DM

Cognitive-motor Rehabilitation Through Low-cost Mobile Augmented Reality Technology

MASTER DISSERTATION

John Douglas Oliveira de Sousa

MASTER IN COMPUTER ENGINEERING

UNIVERSIDADE da MADEIRA

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Master's Degree in Computer Engineering

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Lastly, I would also like to thank all my friends and family, for helping me, not just on an emotional level but also for user testing throughout my project.

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Resumo

O acidente vascular cerebral (AVC) é uma grande causa de incapacidade em adultos, tanto motora como cognitiva. A sua reabilitação é limitada pois, os custos para os sistemas de saúde são muito elevados. Por consequência, houve um aparecimento de tecnologias para a reabilitação, entre elas, a realidade virtual, porque, estas tecnologias oferecem uma solução eficiente e mais económica. Além disso, permitem ainda uma reabilitação motora e cognitiva em simultâneo. Embora estas tecnologias tenham obtido resultados muito favoráveis na reabilitação do AVC, existem ainda aspetos a melhorar principalmente a nível da interação. Para esse efeito, a realidade aumentada oferece novas possibilidade por permitir uma interação mais natural sem a necessidade de transformações visuo-espaciais. Contudo, esta tecnologia ainda é muito recente e a maioria dos estudos são relativos à realidade aumentada espacial, o que necessita equipamento dispendioso.

Nesta dissertação, proponho uma solução barata para um jogo sério usando realidade aumentada imersiva. Este jogo é baseado no Reh@Task do NeuroRehabLab. Durante este estudo, realizei um teste piloto para descobrir qual ângulo de visão seria mais atraente e natural para o utilizador. Os resultados indicaram que quanto maior o ângulo de visão mais natural é o mapeamento da interação e ângulos de visão mais baixos favorecem a imersão. Realizei também uma comparação do jogo de realidade aumentada imersiva com o jogo de realidade virtual não imersiva. Foi demonstrado que a tecnologia de realidade aumentada imersiva utilizada ainda tem limitações que necessitam ser ultrapassadas antes de utilizar estas ferramentas num ambiente de reabilitação

Palavras-chave: Realidade aumentada imersiva, Realidade Virtual, Acidente vascular cerebral, Reabilitação cognitivo-motora.

Abstract
Stroke is a major cause of adult disability in both the cognitive and motor spectrum. However, rehabilitation for these patients is usually limited due to the high costs for health systems. Hence, an era of virtual reality for rehabilitation emerged. These systems allow for effective cognitive and motor rehabilitation, and can be affordable. Although this technology is showing good results in stroke recovery, there is still place for improvement, particularly at the interaction level. Here, augmented reality shows good potential because it allows for a more natural interaction that does not need a visuospatial transformation during interaction. However, this technology is still relatively new, and most solutions are for spatial augmented reality, which requires expensive equipment like projectors.

In this thesis, I propose a low-cost immersive augmented reality game for rehabilitation based on the Reh@Task from the NeuroRehabLab. During these studies, I ran a pilot test to find out what field of view would be more engaging and natural to use. The results indicated that higher degrees on the field of view give more realistic mappings and lower degrees lead to more immersion. Additionally, a comparison between the immersive augmented reality game and the non-immersive virtual reality game was done. Results indicated that the immersive augmented reality technology still has limitations that need to be overcome before using these tools in a rehabilitation setting.

Keywords: Immersive augmented reality, Virtual Reality, Stroke, Cognitive-motor rehabilitation**.**

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Acronyms

AR – Augmented Reality;

VR – Virtual Reality;

SDK – Software Development Kit;

IDE – Integrated Development Kit.

1. Introduction

This chapter is divided into three sections, starting with the motivation and contextualization for using immersive augmented reality in neurorehabilitation. Next, the main goals and objectives of this thesis are presented. Finally, I will describe the general structure of this document.

1.1. Motivation

Stroke is one of the main causes of adult disability, with an incidence of around 15 million people every year [1], leading to chronic motor and cognitive deficits [2]. The target of neurorehabilitation, either motor or cognitive, is to maximize recovery to improve functional independence. Specifically, motor rehabilitation has the purpose of attempting to regain any motor function that has been lost. This is typically done through physical therapy. As for cognitive rehabilitation, this is the process of recovering from cognitive deficits by re-learning the lost functions or by teaching new skills to compensate for the functions that cannot be reinstated. Cognitive rehabilitation focuses on various domains such as executive function, memory and attention.

Throughout the years, with the fast development of novel technologies, numerous studies have addressed the feasibility of bringing virtual reality into the rehabilitation process, through task simulations or serious games [3]. These strategies have several benefits such as having a completely controlled environment and being more engaging. In addition, these technologies are often low-cost, increasing their deploy-ability. In the modern society, games are of huge influence, so it is to no surprise that serious games were created. These games have a greater purpose than just entertainment, they are usually used for education, scientific exploration, healthy simulation, military defence and in the case of this thesis, for rehabilitation [4]. The technology that is commonly used to portray these serious games is virtual reality, that is the process of taking the user into the virtual world. However, virtual reality is not limited to head-mounted immersive displays, and can also be used on traditional computer screens.

More recently, there has been an interest in the use of serious games in Augmented Reality [22]-[32]. This consists of bringing virtual objects into reality. Much like its virtual reality counterpart, it provides controlled environments but also has the advantage of being a more natural interaction because it does not require any visuospatial transformation. Additionally, like virtual reality, augmented reality can be done with an immersive interface and a non-immersive interface. These solutions can be very low cost, using a tablet or smart phone, and be used independently at home without the permanent supervision by a therapist. Moreover, these devices can easily store logs and data from the tasks for later analysis of performance over time for therapists and patients.

Considering that stroke is one of the most common neurological disorders and that only a few studies have been conducted on using immersive augmented reality for neurorehabilitation, this is an area that needs to be further investigated. This thesis provides an opportunity in that direction. For this purpose, this work compares immersive augmented reality and non-immersive virtual reality in stroke rehabilitation, to understand the advantages and disadvantages of each strategy.

1.2. Objectives

For this thesis, the main ambition is to conceptualize and create a cheap solution for a serious game using immersive augmented reality. This serious game will address stroke rehabilitation, and provide the opportunity to be used anywhere. I will be creating a game constructed upon the Reha@Task developed at the NeuroRehabLab [5], which is a memory and attention task based on the paper-and-pencil Toulouse-Piéron cancellation task [6]. These following steps are required to ensure the feasibility of this project:

- The game is to run on a mobile phone;
- It should use a head-mounted display;
- It must be cheap;
- And, it should be portable.

Another important aspect of this thesis is the comparison of immersive augmented reality with non-immersive virtual reality. I will run a study with healthy participants to evaluate usability, presence, engagement and task load.

1.3. Document Structure

This document is partitioned into seven chapters structured in the following way: Chapter 1 - Introduction, contains the motivation and goals of the thesis. In Chapter 2 – State of the art, a literature review is presented that addresses serious games, the use of augmented reality for stroke rehabilitation and the comparison between virtual reality and augmented reality in rehabilitation. The following chapter, Chapter 3 –Methodology, describes how the software is implemented and all the choices regarding interaction and design. Chapter 4 – Field of view pilot test consists of the analysis of the pilot test that was run to find the best field of view to use. As for Chapter 5 – Comparison between Immersive augmented reality and non-immersive virtual reality, it describes a test with healthy participants to compare the interaction methods of both technologies in consonance to the metrics previously defined. As for Chapter 6 – Conclusions, this is where the final results will be discussed, and conclusions are drawn. Finally, Chapter 7 - future work, discusses futures directions of research.

2. State of the Art

This chapter is a literature review on the current state of the art on augmented reality for neurorehabilitation. In order to ensure that this literature review is up-to-date, the search and inclusion criteria of papers for this literature review regarding augmented reality and virtual reality were the following:

- Articles from 2010 onwards;
- Listed in PubMed or Google Scholar;
- Search keywords: Serious games, Augmented reality, Augmented reality for rehabilitation, Augmented reality in health, Augmented reality for post-stroke rehabilitation.

2.1. Traditional neurorehabilitation

Traditional neurorehabilitation aims to aid in the recovery of damage done to the nervous system, be it on the motor or on the cognitive spectrum through, in the case of motor rehabilitation [7], physical or occupational therapy and, in the case of cognitive rehabilitation [8], through specific cognitive intensive tasks. In [2], Langhorne *et al*. define stroke rehabilitation as the process of identifying the patients' problems, defining what tasks that are required to achieve attainable goals, perform such interventions and reidentify the patients' needs by comparing them to the results of the goals set. This process of rehabilitation aims to help the patients recover their functional independence and quality of life. The authors assert that there is strong evidence that task-oriented tasks improve the natural pattern of functional recovery. It is possible to find more common stroke rehabilitation strategies and methodologies, such as constraint-induced movement therapy (CIMT), treadmill training with partial support of body weight and training in community reintegration [9]–[12].

Nevertheless, there are a set of drawbacks to traditional stroke rehabilitation, such as the need of the presence of a therapist to perform the interventions because of their complexity and lack of independence of patients. In addition, these interventions have a steep learning curve as a result of the sheer amount of tasks that are required for each specific impairment [2]. This type of rehabilitation is also especially expensive [13], which by consequence usually cuts on the amount of rehabilitation that is given to the patient [14]. Furthermore, traditional rehabilitation can be demotivational due to lacklustre and delayed effects on the patients and the insufficiency of entertainment [15]. Moreover, for better results, the patients are required to do repetitive activities at home, but due to their cumbersome nature, only a small number of people actually go through the trouble of doing them to the full extent [16].

In summary, traditional therapy does not seem to be enough to aid chronic stroke patients in their full recovery of independence. It is also very expensive and therefore is usually done in limited quantity. Hence, a need for innovative methods has arisen. These methods should supplement the post-stroke patients for a swifter recovery in a more interesting and exciting fashion.

2.2. Virtual reality neurorehabilitation

With an uprise of novel virtual reality rehabilitation games and simulations, we can start to see some benefits surfacing when compared to traditional rehabilitation. For example, these novel strategies tend to be more fun and motivating because they are less predictable and repetitive than physical and occupational therapy [17]–[19]. Moreover, virtual reality brings in the feasibility of making games that do not require the presence of a therapist to perform because of its controlled environment, and this makes it a great and cheap supplementary rehabilitation method. Addition, virtual reality has also proven itself against traditional stroke rehabilitation in stroke recovery, which can be seen in [15], [20].

Another big perk that virtual reality brings is a possible combination of motor and cognitive rehabilitation as found in [15]. A. L. Faria et al. suggest that improvements can be obtained in both domains of rehabilitation by transforming the pen-and-pencil task into a virtual reality game and asking the patient to perform the interaction with the affected arm. Furthermore, it is suggested that the cognitive performance was carried over from the virtual pen-and-pencil task to traditional counterpart. But on the other hand, it is settled that cognitive performance was greater in the pen-and-pencil task.

There are many interfaces to interact with virtual reality games, be it in two dimensions, be it in three dimensions. In [21] we can find a study with stroke patients that assesses which method of interaction is adequate for virtual reality rehabilitation in accordance to both motor and cognitive domains. This study consists of a serious attention game that is interacted with 4 different interfaces (Figure 1. (a) Experimental setup (b) Rehabilitation task), which are the following: the mouse (2D traditional user interface), the air mouse (3D TI), Analysis and Tracking System (2D Natural User Interface) and Kinect (3D NUI). These interfaces were chosen to compare 2D interaction to 3D interaction and to analyse traditional interfaces in relation to natural interfaces. The metrics assessed for motor performance were acceleration, velocity, the range of movement and smoothness. With respect to upper limb movements in the post-stroke patients, better results were obtained with 2D interfaces, probably due to having a surface to support their arm. The authors also conclude that natural interfaces have overall a better motor performance, in both healthy users and post-stroke patients. A. Vourvoupolos et al, also states that respecting the cognitive domain we can see a clear tendency to commit fewer mistakes and get a better overall score in 2D interfaces, although it comes at the expense of lower completion times. Therefore, regarding post-stroke patients, the best compromise is a 2D natural user interface, since in their case it allows for better cognitive and motor performance.

Virtual reality seems to be a positive step for additional rehabilitation, with proven results in motor and cognitive recovery after stroke, that does not require the continuous presence of a therapist, hence reducing the cost of rehabilitation. The equipment is usually cheaper too, with most patients already owning most of the equipment needed. Nevertheless, it still has its rough edges, such as visuospatial transformations that are often required in setups that don’t use a head-mounted display. There is still improvement to be made respecting the interaction methods too, for an even more natural and seamless use.

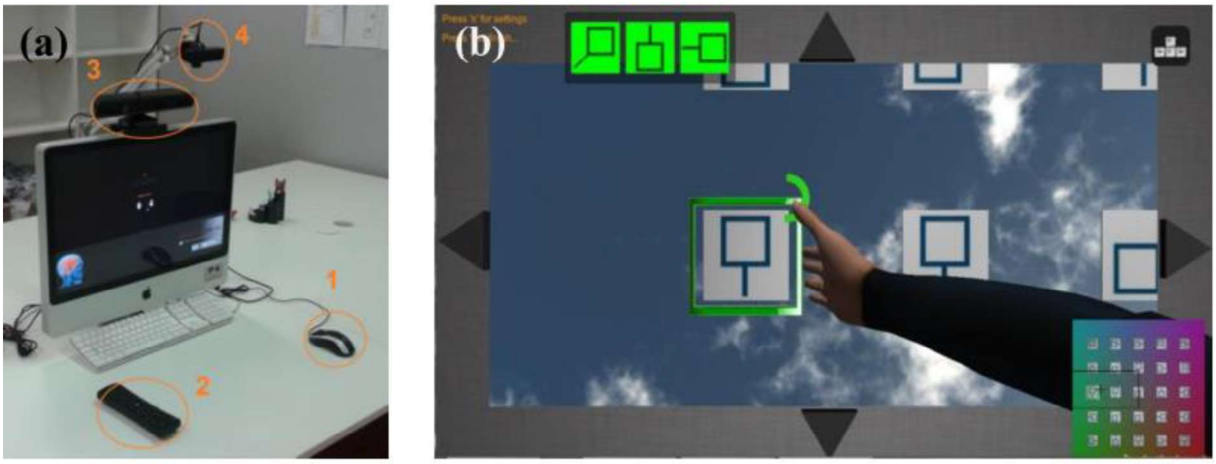

Figure 1. (a) Experimental setup (b) Rehabilitation task [21]

2.3. Augmented reality neurorehabilitation

Augmented reality has the broad definition of augmenting reality by superimposing virtual objects into the user's physical world. In [22], we can see that augmented reality lies somewhere between the real world and augmented virtuality, as well as, it is placed inside the spectrum of mixed reality (Figure 2). Here, B. H. Thomas considers augmented reality and mixed reality to be the same. He also proceeds to state some reasons why augmented reality can create more novel forms of computer games in relation to virtual reality, which is the following: Augmented reality only occupies a portion of the user's field of view you are able to create a more natural interaction than having to take the user to a whole new virtual world; Augmented reality allows the user to view the real world around, therefore creating a less restricted system where the user can roam freely; And lastly, users tend to like the ability to walk around on with their own bodies without the need of using an interaction device such as a controller or joystick. Augmented reality is not limited to spatial projection, as it can be recreated by the utilization of head-mounted displays and handheld devices. B. H. Thomas later refers to a table-based immersive head-mounted display augmented reality as a potentially interesting option, since this enables the game to be more interactive than a regular board game, making for a more exciting experience.

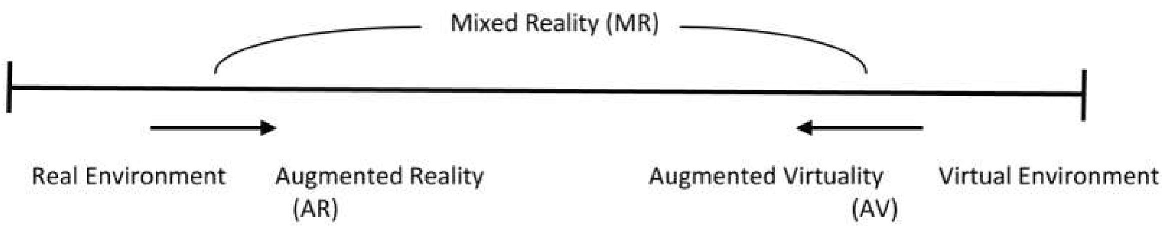

Figure 2. A simplified representation of a Reality-Virtuality Continuum.[23]

Considering augmented reality for rehabilitation purposes, some advantages emerge in comparison with standard desktop applications. In [24], [25], H. M. Hondori et al say that human-computer interfaces like the regular mouse can be restricting because it requires the users to do a visuospatial transformation on the coordinates of the mouse onto the computer monitor, which sometimes can prove to be more difficult than thought considering the condition of the post-stroke patients. Hence why other human-computer interfaces have become a popular subject more recently, interfaces like spatial augmented reality which require no such transformation (Figure 3). To further examine these effects, the authors performed an experiment with 18 patients that suffered from chronic hemiparesis after stroke. These patients' motor performance was measured as each played the variation of a popular game, "fruit ninja", that was implemented in both spatial augmented reality and virtual reality. They hypothesised that due to the uncoupling of the eyes and the hand the task would lead to higher cognitive demand hence causing lower overall game scores.

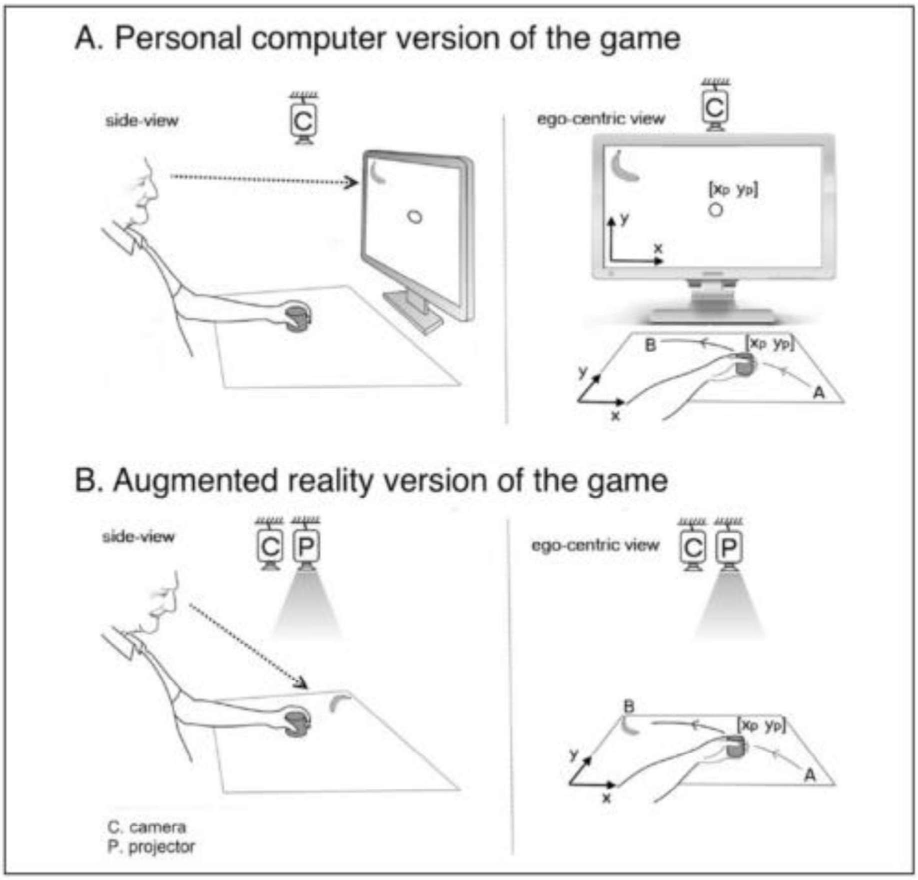

Figure 3. A) Virtual reality setup. B) Augmented reality setup. [24], [25]

Respecting the game, it was based on the popular fruit ninja game, where the player must cut the maximum number of fruit, by placing the cursor over the target, in the smallest amount of time possible. This game was, however, toned down to where the fruit would only appear randomly in one of the four corners of the board. Each round lasted 90 seconds. For both versions of the game the user was asked to use his stroke affected limb to move a small plastic cup, which served as a colour marker, that was tracked by a camera. Although, in the case of the virtual reality game the user had to look at a computer screen to verify where the fruit was (Figure 3. A) Virtual reality setup. B) Augmented reality setup.), whilst in the augmented reality counterpart the user had the fruit projected on the table with a projector (Figure 3. A) Virtual reality setup. B) Augmented reality setup.). To familiarize the patients with the games, they played a round of each game without being analysed or recorded. For the experimental data, the patients were asked to play three rounds of each game, where the order of what game they started on was randomized to prevent biases. After further analysis of the data, they could deduce that the augmented reality counterpart was better regarding speed, consistency and score. It seems that the visuospatial transformation does indeed cause more cognitive demand, although, on the other hand, this might be the desired aspect depending on the patient personal needs.

TheraMem is a novel augmented reality motor rehabilitation game that was used in the following two studies: [26], [27]. It was created on the hypothesis that the system would be used for motor rehabilitation, more specifically for post-stroke therapy. Moreover, according to the authors, a computer game would provide a more interesting user experience that could change the user's judgement on how their impaired limb moves and lastly, the amplification of movement on the debilitated limb would lead to improvements on motor rehabilitation by virtue of neuroplasticity. TheraMem is a simple memory game where the patient must match the cards from two different boards that contain 12 upsides down cards. The user interacts with these cards using nothing but his hands (Figure 4) and for this purpose, the authors implemented finger tracking on the system.

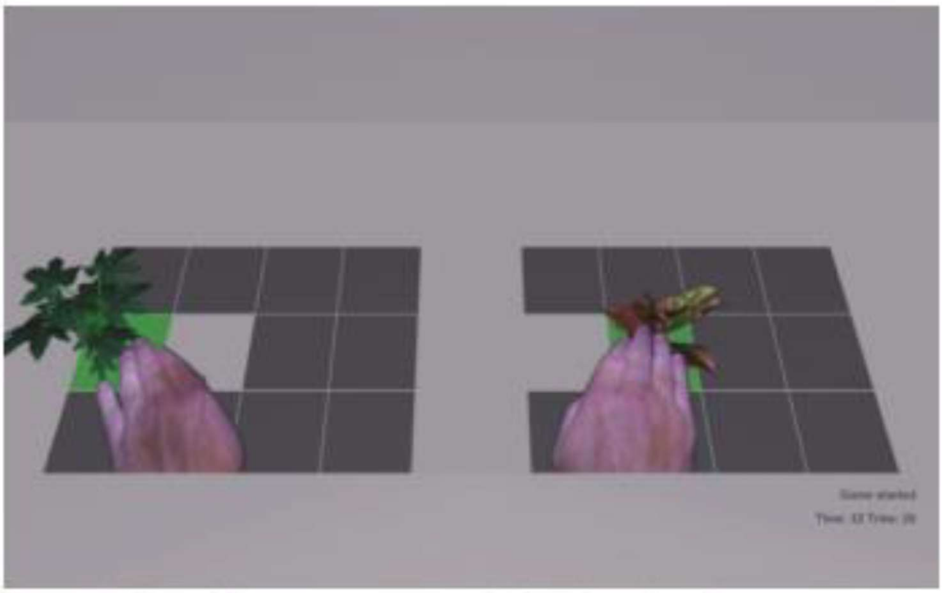

Figure 4. ThermaMem gameplay [26], [27]

The setup consists of two black boxes that contain cameras inside with LEDs to maintain perfect lighting conditions. These boxes have curtains so that the user is unable to see their own hands which lay inside. TheraMem allows a nearby operator to then tweak the interaction as needed. He can amplify the movement of either limb to help the patient have an easier time performing the task at hand. Two scenarios were tested with TheraMem, a scenario where the user was unaware that their hand had amplified movements and another where the user was aware. During the first scenario, they noticed that the users had most difficulty when the amplification was either at its highest point or lowest point. In the second scenario, users said they did not only experience faster movements on the amplified hand but also that the non-amplified hand seemed slower than usual. The authors infer that TheraMem is proof that virtual and augmented reality systems can be used to trick the brain in a positive way causing neuroplasticity to activate, therefore, enhancing and improving motor functions. They mentioned that the clinical feasibility was promising after testing this system with six post-stroke patients, of which 3 had severe impairments that didn't allow them to perform the tasks without assistance however still were able to complete the tasks with the appropriate aid.

Augmented reality is more flexible than virtual reality since it brings virtual objects to a familiar setting, the real world, whilst still having a completely controlled environment, mentions M. Khademi et al in their study [28]. The authors say this allows for a more natural interaction and engaging experience, they even stated that "augmented reality has been reported as highly engaging by patients undergoing therapy". They noticed that most patients are likely to give up on regular therapy and that patients spend almost half their days without engaging in physical activities, which is counterproductive because to ensure a swift recovery it is of utmost importance to maintain an active daily life. To put augmented reality to the test the authors created a game, in both, spatial augmented reality and non-immersive virtual reality. The setup for both versions was a camera to track the placement of the cup the user held, a projector for the augmented reality version and a monitor for the virtual reality interface. The game consisted of a simple task of picking up a cup and placing it on a square that would appear on the table, in the case of AR, or on the monitor. The tests were performed with 14 healthy people (7 male and 7 female) as a proof of concept. The participants had 30 seconds to place the cup into the boxes as many times as they possibly could. After analysing the results, the authors found that the augmented reality interface had obtained significantly higher scores and the users mentioned that it was more intuitive and straightforward.

In [29], it is mentioned that patients do not have a good time using technology that is hard to equip. Therefore, H. Mousavi et al decided to create four spatial augmented reality tasks that only need a low-cost projector, a webcam and colour tags on the patients. This equipment makes these tasks feasible at home or in a clinic environment. This table top system can track the user's hand and measure the range, speed and smoothness of movement. It is then possible to send this information to a therapist or clinic for additional evaluation. The tasks proposed by the authors were heavily influenced by daily life activities because they believe that these would be more helpful to post-stroke patients. The movements performed by the users in these tasks are pointing, grasping, pointing and arm extension. The first task (Figure 5. a) musical reaching task b) water pouring task c) musical pointing task d) object gripping task consisted of the user listening to a musical note and then proceeding to reach out to the box which contained that same note. The user did this several times until he created his own music and received feedback on how well he performed regarding his speed and how many notes he pressed correctly. On this task, the user placed the colour marker on his index finger. As for the second task (Figure 5. a) musical reaching task b) water pouring task c) musical pointing task d) object gripping task), the user was asked to tilt a cup, after performing the tilting motion a blue circle would appear and grow depending on how many times the user tilted the cup. The next task (Figure 5. a) musical reaching task b) water pouring task c) musical pointing task d) object gripping task) was to point out to musical box, where he would receive audio feedback, so the user would know he performed the action. This pointing was repeated using two different postures, one for wrist extension the other for adduction/abduction. On this task, the user used a colour marker on both his finger and his wrist. Finally, the fourth task was to grasp random sized circles. When the motion was completed the user would also receive audio feedback and for this task, he had a colour marker on his finger and thumb.

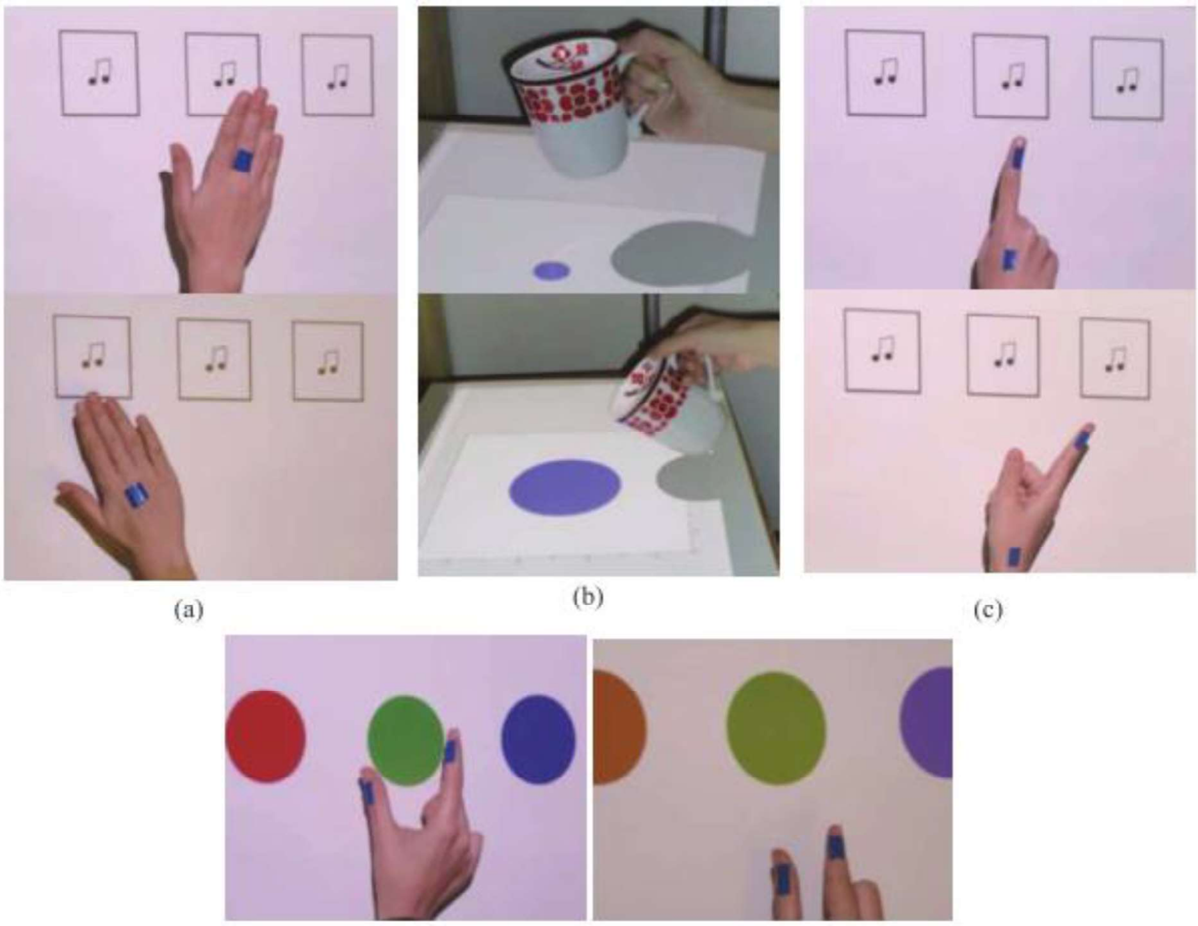

Figure 5. a) musical reaching task b) water pouring task c) musical pointing task d) object gripping task [29]

These tasks were tested using two healthy participants to try and find any critical problems with the system, gain experience in a laboratorial setting and to prove the concept. The authors mention that a key advantage of this system is that the therapist can change the settings to match the patient's needs.

A study was also done on postural control training on post-stroke patients using immersive augmented reality, as can be seen in [30]. The main goal of this project was to find out what kind of impact this type of system would have in assisting balance and gait functions because the loss of postural control is a well-known health problem in post-stroke patients that usually interferes with rehabilitation. The task consisted of watching and listening to the modelled view of how the postural exercise is meant to be done. After achieving more than 80% of the patterns, they were allowed to move on to the next step. According to the results, the patients that used this system saw significant improvements to their balance and gait functions. However, the patients did at times feel nauseous and the study was done on very few patients. All in all, these results seem promising and further research should be done.

Ghostman [31] was created to test the feasibility of telerehabilitation, which consists of rehabilitation through telecommunication networks, for example, over the internet. Ghostman uses a technique the authors call "inhabiting visual augmentation", this is where one person "inhabits" the other person's viewpoint (Figure 6). For this, the authors used a head-mounted display system with crystal liquid displays, cameras and orientation sensors. Due to the high cost of this system, around $3000 (Australian dollars) for each device, it might not be feasible to distribute to every patient's house.

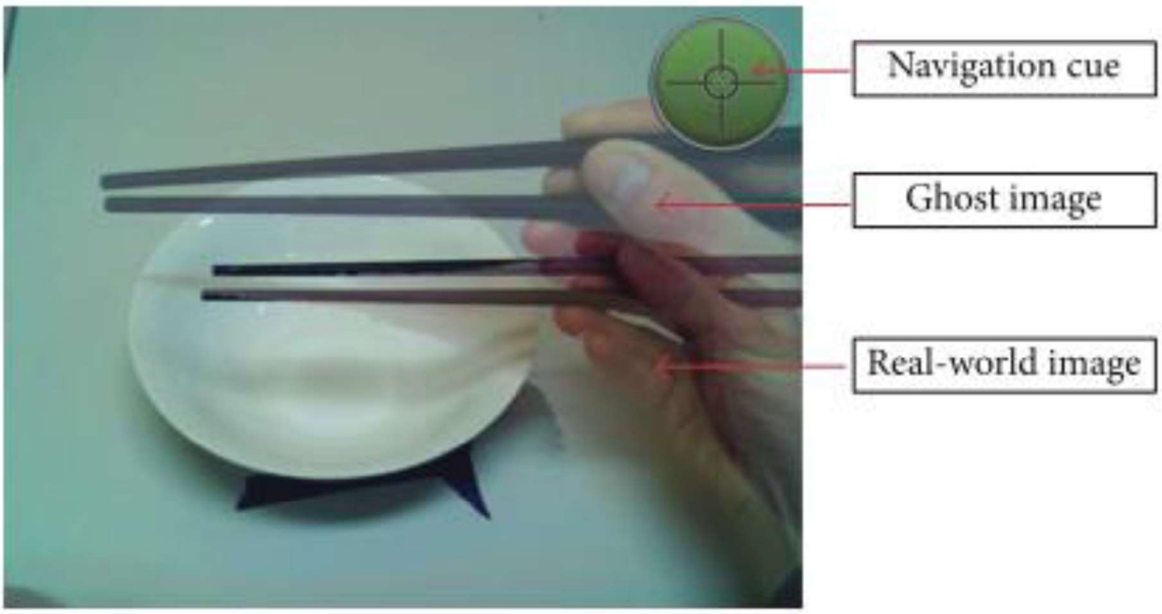

Figure 6. Ghostman in real-time [31]

The task chosen to put this system to the test was simply the use of an instructor who was experienced in using chopsticks to teach a novice user how to use them. Then they used the gained expertise to transfer 20 plastic blocks from one bowl to another. The pilot test consisted of 12 participants, 6 of these used Ghostman and the other 6 got face-to-face training on the same task. These participants were subjects of a 7-minute training session then they were tested 5 minutes after the training session, 24 hours after and lastly 7 days after. The outcome was that the Ghostman users were similarly efficient at performing the task as the users that received face-to-face training. Also, the user experience questionnaires revealed that the users of Ghostman felt as confident as the face-to-face group.

Augmented reality has the novelty of creating games that should be more natural than virtual reality by removing the visuospatial transformation as a factor. These games can also allow the user to move more freely and in some cases, do not require extra gadgets to interact. We can also see that there is plenty of room to study and find the effectiveness of these games in a rehabilitation and clinical setting. However, augmented reality's most limiting factor is the technology used to implement it and its effectiveness compared to rehabilitation still requires more studies [32]. Nevertheless, augmented reality has potential and further studies should be done in this field.

2.4. Conclusions

Traditional rehabilitation is of utmost importance and should be continued to ensure that patients recover their functional independence. However, it can benefit from being supplemented with other rehabilitation methods, such as serious computer games. These virtual reality games can prove to be an amazing asset to keep users motivated in their therapy whilst also permitting the patients to perform both cognitive and motor rehabilitation in simultaneous. It further allows the patient to perform cheap supplementary rehabilitation without the need of a therapist. There is a very big trend towards the usage of natural user interfaces, where although the task becomes slower, it yields better results regarding cognitive rehabilitation. The interaction methods should also be 2D to allow the post-stroke patient to have some sort of arm rest and be as natural as possible to ensure ease of use and good performance.

More and more studies state that augmented reality is promising, as it is a more natural interaction than virtual reality. It does not require the users to perform a visuospatial transformation on the task at hand. It also seems that augmented reality usually comes with fewer gadgets attached, making it for a more simple and straightforward experience. I also conclude that augmented reality has the potential to maintain a controlled environment, as well as, remove the need of a therapist always present much like virtual reality. However, as promising as it seems, there is a lack of design guidelines for augmented reality and there is still few clinical evidence and most of these studies consist of spatial augmented reality, which even though can be considered cheap, still require a projector, which is still a big investment.

Ideally, these rehabilitation tasks should be cheap, hence why I propose the usage of a smartphone, which, nowadays most people already have. Due to the lack of studies with immersive augmented reality, my proposal provides further insight in how head-mounted immersive augmented reality fairs in rehabilitation and how augmented reality compares in terms of presence, engagement, performance and task load with a non-immersive virtual reality counterpart.

3. Methodology

This chapter encompasses the complete description of the augmented reality game that was created, alongside the design and architecture of the software. All implementation choices are portrayed in this section. A brief description of the virtual reality game is also included in this chapter. Finally, the augmented reality marker, commonly known as the game board thought processed and conceptualization is described at the end of this chapter.

3.1. Augmented Reality Game

For this software, I decided to use iterative prototyping that consists of completing a prototype, testing it, encountering the problems via user testing and finally, refining the software. After all these four steps are complete, we restart at step one, in a cyclical fashion, until no difficulty or bug is discovered.

3.1.1. System requirements

To guarantee the feasibility of this thesis the following functional requirements were vital:

- Requirement #1: The game should work on a smart phone;
- Requirement #2: The game's interface should be a head-mounted display;
- Requirement #3: The game should log the player's progress;
- Requirement #4: The game should be usable by post-stroke patients;
- Requirement #5: The tiles should scale accordingly to the game board;
- Requirement #6: The user should be able to interact with his hand;
- Requirement #7: The game's level should be restart-able;
- Requirement #9: The interaction method should be 2D.
- Requirement #10: The virtual buttons must be translucent;
- Requirement #11: The buttons placed higher should have priority;
- Requirement #12: The tiles should have priority over the play, reset and close buttons;
- Requirement #13: The game should have a general timer;
- Requirement #14: While performing the task the GUI should be on the game board;
- Requirement #15: The game should take advantage of the game board's features;
- Requirement #16: The game should take up most of the game board;
- Requirement #17: The game's buttons should all have a timer;

Non-functional requirements:

- Requirement #18: The immersion of the game should not be broken;
- Requirement #19: The general aspect should be consistent with the virtual reality game;
- Requirement #20: The game should be easy to understand;
- Requirement #21: The game should be lightweight to run on most smart phones.

3.1.2. System Architecture

For the conceptual architecture (Figure 7) of this project, after plenty of changes during the implementation stage due to limitations of the technology, I divided the system into 7 logical components. These components are all responsible for a core functionality in the game.

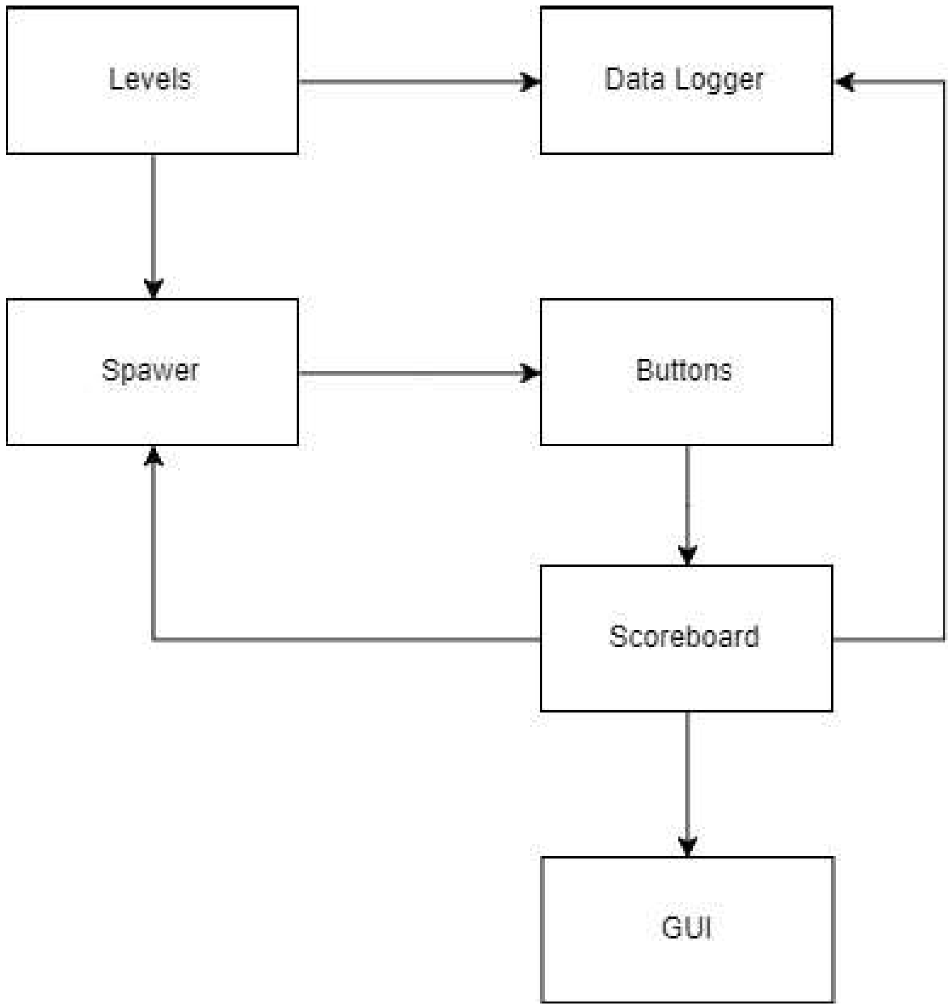

Figure 7. Augmented reality system architecture

3.1.2.1. Levels

This component is responsible for everything related to levels. It contains how the levels are configured, how the levels change, and it even preloads these levels' configuration to ensure a smoother experience on the phone. To add or remove levels all you need to do is to access the levels XML file and add or remove them with the same structure as the levels contained in the file.

3.1.2.2. *Spawner*

This component takes care of the spawning of the virtual buttons and what texture they are meant to show. At the time of spawning, this component takes into consideration the previous score factors. It is also responsible for placing the buttons in the correct places. This component does a pre-load of the levels to ensure that the phone does not lag in real-time execution.

3.1.2.3. *Data logger*

This component is responsible for logging all the player's information on the level he has completed in a CSV file. The saved file uses the name of the user that is entered at the start of the system. The string structure for this file is: Level name, Correct answers, Incorrect answers, Time taken, and Points achieved. This logger saves the data at the end of each level, this choice is due to optimization purposes.

3.1.2.4. *Buttons*

This component is responsible for the all the gameplay interaction. When a button is pressed it uses a strategy design pattern to know what its responsibility is and executes it. It is also responsible for registering these buttons on the system and rendering them when they are required, so when the game board is tracked.

3.1.2.5. *Scoreboard*

This component is responsible for the flow of the game. It takes care of the scoring of the game, hence it has the power to end the level, for example when the player has selected all the correct tiles. This component also contains the timer for the game duration and it also presents the targets the player must achieve.

3.1.2.6. *GUI*

This component is responsible for the GUI of the game but is not restricted to the main menu which appears on the phone screen. It takes care of the menus shown on the game board, like the final score, the memory task target and the scoreboard that is laying on the game board.

3.1.3. Technology

The game engine used in this project was Unity3d (Unity Technologies, San Francisco, USA). It is an extremely versatile engine, which allows for easy ports in practically every operative system. The engine is prepared to create 2D or 3D games with a simple click of a button and is completely free. But the main reason I used this engine was that I already had previous experience in Unity and NeuroRehabLab's Reh@Task was implemented in this engine. Unity lets you pick what programming language you want to use, either C# or JavaScript. Since I have more experience with traditional Object-Oriented languages and because I had previously used C# in projects during my bachelor's degree, I opted for using C#.

I was also required to find a way to implement augmented reality into Unity. For this purpose, I used Vuforia (PTC Inc, Needham, USA). At the time, it was the most advanced free software development kit available. In this SDK, you can create an augmented reality marker, add it to the database and use it in unity to build your scene around this marker. Then it uses the camera, be it the phone's camera, tablet's camera and even webcams, to track the marker. When the marker is found it swiftly shows the virtual objects on top of this marker, in the way you configure it on the scene. It also allows you to change the camera options, to allow for better optimization or quality. You can even add virtual buttons to scenes, these buttons when touched by any object can trigger events, coded by the user. It has occlusion management, so when you only see the marker partially you still get rendered virtual objects.

I had to find a way to transform the phone screen into a head-mountable display, for this I went with the widely used Google's Cardboard SDK, the main reasons being that Vuforia had easy integration with Cardboard SDK and because it is highly documented and used, therefore, any problem encountered usually has a solution online. This SDK allows the use the phone as an immersive virtual reality device, paired with Vuforia it becomes an immersive augmented reality device. You can then tweak the lenses in terms of field of view and distortion correction. It also has an android app that configures your lenses' distortion for the head-mounting device of your choice. It comes with an option to enable or disable a screen marker, that helps you position the phone inside the head-mounting device.

For an integrated development environment (IDE) I used Visual Studio (Microsoft, Washington, USA), instead of the MonoDevelop (Xamarin, San Francisco, USA) that comes pre-packaged with Unity, the main factor that lead me to this choice was an amazing plug-in that Visual Studio has called ReSharper (JetBrains S.R.O., Prague, Czech Republic), this plug-in allows for real-time debugging, it gives real-time optimization tips, it helps in naming conventions and it has great support for refactorization.

Lastly, I used BitBucket (Atlassian Corporation Plc, Sydney, Australia) in combination with SourceTree (Atlassian Corporation Plc, Sydney, Australia) for version control, so I would have guaranteed backups of all my project.

3.1.4. Software Description

This software is heavily based on the NeuroRehabLab's Reh@Task, it is an immersive augmented reality solution to the Toulouse-Piéron cancellation task. This is a task where we must find certain targets in an array of distractors. This variation transforms the smartphone into a head-mountable display and uses the phone's back camera to find the AR marker. This application also benefits from having Cardboard app [33] installed on the phone. This application allows the configuration of the distortion for the lenses of the head-mounting device.

Regarding the GUI of this game, they were all adaptations for phones based on the Reh@Task's GUI. Starting with the start screen (Figure 8), on this menu, the user must input his/her name. This menu is to be used before placing the phone inside the head-mounting device, hence why the screen is not yet split. This name is then used to create a log file for that same user. If a log file with that name already exists, then the information from the new session will be appended to it. Pressing the play button on this menu will take the player into the AR adaptation of the game, a loading screen in between this scene and the AR scene, to let the user know that the game will actually be loaded, and the application has not crashed.

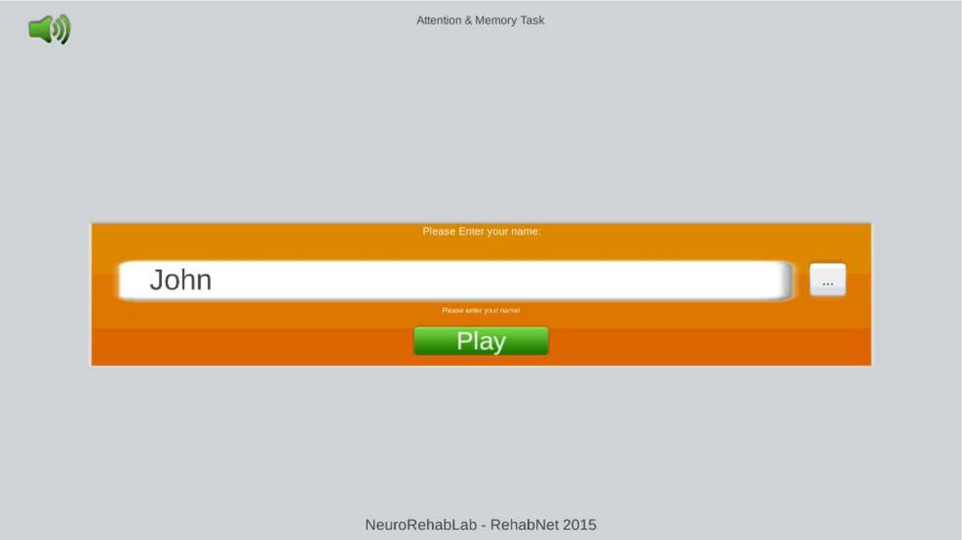

Figure 8. Start screen

The scoreboard is placed on top of a prism. This is to allow the player to easily see the score whilst sitting without having to move the game board. The scoreboard (Figure 9) is responsible for showing the target images that the user should find in the play area of the game board. It also has the timer and the score on it. The score is calculated as follows:

$$\text{Score} = \frac{((\text{correct choices} * 10) - (\text{Incorrect choices} * 10))}{\text{Tiles spawned}} \quad (1)$$

Figure 9. Scoreboard

Regarding the virtual buttons, these are all the buttons that appear on the game board. They all have a degree of transparency added to them. This decision was made so that the interaction would be more natural because the feeling of the user's finger disappearing could cause a break in immersion. These buttons are the core of the game. There are four different types of buttons: the play button, the reset button, the close button and finally the game tiles. All the buttons when pressed have a timer that appears in the top right corner to indicate they're being pressed. They also have priority levels. The tiles have priority over the other types of buttons and tiles that are in higher columns have priority over the tiles found below. This feature was added to ensure the user does not accidentally exit when pressing a tile. Moreover, this way the user does not have to worry about pressing all the tiles in lower columns when trying to reach a tile. Their event is only triggered after the timer finishes. This functionality is to prevent accidental clicks. These buttons' events are coded with a strategy design pattern to allow each type of button to have their own implementation without interfering with the game board handler's functionality.

The play button (Figure 10. A) is responsible for starting every level. This includes going to the next level. This button is highlighted to indicate it is ready to be pressed, therefore, if there is no highlight on the button it wouldn't register presses. The reset button (Figure 10. B) restarts the level the user is on in terms of difficulty. The target tiles and distractors are all different. The close button (Figure 10. C) takes the user back to the starting screen.

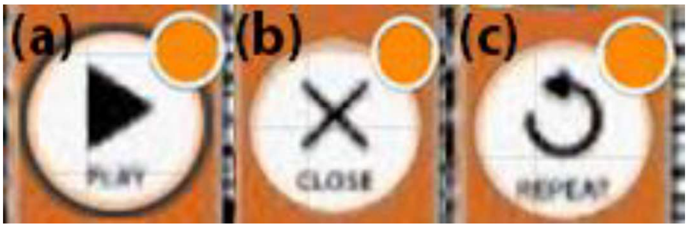

Figure 10. Static game board buttons

The tiles are a core feature of this game. They are the objects the users should interact with to play the game. These buttons have random textures attributed to them at the start of the level. When these buttons are pressed, they give audio feedback and an orange border appears around the tile (Figure 11. A). After the timer ends, if the tile is a target then a green border stays on the tile (Figure 11. B). The score is updated, and that tile can no longer be pressed. If the tile is not a target, a red border appears instead (Figure 11. C). Due to limitations in the Vuforia SDK, I was not able to create these buttons dynamically, so all the buttons exist in the scene but are activated and deactivated when needed.

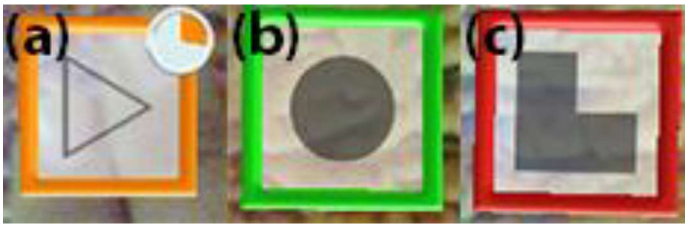

Figure 11. Gameplay tiles

For the spawning of this game, it spawns the levels according to an XML file which contains the configuration of the level. On this configuration file, you can change what symbols you want to use, on the tiles and targets, how many columns and rows to use in the level, how many targets are to be found and how long does the game last and the pressed take. The correct way to structure this information can be found in Figure 12. All the levels and configurations are preloaded to ensure that the game does not lag in real time. The spawned tiles are then ordered in a way that fits the game board when there are more than 7 times in a row the buttons become smaller to fit the board better.

```xml
<L5>
  <columns>5</columns>
  <rows>3</rows>
  <targets>4</targets>
  <correctchoices>4</correctchoices>
  <showcorrect>true</showcorrect>
  <timer>28.876</timer>
  <picTimer>0</picTimer>
  <category>Cat_Symbols</category>
  <useDistractors>true</useDistractors>
  <imagesToDisplay></imagesToDisplay>
  <useMemory>false</useMemory>
  <valence>false</valence>
  <selectionTime>4.794</selectionTime>
</L5>
```

Figure 12. XML configuration file

After a level has ended, either due to the timer ending or the user finding all the targets on the board, a GUI appears with the user's total score (Figure 13) for that session. It also indicates the player that if he wants to go to next level he should press the play button. Due to the preloading of the level configurations and textures, the next level spawns instantly with no perceptible lag.

Figure 13. Total score

On a final note, to play this game is simple. All the user needs to do is to enter his/her name on the start screen. Then after the main scene loads, the user places the phone on the head-mountable device according to the screen marker. To start the game, the user just needs to press play. Then, the tiles will appear on the game board and the targets on the scoreboard. To play, the user just presses the tiles on the game board, according to the targets that should be found (Figure 14).

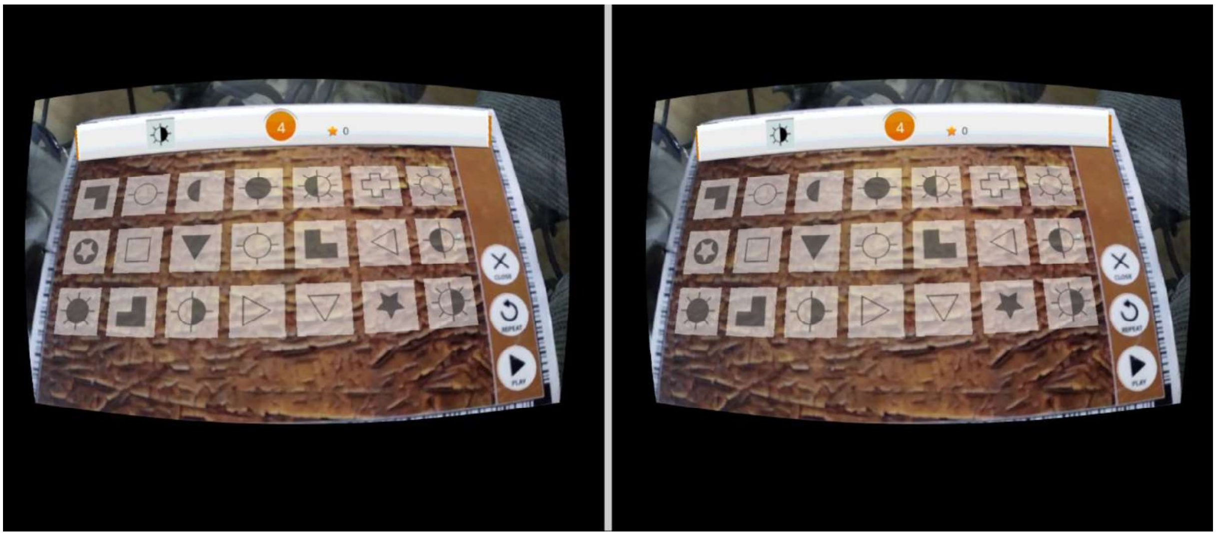

Figure 14.Full gameplay on the phone

3.2. Virtual Reality Game

The game used in this work was developed in the NeuroRehabLab [5], and it is a non-immersive virtual reality game based on the Toulouse-Piéron cancellation task [6]. The purpose of this game is to train motor and cognitive competencies simultaneously to optimize recovery after stroke.

3.2.1. Software Description

This is a game based on an attention task where the users must find target symbols in a pool of distractors. The users have a limited amount of time to find all the symbols before the level ends. This software logs the all the user's actions, including, the arm movements, score, time, level and the symbols.

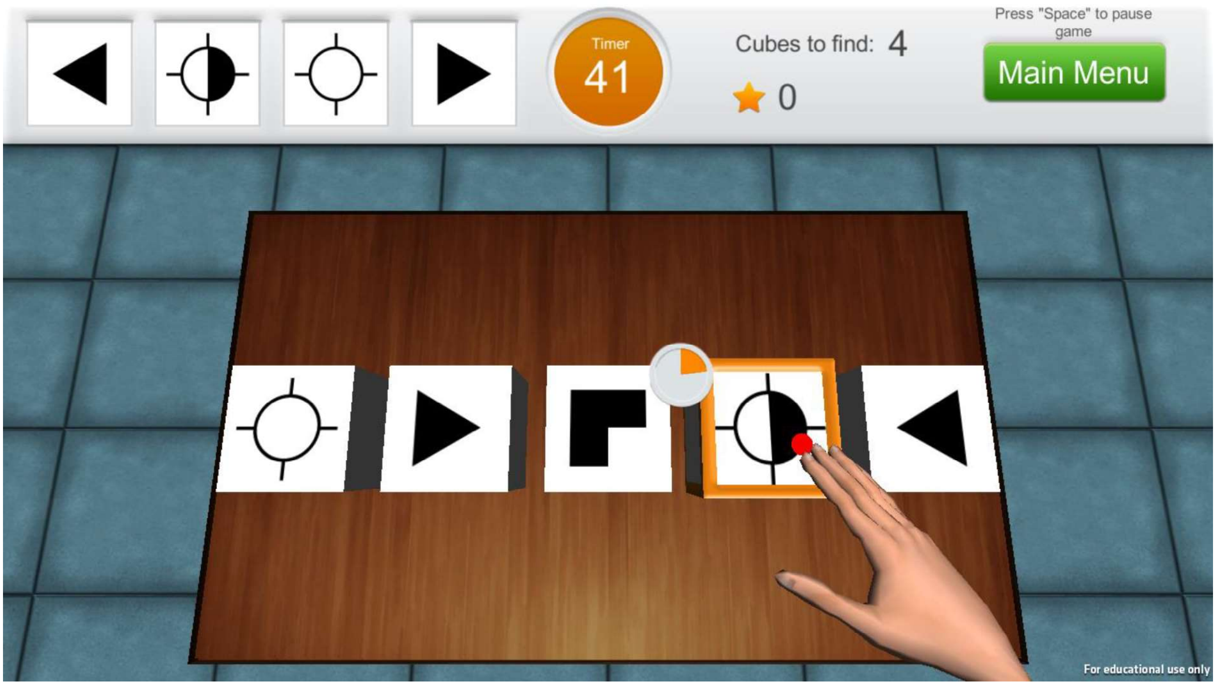

Figure 15. Gameplay of the virtual game

This game uses a 2D natural user interface, called Analysis and Tracking System (AnTS), to interact with the game. This interface allows for repetitive arm reaching exercise, that is aimed to aid in motor rehabilitation. This can be calibrated before starting the interventions to the patient's level of physical ability. Levels can be added or removed in the game in the same way as the AR counterpart, by changing the levels XML file. The symbols that are used to spawn are also changed in this XML file, this was implemented to make for a more versatile gameplay. It is worth noting that this system already has 120 levels in this XML file, these levels were defined through a participatory design study [34].

3.3. Augmented reality marker

For Vuforia SDK an augmented reality marker is needed, so it can track where to superimpose the virtual objects. This marker gets rated by the Vuforia system, from 0 to 5 stars. What this rating means is how well I'll work for easy tracking and interaction. For a marker to be highly rated it should have many irregularities, it should not repeat itself and should have decent contrast. After several design cycles, we were able to achieve a good target marker (Figure 16. Augmented reality game board) for the Vuforia system, this marker got rated as a 4 out of 5.

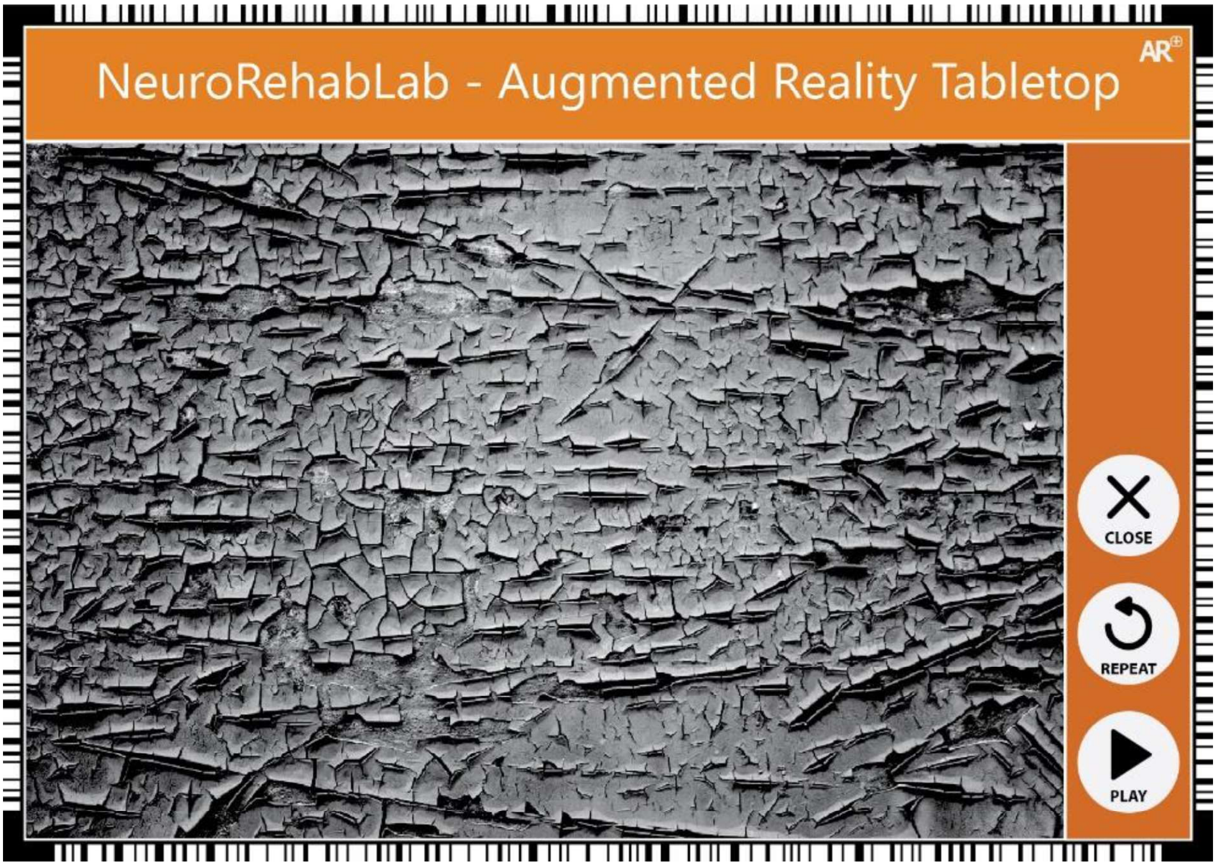

Figure 16. Augmented reality game board

This design was made to help keep the consistency of the GUI on the software, we also opted to keep static buttons on right-hand side because these buttons will be present throughout the whole game. The scratched surface inside is to give more details to the game board. As seen in Figure 17, these details provide better tracking and also help in the interaction because what Vuforia does to track interaction is check how many of these features are being covered up at any given time.

The game board for this project was printed onto an A2 PVC board (Figure 18). The reason for choosing PVC was because it is a more durable material than cardboard. Because post-stroke patients with higher levels of impairment typically need to rest their arm on the game board, this option was appropriate in terms of stability and durability. Respecting the size, I decided to use A2 because if it was any smaller, post-stroke patients could have a hard time interacting with the tiles due to precision issues. However, I still wanted to make this board as portable as possible, so the PVC board was cut in half with a supporting tape on the back, allowing the board to bend into an A3.

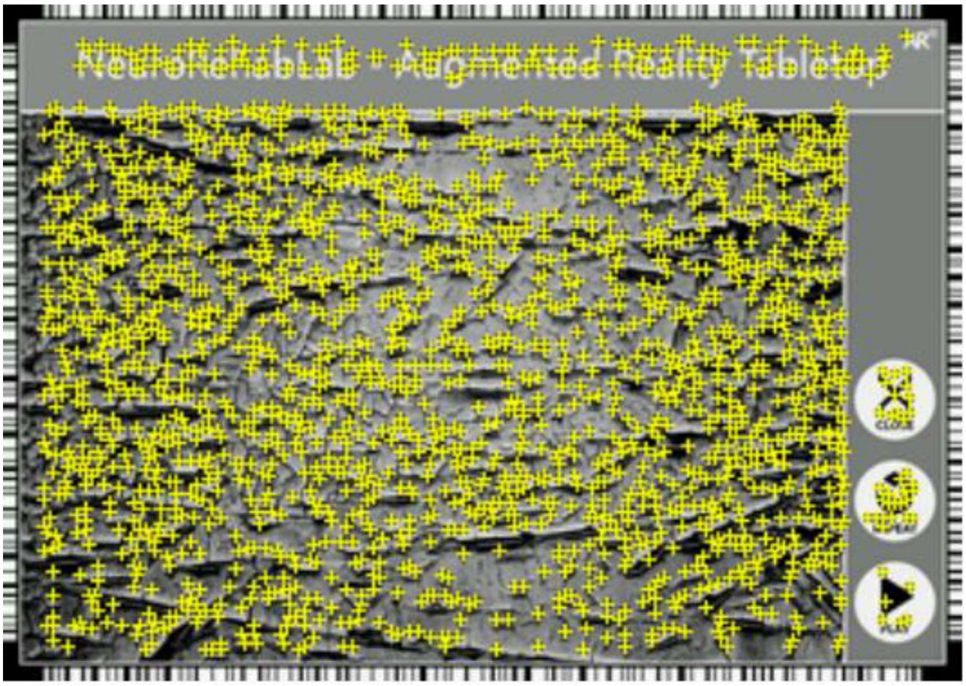

Figure 17. Tracking features

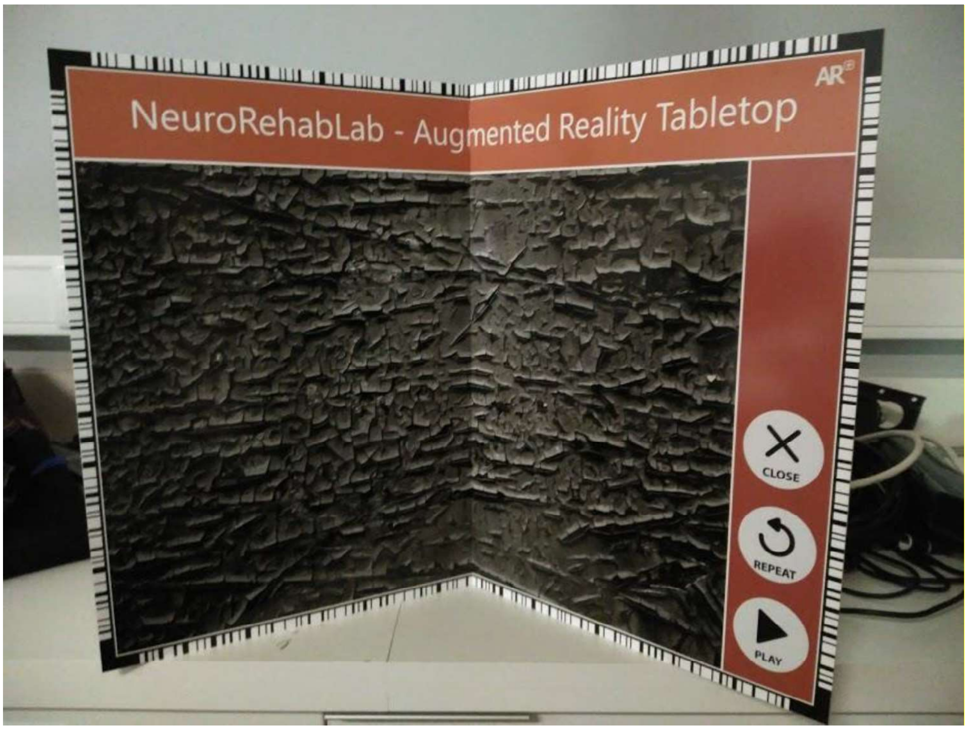

Figure 18. A2 PVC Gameboard

4. Field of View Pilot Test

This pilot test was run to understand which field of view was more appropriate for a more natural and engaging experience whilst still being immersive.

4.1. Materials

The materials required for this test were the following:

- A smart phone;
- An augmented reality marker;
- VRBox2 head-mounting device.

4.2. Methods

To decide which field of view would be best, three demo scenes were created. These scenes were all based on the virtual buttons demo scene from Vuforia (Figure 19. Vuforia teapot demo scene). In this scene, the only possible interaction is changing the colour of the teapot by pressing one of the virtual buttons below. The only modifications done to this scene was the AR marker that was used and the fields of view. The chosen fields of views to test were: 50º, 60º and 70º. These fields of view were chosen because 70º allowed the users to have all the game board on the screen, 50º is the most widely used field of view and I added 60º as a middle ground.

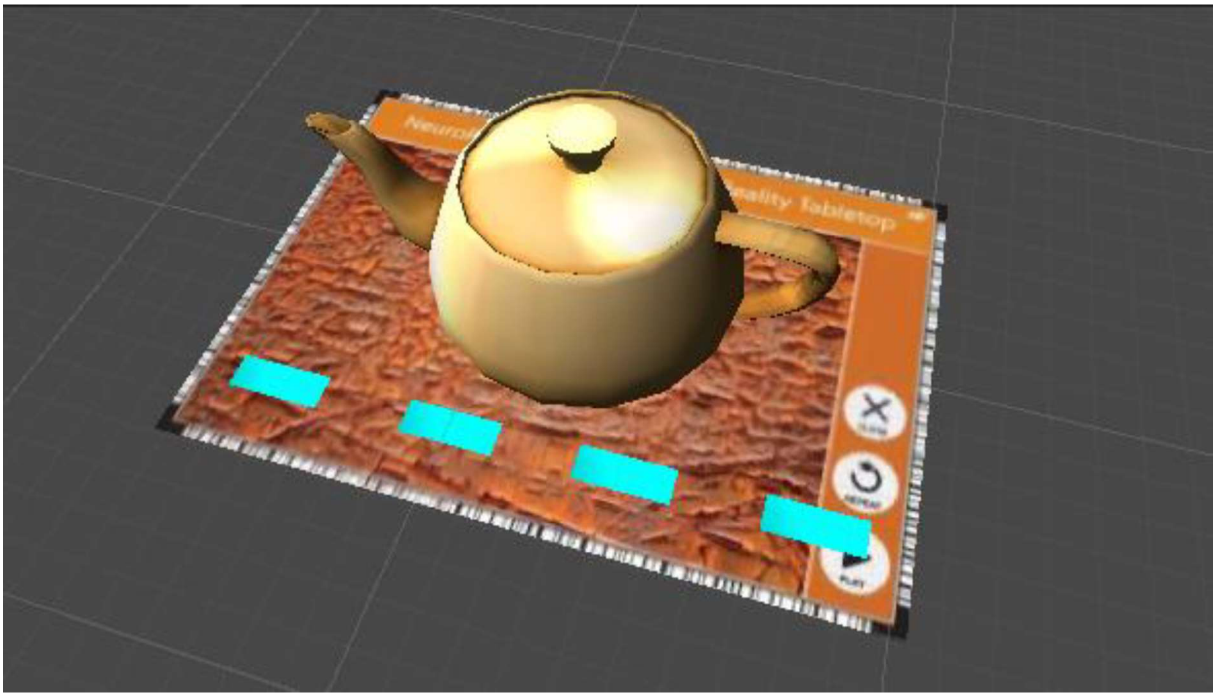

Figure 19. Vuforia teapot demo scene

Regarding the setup, the user was seated in front of a table with the AR marker placed in front of him, these users were then asked to wear the VRBox2 head-mounting device, which had a smart phone, a Samsung Galaxy S4 (OS: LineageOS 14.1, CPU: Quad-core 1.9 GHz Krait 300, RAM: 2 GB, GPU: Adreno 320)[35], running the game. The users had to correct the lenses in VRBox2 to their preference before performing the tasks.

19 users (4 females and 15 males, mean age = 25.3 ± 3.6) participated in this test. Every user tested all the scenes seated in front of the augmented reality marker, with 1/3 of the participants starting on the 50º, 1/3 starting on the 60º and lastly 1/3 starting on the 70º degrees demo. These demos were tested one after another to ensure that the users had a way to compare the fields of view. The experiment lasted around 10 minutes altogether.

After testing all the demo scenes, the users were asked to complete a System Usability Scale questionnaire (Appendix A)[36]. In addition, they were interviewed and asked about which version of the demo scene they preferred and why.

4.3. Results

After applying the formulas required to obtain a score in the system usability scale (Table 1) I saw that the 50º got an average score of 78.94 ± 16.29, the 60º got an average score of 84.87 ± 12.09 and finally the 70º obtained an average score of 85.66 ± 11.02. A more in-depth analysis yielded that the 70º also had a noticeably more consistent SUS score (Figure 20). These results show that all the demo scenes were thought to be highly usable. Scores above 70 points are considered B grades and scores above 80.3 points are considered A grades.

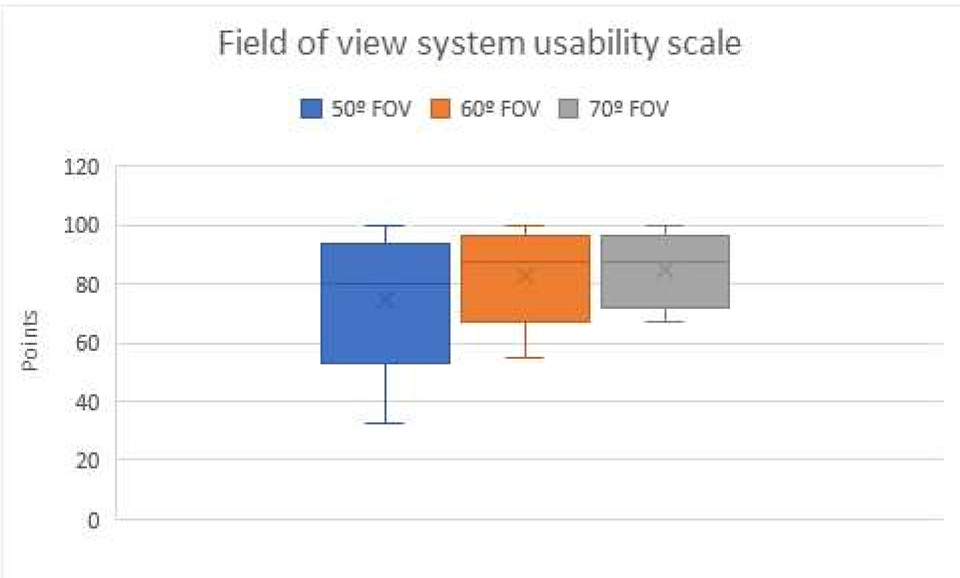

Figure 20. FOV System usability scale boxplot

	50º FOV	60º FOV	70º FOV
System Usability Scale Score	78.94 ± 16.29	84.87 ± 12.09	85.66 ± 11.02

Table 1. Average scores on the System Usability Scale

The interviews yielded some very interesting results. When asked about the preferred field of view, I got a 3-way tie, where 6 people voted in each of these fields of view and one said that it really did not make any difference to him. When it comes to why people preferred the 50º field of view the pros were usually that it gave a much bigger feeling of immersion, but it seemed like it had too much zoom. As for the 60º field of view, people tended to express that they felt this degree was the most natural out of all the other fields. Lastly, for the 70º field of view, most people commented they liked the way the mapping felt, more like how their eyes perceived the distances, as well as, they liked how they could see more of the game board. However, it was considered slightly less immersive. One of the testers had some very interesting feedback. He decided to get up and move around with the head-mounted display still on and he stated that the 50º version was his favourite for this task because he felt more immersed in the task. But he would prefer the 70º if the task required him to move around the same because the mapping to the real world felt more precise.

4.4. Conclusions

After analysing these results, I found that all fields of views were a plausible option from the interviews. However, keeping the system usability scale in mind and even though they're all rated as highly usable on these scales, I decided to use the 70º field of view because it scored highest and was more consistent on the scale. Additionally, I believe that it would be an interesting decision to try to compare these fields of views with stroke patients because, as mentioned in the state of the art in papers [26], [27], augmented reality might be a way of "fooling" the mind in a beneficial manner. Therefore, the field of view's zooms might be a way to obtain perceptual arm movement amplification much like TheraMem.

5. Comparison between Immersive augmented reality and non-immersive virtual reality

This study was held to try to compare immersive augmented reality to non-immersive virtual reality regarding its application in rehabilitation. The metrics that I will be comparing are performance, engagement, usability, presence and task load.

5.1. Materials

The materials used in this study were the following:

- A smart phone;
- An augmented reality marker;
- The VRBox2 head-mounting device;
- iMac computer;
- PS2eye camera;
- Analysis and Tracking System (AnTS) [21].

5.2. Methods

Preliminary data was collected from 15 healthy users (4 females and 11 males, mean age = 25.19 ± 5.27). The users did a run of each of the games, before data being collected and analysed, to ensure familiarization with the task. The participants were divided evenly regarding the interface they were chosen to use first, ½ of them started on the immersive augmented reality game and the other ½ started on the non-immersive virtual reality game.

For the setup, in the augmented reality game (Figure 21) the users were seated in front of a rectangular box that held up the augmented reality marker. These users were asked to wear the VRBox2 head-mounting device, which had a smart phone, a Samsung Galaxy S4 (OS: LineageOS 14.1, CPU: Quad-core 1.9 GHz Krait 300, RAM: 2 GB, GPU: Adreno 320)[35], running the game. The users had to correct the lenses in VRBox2 to their preference before performing the tasks.

For the virtual reality setup (Figure 22), the users were seated in front of a table which had an iMac (OS: Windows 7, CPU: Intel core 2 duo E8235 @ 2.80GHz, RAM: 2Gb, GPU: ATI mobility Radeon HD 2600 XT), with a PS2eye camera, mounted on top with a bird's eye view to run the AnTS. The calibration of AnTS was done before performing the task.

When at the given interface the users had to perform 8 difficulty levels. These levels were selected in a way to ensure plenty of interaction through the game, starting off at a very easy difficulty level scaling up exponentially until the final level. After performing each task, the user was asked to respond to three different questionnaires. A System Usability Scale (Appendix A) [36] to test the usability of each game, A Presence Questionnaire (Appendix B) [37] to evaluate the engagement and presence the user felt and finally, a NASA Task Load Index (Appendix C) [38] to evaluate the task load. The users were also evaluated in performance, such as, how long they took in general per system and how many points they scored overall. Additionally, I interviewed each user to know their honest opinions of each game and how they fared against each other.

Figure 21. Augmented reality setup

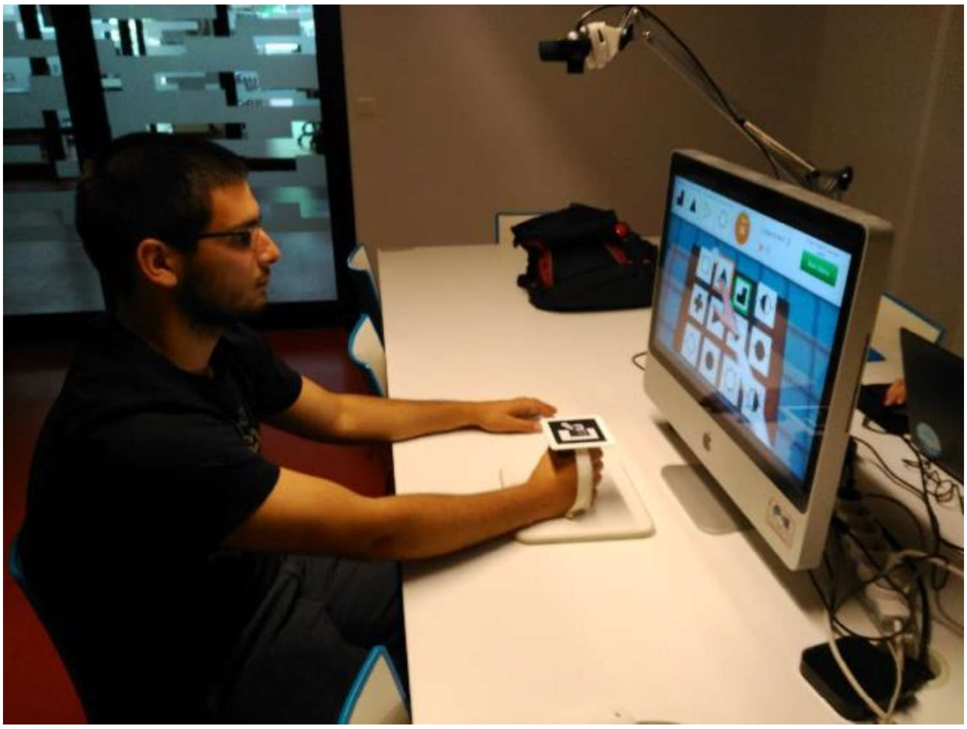

Figure 22. Virtual reality setup

5.3. Results

After applying the formulas to obtain a score in the System Usability Scale (Table 2, Figure 23), I found that the augmented reality achieved an average score of 66.5 ± 22.26, which is far lower and less consistent than the virtual reality counterpart that obtained an average score of 81.17 ± 13.09. This means that in the case of the augmented reality, the participants found the game decently usable; on the other hand, they found the virtual reality game to be extremely usable. Scores above 60 get a C grade, while grades above 80.3 get an A grade. Interestingly, the AR still got pretty decently high scores in some instances, this was probably the taller people, since their better viewing angle yielded a more usable experience with less tracking issues.

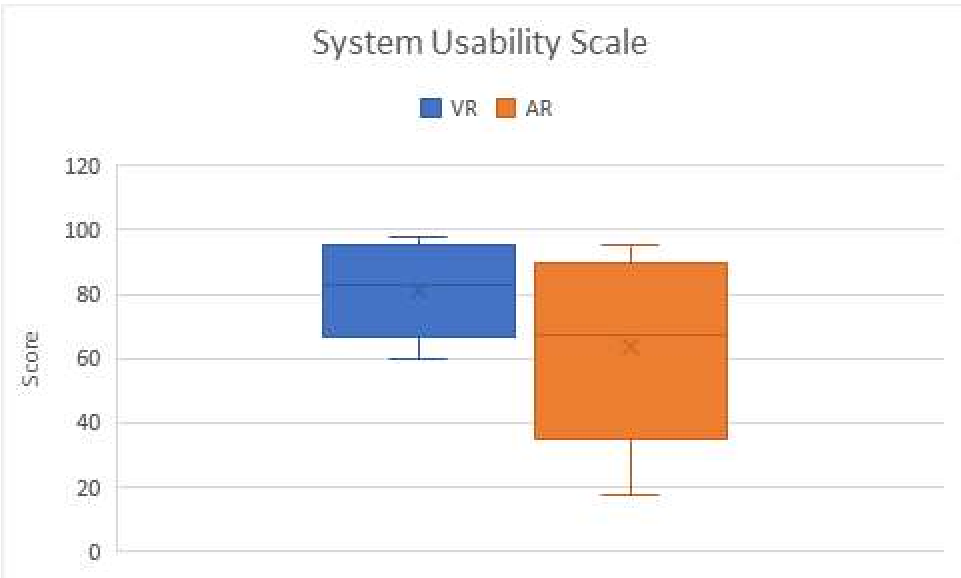

Figure 23. System usability scale boxplot

	Augmented reality	Virtual reality
System Usability Scale	66.5 ± 22.26	81.17 ± 13.09
NASA Task Load Index	46.63 ± 22.00	24.78 ± 11.00

Table 2. SUS and NASA TLX scores for augmented reality and virtual reality.

Figure 24. TLX total score boxplot

As for the NASA Task Load Index (Table 2, Figure 24), the augmented reality system got an overall score of 46.63 ± 22.00, which means on average it has almost twice as much task load than the virtual reality correspondent that scored 24.78 ± 11.00. There was also a clear outlier, that rated the task load almost maximum, he had a very hard time understanding the technology which caused a lot of frustration. Further analysing these results, seen in Table 3 and Figure 25, the mental demand is about the same in both systems, with a score of 2.96 ± 1.90 for the AR game and a score of 2.64 ± 1.54 on the VR game. This makes sense since the task levels have the same cognitive difficulty. Considering the physical demand, AR scored higher on this one, obtaining a score of 5.24 ± 3.64 and the VR scoring 2.76 ± 2.22. This is probably because the AnTS helps maintain the arm position. The AR game deemed to consistently require more effort than the VR game, these scores being 15.11 ± 7.10, which is basically the 3rd quartile in the VR's effort boxplot, in comparison with 8.36 ± 6.02. This has a big impact on performance, seeing that it was rated on average, with a score of 11.56 ± 6.17, higher than most scores found of the VR counterpart. The AR modality had more failures than the VR game, that scored 4.53 ± 3.37. I can also deduce this influenced the frustration levels in the gameplay, as AR scored 11.82 ± 7.44, while VR scored 6.49 ± 7.27. For this project, the temporal demand was considered a non-factor because both tasks had the same duration.

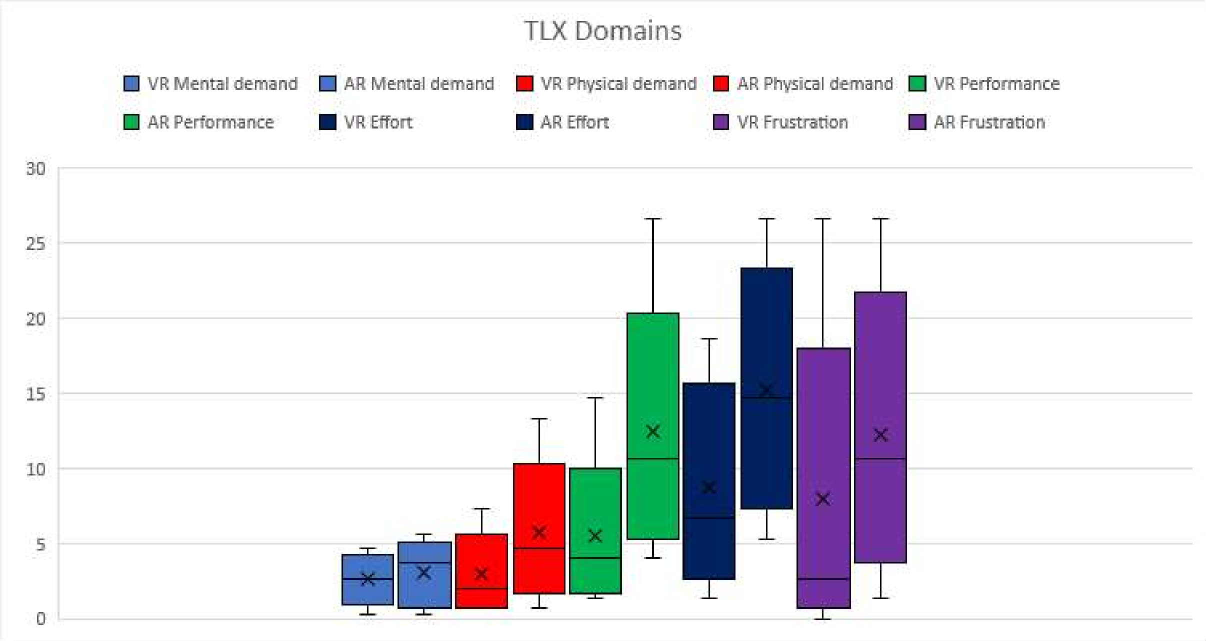

Figure 25. In depth TLX boxplot

	Augmented reality	Virtual reality
Mental demand	2.96 ± 1.90	2.64 ± 1.54
Physical demand	5.24 ± 3.64	2.76 ± 2.22
Performance	11.56 ± 6.17	4.53 ± 3.37
Effort	15.11 ± 7.10	8.36 ± 6.02
Frustration	11.82 ± 7.44	6.49 ± 7.27

Table 3. Average scores of the components of the NASA TLX

Regarding the presence questionnaire (Table 4, Figure 26), surprisingly the AR game obtained a score of 36.73 ± 7.00, which is only a marginal advantage on realism regarding the non-immersive VR game, that scored 36.6 ± 8.69. Additionally, the possibility to examine on the AR game, with a score of 16.67 ± 2.41, was only slightly higher than the VR game, which got scored 15.73 ± 4.63. However, taking a look at the boxplots, we can also deduce that AR was considered more consistently realistic and possible to examine than VR, which makes some sense due to augmented reality's nature. Moreover, we can see the tables start to turn, AR got a score of 15.2 ± 3.27 in the possibility to act, where virtual reality obtained 18.2 ± 3.10. For the quality of the interface, there is also preference towards the VR game, with a score of 11.00 ± 3.88 in comparison to AR's 13.93 ± 2.95. And lastly, the self-evaluation of performance also got a lead from the VR game, that scored 11.33 ± 3.11 compared to AR's score of 10.00 ± 2.43.

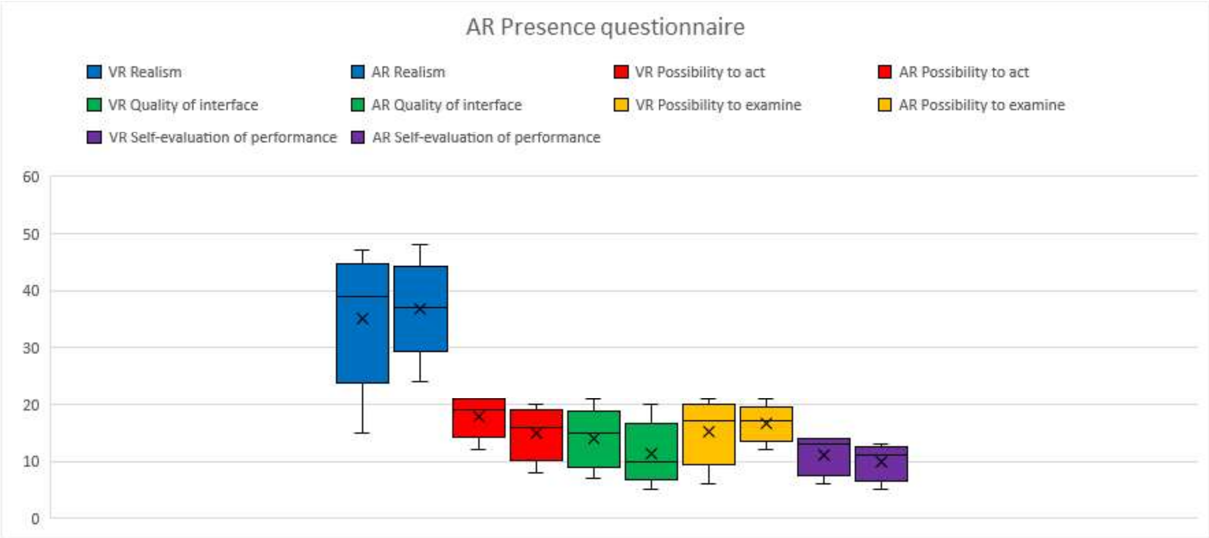

Figure 26. Presence Questionnaire boxplot

	Augmented reality	Virtual reality
Realism	36.73 ± 7.00	36.6 ± 8.69
Possibility to act	15.2 ± 3.27	18.2 ± 3.10
Quality of interface	11.00 ± 3.88	13.93 ± 2.95
Possibility to examine	16.67 ± 2.41	15.73 ± 4.63
Self-evaluation of performance	10.00 ± 2.43	11.33 ± 3.11

Table 4. Presence questionnaire scores

For the mean score and time (Table 5) of each interface, we can see a large difference. Augmented reality took on average 246.33 ± 23.79 seconds while getting an average score of 246.33 ± 23.79 points. This is almost a 25-second difference compared to virtual reality. The VR task took on average 185.46 ± 6.00 seconds, where everyone was able to complete the eight levels below 200 seconds (Figure 27), with an average score of 284.00 ± 7.37, these scores are very close to the maximum points available in this task which was 290 points. It was almost unanimous that everyone on the VR game scored more than on the AR game (Figure 28). There was also no mistake made in the virtual reality game, whilst one person committed a mistake on the augmented reality.

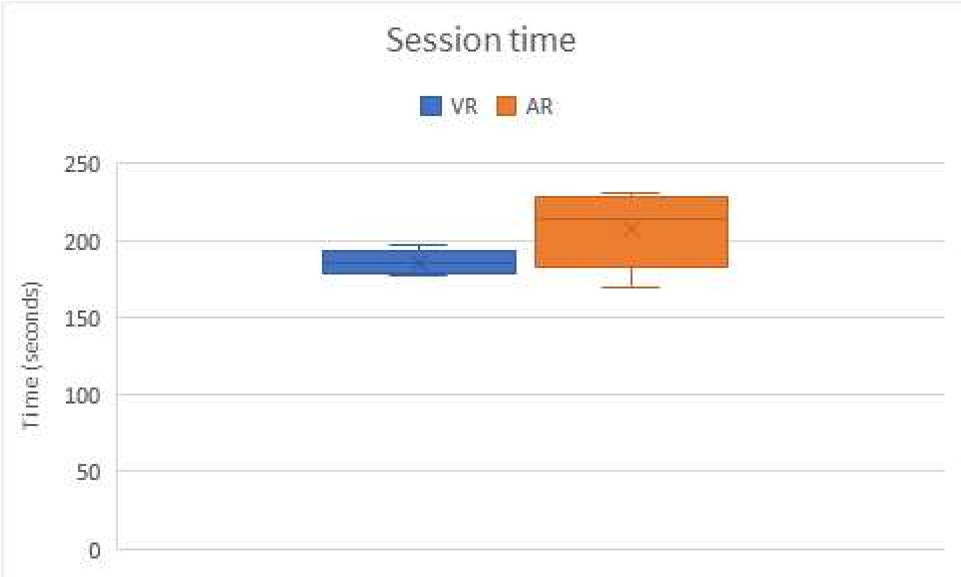

Figure 27. Session time boxplot

Figure 28. Session points boxplot

	Augmented reality	**Virtual reality**
Time (seconds)	209.60 ± 19.19	185.46 ± 6.00
Score	246.33 ± 23.79	284.00 ± 7.37
Mistakes	00.33 ± 0.49	00.00 ± 00.00

Table 5. Average score and time for each game session

For a deeper analysis, I extracted the individual times (in seconds) taken on each level. We can see that on average, at no time was AR level completed faster than on the VR game. I also found that on level 7 (Table 6), no one could complete the level with the full score on the AR game, as seen by the time of 34.96 ± 00.00, which is the duration that level 7 has. On the other hand, a large group could complete it on the virtual reality game.

Finally, regarding the interviews, when I asked what was their opinion on the games, the answer was usually that they found the AR game exciting and fresh, but due to the tracking issues that come with this technology, they found the VR to be more reliable. They said that the tracking issues occurred when they moved their heads too much at the time of activation of these virtual buttons, this is probably caused by the angle of view because these issues were more prevalent in the shorter participants. The glossy AR marker probably shares some to the fault too, as it would sometimes cause part of the game board to be hidden by light. They also mentioned that if the pressing time was lower they would have had an easier time performing the tasks at hand.

	Augmented reality	**Virtual reality**
Level 1	30.99 ± 8.86	28.66 ± 1.20
Level 2	22.47 ± 5.45	19.82 ± 2.37
Level 3	32.39 ± 4.83	26.60 ± 2.47
Level 4	31.57 ± 2.15	25.80 ± 2.31
Level 5	27.89 ± 1.68	24.44 ± 1.52
Level 6	20.52 ± 3.45	19.22 ± 1.67
Level 7	34.96 ± 00.00	34.63 ± 0.64
Level 8	8.82 ± 1.71	6.30 ± 0.60

Table 6. Average times (in seconds) per level

5.4. Conclusions

A mix of technology limitations and the sub-optimal material seems to have made the cheap immersive augmented reality solution fall short of expectations. Even though, it did seem to excite the participants, problems in loss of tracking in moments of interaction caused it to be less usable than the virtual reality solution. The interaction difficulties seem to have also influenced the task load, having induced more effort, hence also adding lack of performance and frustration. Most surprising was that the augmented reality did not surpass the virtual reality solution in realism by much. I found this intriguing because I was expecting an improved performance in the augmented reality condition because the physical world was always present.

It is worth mentioning that the virtual reality solution has been extensively tested, with both healthy users in laboratory conditions and patients in rehabilitation settings. It should also be noted that the augmented reality SDK I am using in this project is already 2 major versions old. Therefore, with an up-to-date SDK, these tracking issues might be solved. Something that would also help the tracking issues is a matte surface on the AR marker. Because of laser printing, the surface of the AR marker is too glossy.

All in all, I do believe that solutions like this one deserve further study, the main reason this system caused frustration was the loss of tracking whilst pressing a tile, this was due to the timers on the tile. Hence, it might also make sense trying different times for activation of the buttons on this game and maybe enhance the difficulty in some other way. Other tasks might not have this problem because they might not require timers. Another feasible solution is one where the interaction is 3D, this would allow the marker to be in an upright position, giving the camera a better angle of the marker.

6. Conclusions

This thesis sought out to explore the applicability of cheap mobile immersive augmented reality for stroke rehabilitation. An augmented reality task inspired by the Toulouse-Piéron cancellation task was developed and used to compare against a non-immersive virtual reality game of the same nature.

A field of view pilot test was executed to understand which field of view would give a more natural and engaging experience. All these fields of views deemed to be worthy of choice. With further studying in this domain, it might be possible to create a system to “trick” the brain, with the zoom effect from changing the fields of view, and induce benefits regarding neuroplasticity.

However, when the augmented reality system was compared against its highly reliable non-immersive virtual reality ancestor, the results showed that it was more cumbersome to use due to tracking issues inherent to the technology at hand. These tracking issues interfered with the interaction, breaking the engagement. It seems this technology is not yet mature enough for the task that was used. In the tests with healthy participants, they stated that the timers on the buttons for the task were too long. This shows that these timing from the VR cannot be translated directly and should be tested and tweaked to fit the task more optimally. I would like to mention that the Vuforia SDK I am using is currently 2 major versions behind the current SDK.

There is still a clear lack of design guidelines regarding this type of technology, where I believe this thesis was a step in the right direction to uncovering more interesting facts on augmented reality.

Regarding the questionnaires, since there was no official translation to most of them I used the original English questionnaires. Looking back, I think this might have caused some misinterpretation, especially on the presence questionnaire. More specifically, in respects to realism and possibility to examine because even if the AR system was less usable it should still shine in realism and has far more angles to examine the task.

Nevertheless, I do believe that other tasks might render more suitable for this technology and so, more investigation should be done in this field because these systems prove to be extremely cheap.

7. Future Work

This project would probably benefit from being upgraded on the SDK, this would imply also updating the game engine. Hopefully, with an up-to-date SDK, some of the tracking issues would be fixed. Also, it would have been helpful to have better documentation on Vuforia's software. For most of this project, I only had the forums to turn to. Additionally, I would like to be able to create virtual buttons dynamically, for optimization purposes.

The AR marker should also be worked on. It obtained a rating of 4 out of 5, which means with a little more tweaking it can achieve a rating of 5. Hence, also fixing some of the tracking issues. I would also like to make the printing material matte, to ensure no reflexions interfere with the gameplay, and to allow for gameplay in more conventional lighting.

Further study could also be conducted on what the optimal setup would be for this technology regarding the angle of where the marker should be placed whilst still being easily used by stroke patients with their affected limb.

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Appendix

Appendix A

System Usability Scale

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

Appendix B

Figure 8.6

NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name	Task	Date

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

Appendix C

PRESENCE QUESTIONNAIRE

(Witmer & Singer, Vs. 3.0, Nov. 1994)*

Revised by the UQO Cyberpsychology Lab (2004)

Characterize your experience in the environment, by marking an "X" in the appropriate box of the 7-point scale, in accordance with the question content and descriptive labels. Please consider the entire scale when making your responses, as the intermediate levels may apply. Answer the questions independently in the order that they appear. Do not skip questions or return to a previous question to change your answer.

WITH REGARD TO THE EXPERIENCED ENVIRONMENT

1. How much were you able to control events?

|_______|_______|_______|_______|_______|_______|_______|

NOT AT ALL SOMEWHAT COMPLETELY

2. How responsive was the environment to actions that you initiated (or performed)?

|_______|_______|_______|_______|_______|_______|_______|

NOT RESPONSIVE MODERATELY RESPONSIVE COMPLETELY RESPONSIVE

3. How natural did your interactions with the environment seem?

|_______|_______|_______|_______|_______|_______|_______|

EXTREMELY ARTIFICIAL BORDERLINE COMPLETELY NATURAL

4. How much did the visual aspects of the environment involve you?

|_______|_______|_______|_______|_______|_______|_______|

NOT AT ALL SOMEWHAT COMPLETELY

5. How natural was the mechanism which controlled movement through the environment?

|_______|_______|_______|_______|_______|_______|_______|

EXTREMELY ARTIFICIAL BORDERLINE COMPLETELY NATURAL

6. How compelling was your sense of objects moving through space?

|________|________|________|________|________|________|________|

NOT AT ALL | MODERATELY COMPELLING | VERY COMPELLING

7. How much did your experiences in the virtual environment seem consistent with your real world experiences?

|________|________|________|________|________|________|________|

NOT CONSISTENT | MODERATELY CONSISTENT | VERY CONSISTENT

8. Were you able to anticipate what would happen next in response to the actions that you performed?

|________|________|________|________|________|________|________|

NOT AT ALL | SOMEWHAT | COMPLETELY

9. How completely were you able to actively survey or search the environment using vision?

|________|________|________|________|________|________|________|

NOT AT ALL | SOMEWHAT | COMPLETELY

10. How compelling was your sense of moving around inside the virtual environment?

|________|________|________|________|________|________|________|

NOT COMPELLING | MODERATELY COMPELLING | VERY COMPELLING

11. How closely were you able to examine objects?

|________|________|________|________|________|________|________|

NOT AT ALL | PRETTY CLOSELY | VERY CLOSELY

12. How well could you examine objects from multiple viewpoints?

|________|________|________|________|________|________|________|

NOT AT ALL | SOMEWHAT | EXTENSIVELY

13. How involved were you in the virtual environment experience?

|________|________|________|________|________|________|________|

NOT INVOLVED | MILDLY INVOLVED | COMPLETELY ENGROSSED

14. How much delay did you experience between your actions and expected outcomes?

|________|________|________|________|________|________|________|

NO DELAYS | MODERATE DELAYS | LONG DELAYS

15. How quickly did you adjust to the virtual environment experience?

|________|________|________|________|________|________|________|

NOT AT ALL | SLOWLY | LESS THAN ONE MINUTE

16. How proficient in moving and interacting with the virtual environment did you feel at the end of the experience?

|________|________|________|________|________|________|________|

NOT PROFICIENT | REASONABLY PROFICIENT | VERY PROFICIENT

17. How much did the visual display quality interfere or distract you from performing assigned tasks or required activities?

|________|________|________|________|________|________|________|

NOT AT ALL | INTERFERED SOMEWHAT | PREVENTED TASK PERFORMANCE

18. How much did the control devices interfere with the performance of assigned tasks or with other activities?

|________|________|________|________|________|________|________|

NOT AT ALL | INTERFERED SOMEWHAT | INTERFERED GREATLY

19. How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities?

|________|________|________|________|________|________|________|

NOT AT ALL | SOMEWHAT | COMPLETELY

IF THE VIRTUAL ENVIRONMENT INCLUDED SOUNDS:

20. How much did the auditory aspects of the environment involve you?

|________|________|________|________|________|________|________|
NOT AT ALL SOMEWHAT COMPLETELY

21. How well could you identify sounds?

|________|________|________|________|________|________|________|
NOT AT ALL SOMEWHAT COMPLETELY

22. How well could you localize sounds?

|________|________|________|________|________|________|________|
NOT AT ALL SOMEWHAT COMPLETELY

IF THE VIRTUAL ENVIRONMENT INCLUDED HAPTIC (SENSE OF TOUCH):

23. How well could you actively survey or search the virtual environment using touch?

|________|________|________|________|________|________|________|
NOT AT ALL SOMEWHAT COMPLETELY

24. How well could you move or manipulate objects in the virtual environment?

|________|________|________|________|________|________|________|
NOT AT ALL SOMEWHAT EXTENSIVELY

Last version : March 2013

*Original version : Witmer, B.G. & Singer. M.J. (1998). Measuring presence in virtual environments: A presence questionnaire. *Presence : Teleoperators and Virtual Environments*, *7*(3), 225-240. Revised factor structure: Witmer, B.J., Jerome, C.J., & Singer, M.J. (2005). The factor structure of the Presence Questionnaire. *Presence, 14*(3) 298-312.

Questionnaire sur l'État de Présence (QÉP)
Laboratoire de Cyberpsychologie de l'UQO

Validation of the French-Canadian version developed by the UQO Cyberpsychology Lab:

- 101 participants completed the questionnaire following an immersion in a virtual environment;
- Cronbach's Alpha = .84
- Now 19 items (for VEs without sound/touch) et 24 items (for VEs with sounds/touch)

Scoring :

Total : Items 1 to 19 (reverse items 14, 17, 18)

- « Realism » : Items 3 + 4 + 5 + 6 + 7 + 10 + 13
- « Possibility to act » : Items 1 + 2 + 8 + 9
- « Quality of interface » : Items (all reversed) 14 + 17 + 18
- « Possibility to examine » : Items 11 + 12 + 19
- « Self-evaluation of performance » : Items 15 + 16
- « Sounds* » : Items 20 + 21 + 22
- « Haptic* » : Items 23 + 24

* NOTE : Scoring of « *sounds* » and « *haptic* » are not part of the factor analysis of the French version.

Norms (French version) :

	Moyenne	**Écart type**
Total	104.39	18.99
« Realism »	29.45	12.04
« Possibility to act »	20.76	6.01
« Quality of interface »	15.37	5.15
« Possibility to examine»	15.38	4.90
« Auto-évaluation de la performance »	11.00	2.87

Last version : March 2013

*Original version : Witmer, B.G. & Singer. M.J. (1998). Measuring presence in virtual environments: A presence questionnaire. *Presence : Teleoperators and Virtual Environments*, *7*(3), 225-240. The factor structure of the Presence Questionnaire. *Presence, 14*(3) 298-312. Revised factor structure: Witmer, B.J., Jerome, C.J., & Singer, M.J. (2005). The factor structure of the Presence Questionnaire. *Presence, 14*(3) 298-312.