used in order to prevent the different accompaniments from affecting the level of engagement. This limitation could be avoided with the purpose of engaging the player with its favourite music genres. Nowadays, there is an ever increasing number of labels releasing songs in the form of stems (or individual instrumental/vocal parts), or sending stems of classic songs to specific labels, performers or digital outlets. With due regard to the regulations governing the rights to music, some of these pieces could be incorporated into the game.

6.2.2 Testing new configurations

The configurations available from the control panel allow many new tests of different combinations, changing the balance to discover new playing styles. Many interesting cases have been left for the future, as a proper experimental procedure for each configuration requires at least an hour per user. This thesis was limited to two borderline cases to see what they share and differ.

6.2.3 Experimenting with obstacle height

During the last phase of the tests, an interesting idea arose to further diversify the set of movements the user has to perform to reach the target. In particular, one could imagine a scenario in which the obstacles on the grid do not only appear at a fixed height, but also have a height in the z-plane. These variable heights and combinations of heights, if properly implemented, could force the user to make certain movements in order to reach the green tile without making a mistake.

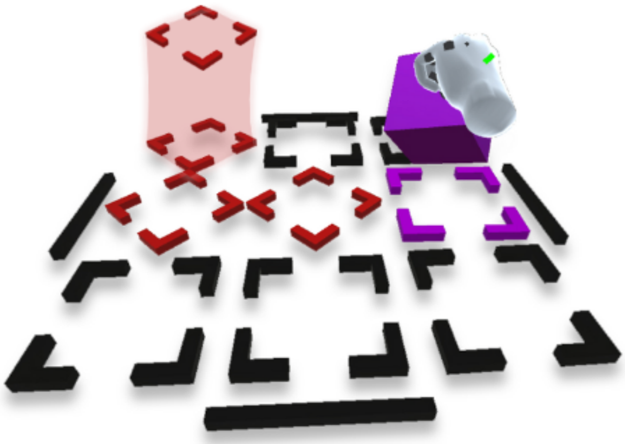


Figure 6.1: Obstacles with variable height (concept).

6.2.4 Experimenting with physical objects

Purely virtual interactive objects were used in the work carried out in this thesis. Although this strategy led to good versatility, there were some situations where the lack of a physical object caused uncertainty in movements, especially for less experienced users [5.4.3]. The idea of replacing the virtual cube with a physical object, mapped in a virtual space using appropriate markers and cameras, could be tested to restore the sense of physicality.

In favour of this extension, the cube is the only element of the experience that doesn't change colour or shape during the experience, and can therefore be translated into physical form without having to make excessive changes to the game's logic. Therefore, the possibility of using more than one object could be considered, and different forms could be tested in place of the cube.

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