Universidade do Minho
Escola de Engenharia
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Evaluating Constrained Users Ability to Interact with Virtual Reality Applications

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Master dissertation
Master Degree in Informatics Engineering

Dissertation supervised by
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Tiago Ramos Ribeiro

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ABSTRACT

This Master's Project presents a comprehensive exploration of a novel Virtual Reality (VR) application designed to evaluate and enhance user performance within the context of constraints experienced by individuals, including those confined to an Intensive Care Unit (ICU). The work unfolds through a detailed examination of the proposal, development, and assessment phases.

The proposal lays the foundation for the project, emphasizing the need for an immersive technology-based solution to assess ICU patients' abilities. It includes a well-structured system architecture, deployment architecture, and data architecture. This framework guides the subsequent phases, offering insights into the development and assessment processes.

In the development phase, the practical realization of the VR application is explored. It highlights adjustments tailored to the specific needs of ICU patients, offering valuable insights into user progress, reducing dependency on external assistance. Eight distinct tasks are detailed, categorized based on complexity and fundamental functionalities.

The assessment phase evaluates the real-world impact of the VR application through three interventions. While limited to non-ICU environments, these interventions capture data from users who share critical constraints with ICU patients. The assessment involves correlation analysis of numerous variables, including age, cognitive function (assessed through the Mini-Mental Status Examination), and prior VR experience. The results unearth significant correlations, shedding light on age-related differences, the influence of cognitive ability, and the impact of prior VR exposure on task performance.

This comprehensive exploration represents an essential contribution to the burgeoning field of VR applications for healthcare, specifically targeting constrained user groups like ICU patients. The findings underscore the significance of considering user characteristics, prior experience, and cognitive function when designing VR interventions. Further research is warranted to refine assessment methodologies and expand the scope of real ICU patient testing, ultimately paving the way for improved patient care and enhanced rehabilitation practices.

Keywords: Virtual Reality, Intensive care, Cognitive resilience, Non-pharmacological therapies

RESUMO

Este projeto de mestrado apresenta uma exploração abrangente de uma nova aplicação de Realidade Virtual (RV) concebida para avaliar e melhorar o desempenho do utilizador no contexto dos constrangimentos vividos pelos indivíduos, incluindo os que estão confinados a uma Unidade de Cuidados Intensivos (UCI). O trabalho desenrola-se através de uma análise pormenorizada das fases de proposta, desenvolvimento e avaliação.

A proposta estabelece as bases do projeto, salientando a necessidade de uma solução imersiva baseada na tecnologia para avaliar as capacidades dos doentes da UCI. Inclui uma arquitetura de sistema bem estruturada, uma arquitetura de implementação e uma arquitetura de dados. Esta estrutura orienta as fases subsequentes, oferecendo informações sobre os processos de desenvolvimento e avaliação.

Na fase de desenvolvimento, é explorada a realização prática da aplicação de RV. Destaca os ajustes adaptados às necessidades específicas dos pacientes da UCI, oferecendo informações valiosas sobre o progresso do utilizador, reduzindo a dependência da assistência externa. São detalhadas oito tarefas distintas, categorizadas com base na complexidade e nas funcionalidades fundamentais.

A fase de avaliação avalia o impacto da aplicação de RV no mundo real através de três intervenções. Embora limitadas a ambientes não UCI, estas intervenções captam dados de utilizadores que partilham restrições críticas com doentes da UCI. A avaliação envolve a análise de correlação de numerosas variáveis, incluindo a idade, a função cognitiva (avaliada através do Mini-Mental Status Examination) e a experiência anterior em RV. Os resultados revelam correlações significativas, lançando luz sobre as diferenças relacionadas com a idade, a influência da capacidade cognitiva e o impacto da exposição prévia à RV no desempenho da tarefa.

Esta exploração exaustiva representa um contributo essencial para o crescente campo das aplicações de RV nos cuidados de saúde, visando especificamente grupos de utilizadores limitados, como os doentes de UCI. Os resultados sublinham a importância de considerar as características do utilizador, a experiência anterior e a função cognitiva ao conceber intervenções de RV. Justifica-se a realização de mais investigação para aperfeiçoar as metodologias de avaliação e alargar o âmbito dos testes em doentes reais de UCI, abrindo caminho a melhores cuidados para os doentes e a melhores práticas de reabilitação.

Palavras-chave: Realidade Virtual, Cuidados intensivos, Resiliência cognitiva, Terapias não-farmacológicas

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ACRONYMS

H

HUD Head-up display.

I

ICU Intensive Care Unit.

IVR Immersible Virtual Reality.

M

MMSE Mini-Mental Status Examination.

U

UX User Experience.

V

VR Virtual Reality.

1

INTRODUCTION

In this first chapter of the dissertation, the Master's Project is introduced along with its context and motivation. Furthermore, the necessary objectives to complete it are also detailed, the research hypothesis and the corresponding research methodology are specified and the document structure is presented.

1.1 CONTEXT AND MOTIVATION

The intensive care unit (ICU) is a noisy and stressful environment in which critically ill patients are exposed to physical and psychological stressors, including sensory overload and deprivation, isolation, temporal disorientation, and a sense of lack of control. (Merliot-Gailhoustet et al., 2022)

Critical care medicine has seen a cultural shift as the focus on improving survival rates has been expanded to include the long-term quality of life arising from health after discharge (Hopkins et al., 2015). The health impairments seen in intensive care patients, collectively referred to as the post-intensive care syndrome, include persistent physical, psychiatric, and cognitive impairments (Chen and Peng, 2006).

Long-term cognitive impairment affects between 50% and 75% of patients, regardless of the cognitive status prior to ICU admission, preexistence of brain damage and patient age (Brummel et al., 2013). Long-term cognitive impairment often begins as acute brain dysfunction (delirium and coma), leading to subsequent impairments in neurocognitive functions, including information processing, concentration, attention, learning and memory, and executive functions (Merliot-Gailhoustet et al., 2022). The consequences of reduced cognitive ability in these patients are particularly severe, starting with a reduction in the effectiveness of treatment in the intensive care treatment itself, to a generalized reduction in the quality of life after discharge from the ICU (Hofhuis et al., 2007).

Current interventions to prevent cognitive decline in ICU patients include preventive and corrective measures, as well as drug therapy during and after the ICU stay (Karnatovskaia et al., 2014). Preventive strategies typically include early physical rehabilitation, sleep management, minimizing the use of sedatives and psychological support. These approaches have been validated by the results of studies that demonstrated that early mobilization and physical training, as well as sedation management, can indeed reduce cognitive dysfunction (Ferre et al., 2021).

Although these strategies have shown to reduce delirium, they have not yet proved to prevent cognitive deterioration. Several authors (Hofhuis et al., 2007; Karnatovskaia et al., 2014) highlight the potential benefit of early cognitive and physical therapy during the ICU stay. However, most studies were conducted in critically ill patients after the ICU stay, and therefore, evidence from intervention studies in critically ill patients remains scarce, especially during the ICU stay. The early onset of intervention is presumed to be one of the main factors in reducing later cognitive and psychological morbidity, preventing the development of cognitive impairments and improving cognitive function after ICU discharge.

Virtual Reality (VR) using virtual reality glasses has been shown to be successful and produce promising results in reducing pain, anxiety and delirium in ICU patients (Ong et al., 2020; Gerber et al., 2017). Most interventions use visual experiences of relaxing environments, typically natural landscapes, without involving any cognitive task or requiring any physical intervention by the patient (Merliot-Gailhoustet et al., 2022). However, experiments involving cognitive tasks, have already been conducted without the use of virtual reality goggles, which provide a greater sensory immersion (Turon et al., 2017).

It is clear that further investigation is needed to better understand the possibilities of Immersive VR to improve cognitive ability of ICU patients.

Virtual reality scenarios are becoming increasingly popular in the medical industry as a way to provide comfort to patients, particularly those in intensive care units. VR interventions can provide a sense of familiarity, safety, and relaxation in a clinical environment. However, in order for these interventions to be effective, it is necessary to understand the ability of ICU patients to interact with them platforms. By observing these patients in authentic settings, we can better comprehend their interactions with VR and its potential to enhance their well-being. Such insights will guide the creation of VR environments specifically designed for ICU patients, ensuring a more comfortable experience for them.

1.2 OBJECTIVES

The development of this Master's Project has the following main objectives:

- Study and develop solutions based on immersive VR to stimulate and improve the physical and cognitive abilities of constrained users.
- Assess the ability of constrained users ability to interact with VR applications.

The development of this Master's Project also has the following secondary objective:

- Explore the application of more prolonged VR interventions.

1.3 RESEARCH HYPOTHESIS

The research hypothesis that will be proved with this Master's Work is stated bellow:

"It is hypothesized that constrained users, such as individuals with physical disabilities or elderly individuals, can effectively interact with VR applications through the use of assistive technology and alternative input methods, resulting in a higher level of user satisfaction and engagement in VR experiences."

1.4 RESEARCH METHOD

The development of this Master's work is going to follow a design research throughout an academic year, composed of the following steps:

- Literature review on the evaluation of user ability in interaction applications.
- Specification of an evaluation application to access ICU patients ability to interact with VR for patients in ICU.
- Implementation of the specified solution in a VR platform.
- Conception of the test protocol to be conducted at the University Hospital Center of São João.
- Execution of tests and analysis of results.

Design research is invaluable because it provides a structured and evidence-based approach to investigating complex design-related problems, ensuring the research aligns with established academic standards. By employing formal research methods, conducting a comprehensive literature review, and applying theoretical frameworks, academic design research offers a rigorous foundation for exploring research questions and making substantial contributions to the field. This approach not only enhances the quality and depth of the thesis but also demonstrates a researcher's commitment to advancing knowledge and scholarship in their chosen discipline, thereby making the thesis more credible and influential in the academic community.

1.5 DOCUMENT STRUCTURE

This document is composed by four different chapters with the following contents:

1. Introduction - In this chapter, we give context and motivation as well as the main goals of this thesis. After it, a research hypothesis is proposed. And lastly, we propose a research methodology to be followed.
2. VR interventions in the ICU - On the second chapter, we give an overview on the current state of the art for the proposed tasks that will be developed.
3. Proposed Approach - In the third chapter, we are going to propose a solution to the problem and also represent the architecture of the project in order to have a better overview of all of the system's components.
4. Development - On the fourth chapter, it is presented all the choices developed as well as the tools used.
5. Assessment - In the fifth chapter, we show how the tests were done as well as the final results and discussions.
6. Conclusion - The sixth and last chapter, includes the conclusions, as well as the future work.

2

VR INTERVENTIONS IN THE ICU

The use of Virtual Reality (VR) technology in healthcare, particularly in the intensive care unit, is a relatively new and developing field. However, studies have suggested that VR can be a useful tool for improving cognitive function and reducing symptoms of delirium and anxiety in ICU patients.

Some studies (Bruno et al., 2022b; Ong et al., 2020) have specifically focused on the use of VR in the ICU as a means of reducing delirium. These studies have shown that VR can be effective in reducing the incidence and duration of delirium, as well as improving cognitive function in ICU patients.

Another area of research has focused on using VR to reduce anxiety in ICU patients. Studies (Donnelly et al., 2021; Gerber et al., 2017; Merliot-Gailhoustet et al., 2022; Turon et al., 2017) have shown that VR can be an effective tool for reducing anxiety and promoting relaxation in these patients.

Additionally, other studies (Bruno et al., 2022b,a) have also explored the use of VR in the ICU as a means of providing distraction and improving overall well-being. These studies have suggested that VR can be a useful tool for improving the overall experience of being in the ICU for patients and their families.

Currently, there are many articles (Merliot-Gailhoustet et al., 2022; Hopkins et al., 2015; Chen and Peng, 2006; Brummel et al., 2013; Hofhuis et al., 2007; Karnatovskaia et al., 2014; Ferre et al., 2021; Bruno et al., 2022b; Donnelly et al., 2021; Bruno et al., 2022a; Ong et al., 2020; Gerber et al., 2017) reporting how important the use of VR intervention is, however, they still lack information relative to the parameters and variables used around the intervention itself. A more detailed study on this variables would allow a more deep understanding on how important VR intervention is on ICU patients and in which way does it help preventing cognitive decline.

Recently it was published an article (Vlahovic et al., 2022) mentioning and studying VR game mechanics in order to better comprehend the impact it does on today's VR video games, but it also lacks information on their implementation and testing with ICU patients.

In the field of human-computer interaction, researchers have sought to understand and predict the speed and accuracy of movement for pointing tasks. One commonly used model for this is Fitts's law, which was originally developed for two-dimensional *pointing tasks* on a computer screen (Murata and Iwase, 2001). However, with the rise of VR applications, there is a need to extend Fitts's law to better understand pointing in three-dimensional (3D) space. Fitts's Law is a fundamental principle in human-computer interaction that quantifies the relationship between the time it takes to select a target, the distance to that target, and the size of the target. It states that larger targets are easier to select, shorter distances lead to faster selections, and it offers a mathematical formula to predict movement time based on these factors.

This is the focus of the article "Extending Fitts's law to a three-dimensional pointing task" (Murata and Iwase, 2001). The authors conducted a study to determine the accuracy and speed of movement for *3D pointing tasks* in VR. They found that the traditional Fitts' law model could not accurately predict pointing performance in VR and thus developed a modified version of the law specifically for 3D pointing.

By understanding the accuracy and speed of movement in 3D pointing tasks in VR, we can better evaluate the user experience for individuals with constraints, such as those with motor impairments. For example, the modified version of Fitts' law could be used as a benchmark to assess the effectiveness of VR interfaces designed for constrained users.

In (Clark et al., 2020), the authors present a study on the extension of Fitts's law in 3D virtual environments using low-cost VR technology. They carried out experiments to assess the relationship between target distance and selection time for objects located in different depths in a VR environment. The results showed that the traditional Fitts's law formula does not accurately predict selection time for objects located in different depths in a VR environment, highlighting the need for further research in this area. The authors suggest that the current low-cost VR technology presents new challenges and opportunities for research into the human-computer interaction in VR environments.

This study provides important insights into the limitations of current low-cost VR technology in predicting selection times for objects located in different depths, and underscores the need for further research to understand the implications of this technology for human-computer interaction in VR environments. The findings of this study can help to inform future research on the evaluation of constrained users' ability to interact with VR applications, particularly with regard to the impact of depth and other factors on selection time and accuracy (Clark et al., 2020).

There are a few studies exploring the use of virtual reality in the ICU to provide distraction and improve overall well-being but they still lack information about the parameters and variables used for the intervention.

Therefore, the implementation of basic virtual reality tasks in ICU patients and intensive testing is necessary to evaluate which tasks or complexity levels can be achieved. This approach will allow an overview of what elements should be considered for the implementation of virtual reality in ICU patients. In addition, it will allow us to identify the factors that may affect these patients' ability to interact with virtual reality applications and improve their experience in the ICU setting.

In our project, the approach adopted is to implement and test some basic VR tasks with ICU patients to identify which tasks and what levels were accomplished by patients in order to get an overview on which elements should be considered when going for a VR approach.

The next subsections introduce the basic tasks that will be proposed to be completed by ICU patients, categorized by their atomicity.

2.1 ATOMIC TASKS

The atomic tasks are the simpler and most basic tasks a patient can complete. This also means that subsequent and more complex tasks will use combinations of these atomic ones in order to create some more challenging activities.

2.1.1 *Head Task*

In this task, the patient will be asked to control an object using only his head. Starting from an easy and simple level where objects would appear in between X or Y axis range in a low angle range, to a level where the angle would start to raise and both axis would be used. Some related tasks were implemented on users outside of ICU context (Clark et al., 2020), but in this case, the task is simple enough to be used on ICU patients.

Figure 1 represents a good example of what this task must be. Note that the cube must move using only the patient's head. This will give us important data on, for example, how many degrees could the patient's head move, from side to side and up and down.

2.1.2 *Arms Task*

In this task, the patient will attempt to hit a object (something like a ball or a balloon) in the air in order to motivate the patient in raising the arms up and around to see how far up can the patient reach. For this to be measured, the idea is to start with low height objects, so it can be easy for the patient to elevate just his forearm, and, as the levels advance, the objects appear increasingly higher and more difficulty to reach.

Note that this task only needs for the patient to raise the arms to a certain point, and it does not need any further action, such as, for example, pressing a button.

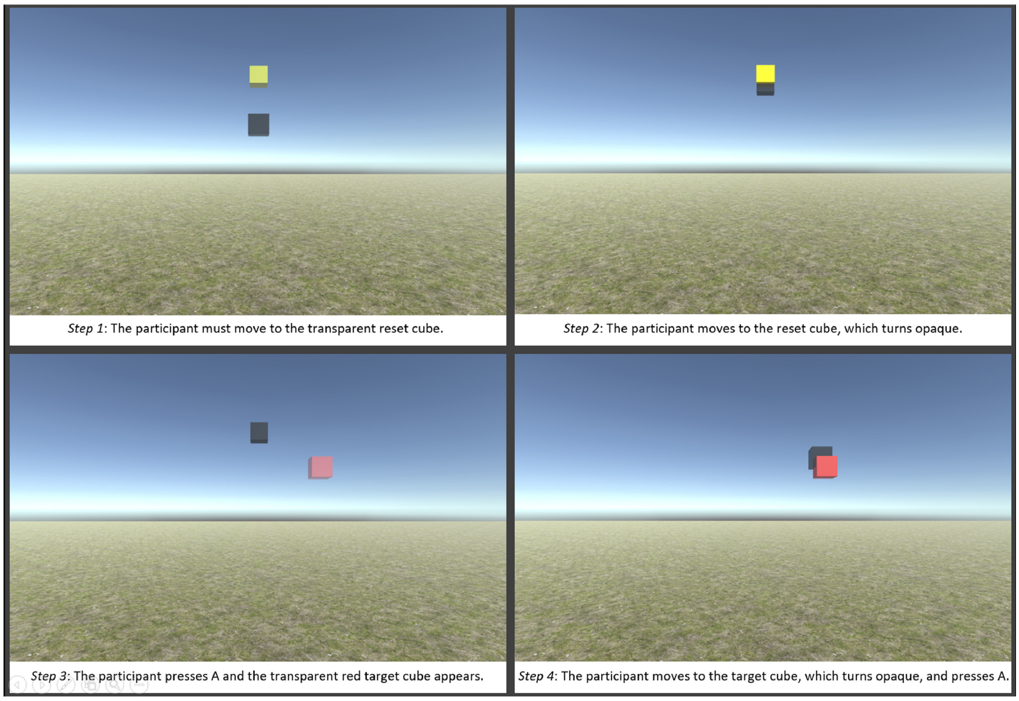


Figure 1: The sequence of events during each experimental trial from the participant's point of view (Clark et al., 2020).

2.1.3 *Fingers Task*

In this task, patients will try to press each and every button on the VR controller. The objective is to test how well the patient can press each button. For instance, it will be monitored how many users can press each button, how much time it took for them to press them, did they click on wrong buttons instead, how many times it was pressed, etc. This will give an overview of which buttons are easier and which buttons are harder to press.

Starting on the easiest button to press, so supposing that the Triggers are the easiest button to press, then this button would be highlighted first, in order for the user to press it. Then we would progressively choose harder buttons to press in order to conclude which ones could not be pressed by most of the patients. Eventually, on the harder difficulty, we would ask for the patient to press for a series of buttons and also a combinations of buttons. The time a button is pressed it is also a variable to be studied and so, on this last levels, it would be asked to press the buttons for a longer time.

In terms of VR scenery, each action will trigger an event so that the patient has some feedback each time a button is pressed. For example: once the Grip Button is pressed, a water fall would start flowing; or a dolphin would come out of the sea if the user pressed the B button.

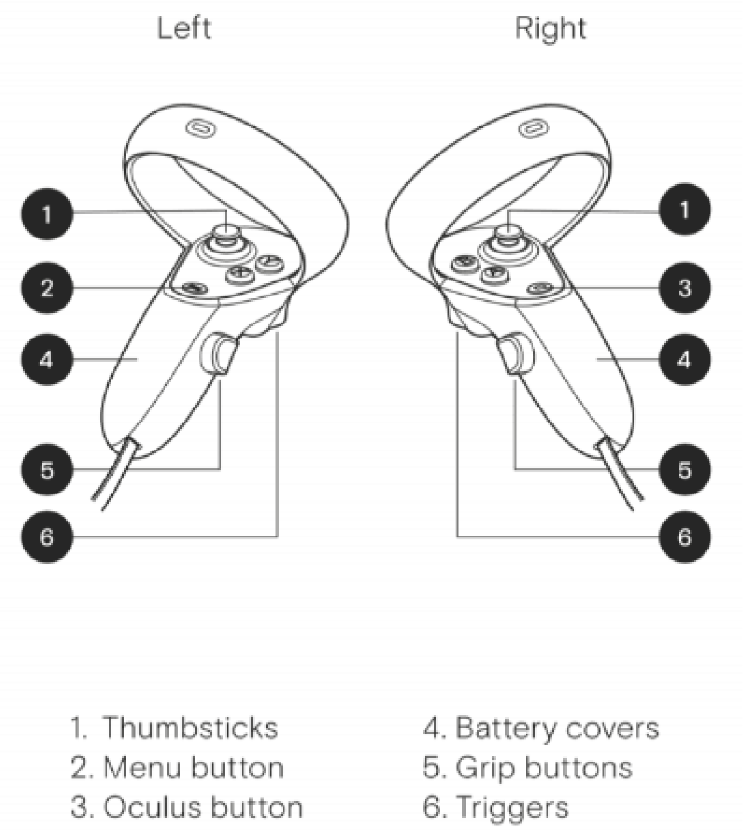


Figure 2: V. Nepor , Overview of the Oculus controller buttons.
GameArter, 2020 [Online]. Available:
https://www.gamearter.com/blog/xr-input-manager-controllers.
[Accessed: 29-Oct-2022]

2.2 ATOMIC MIXED TASKS

In the new set of VR tasks below, some atomic tasks will be mixed so that it becomes possible to better comprehend which factors are affecting patient's performance on realizing an activity.

2.2.1 *Pick and place Task*

Similar to one of the tasks done in the project developed by Vlahovic (Vlahovic et al., 2022), this task will be based on picking up an object and placing it on a target.

Starting with a big target, the task will raise in difficulty by lowering the radius of the target so that the patient's accuracy needs to be better/higher. As the target size changes, the object's size itself is also a variable to change in order to increase difficult. So that a starting big object would be more easy to accomplish than a smaller object in harder levels. The orientation of the object itself is also a variable. Since it is easier to just place an object with no orientation, that would be the start for the first levels, and the last ones, the orientation would be taken in consideration so that the object needs to face a certain angle for the task to be completed.

On top of this mentioned variables, the distance of the target and object is also considered. This means that the first levels the object and the target itself is going to be very close to the patient. On later levels, this is going to vary so that the target and object is positioned far from the patient so that it require extra effort and motion from the patient.

2.2.2 *Pointing Task*

In this task, based on Murata and Iwase article (Murata and Iwase, 2001), the patient needs to point at a specific target for a couple of seconds.

The difficulty on this task would be to reduce the size of the targets and to implement moving targets on harder levels. In addition, the trajectory of the moving target could vary upon harder levels as well as the speed of the target's movement.

2.2.3 *Painting Task*

On the painting task, will be shown to the patient a figure on a rectangle. The patient then needs to clear or paint this figure in order to complete the task. For example, an all black rectangle with a yellow square on it. Then this yellow square needs to be painted black in order to make it disappear from the rectangle itself. Similar on how its done on the Penumudi's project (Penumudi et al., 2020) shown in Figure 3.

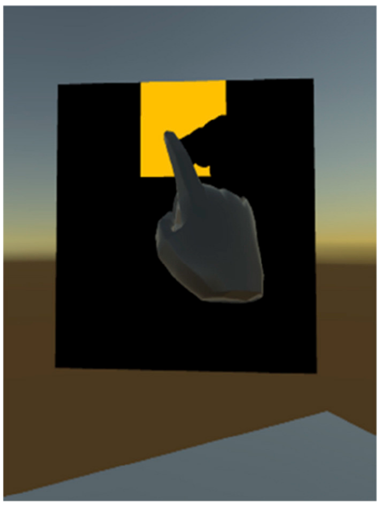


Figure 3: Painting task with virtual hand gestures (Penumudi et al., 2020).

2.3 Extra Secondary Tasks

These last tasks refers to some extra secondary tasks that will be developed later on. They are a mixture of atomic tasks and mixed atomic tasks, so that it will result on harder tasks to complete. The objective of these is to further test the capability of patients and to make them use their body and cognitive abilities.

2.3.1 *Throwing Task*

In this task, the patient will be asked to pick up an object and throw it at a specific target.

The difficulty on this task would be to reduce the size of the target, as well make it movable in order to vary the throwing force.

There is two ways to approach this task. The first possibility is to have the target on the ground so that the distance from the patient to the target will directly influence on the velocity of the object that needs to be thrown. This means that the further away the target is, the more force the patient needs to execute. The second possibility would be to have the target on a wall or a side plane. Unless the target is placed in a very high place or the position of the wall/plane can be moved, the need of a increased throwing force is nullified. This means that there would need to be an extra variable that would measure the force applied to the object when it hit the target.

2.3.2 *Finding Task*

In this task the user will be asked to find a certain object in between many diverse distracting objects.

In order to complicate this task, the number of distracting objects will be higher, the size of the target object to find will be reduce, and also the colors and the pattern of the target, or objects around it, will be more camouflaged.

2.3.3 *Omnidirectional Pointing Task*

This tasks prompts the patient to point to one of the many targets omnidirectionally positioned. This means that, similar to the pointing task mentioned previously, there would be targets positioned in front of the patient. The idea is identical to one of the tasks used in Penumudi's project (Penumudi et al., 2020), represented in Figure 4.

The difficulty variables in this task would be the number and size of the targets and, as an extra variable, the targets would have circular movement in order to be harder to click precisely on them.

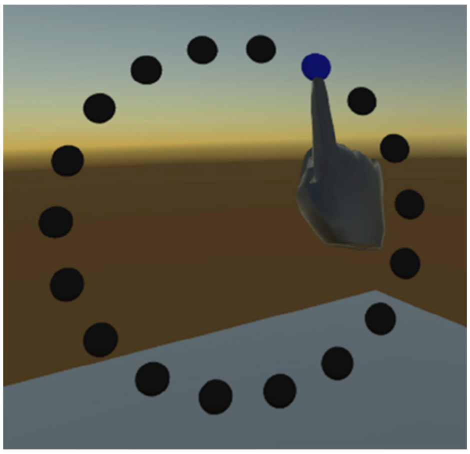


Figure 4: Omnidirectional pointing task (Penumudi et al., 2020).

2.3.4 *Point and go Task*

The concept on the point and go task is to test the patient movement around a section, so in this task the patient will be asked to point and click on a target in order to teleport it to the respective place.

The difficulty would be the size of the targets and the distance to it.

2.3.5 *Point and Grab Task*

As seen in Poupyrev's project (Poupyrev et al., 1997), in this task, the patient will be asked to grab a distant object by pointing at it and click grabbing the object. Similar to the pick and place task but in this one the objective is focus on picking the object with a pointing mechanism. It allow a different approach to the problem and different conclusions can be made if the outcome of the results vary too much.

To complicate this task, some variables will be modified. Such as target's size and the number of distracting objects around the target.

2.4 EXTRA SECONDARY TASKS - COGNITIVE TRAINING

Lastly, this section is also about some extra secondary tasks that was proposed to be more complex than the previously ones. This means that these tasks will not only evaluate a more complex interaction of a task in VR but will also evaluate cognitive capability.

2.4.1 *Magnetic Fishing Task*

The idea of this task is to implement a fishing pool where fishes are standing still and the patient will be asked to fish target fishes in order to complete the task. The fishing rod would be similar to a magnet so that when close enough on a fish, it would hook it on to the rod.

The starting levels would be just one or two big fishes and, at the latest levels, end up with more and smaller fishes.

2.4.2 *Catching Butterflies Task*

This task is similar to the previous one (Magnetic Fishing Task), but instead of catching fishes on a fishing pool, the patient will be presented with butterflies up in the air and a bug net tool to use it to catch them.

The difficulty on this task would be to add more butterflies to catch and their size, as well adding movement to them.

2.4.3 *Simon Says Task*

The idea on this task is to mimic the well known "simon says" memory game. In this task, the patient will be shown some buttons with colors and a sequence on them. This sequence would be show as the form of lights turning on and off on the buttons and also with sounds backing the lights up, so that its easier to memorize the sequence.

The first levels would be just 3 or 4 buttons and short sequences. After raising the levels, more button can be implemented and longer sequences will be shown. Also, the size of the buttons as well infinite sequences can also be implemented.

2.4.4 *Piling Task*

In this task, patient will be asked to stack blocks in order to create a tower without them falling. Much similar as the well known game "Jenga" but reversed, that is instead of removing blocks, the patient will stack them together.

This idea was based on Harris's project (Harris et al., 2020), where the game he created is shown in Figure 5.

For a more harder version, the number and size of the objects to stack will vary upon levels.

Figure 5: Virtual reality block stacking game (Harris et al., 2020).

2.4.5 *Opening Task*

In this task, it will be shown to the patient a box and various keys. The patient then will need to choose the correct key for the box.

This task can be harder by raising the number of keys available to the user, by lowering the size of the key hole or the keys itself.

2.4.6 *Mixing Task*

The idea of this task is to have many beakers with different colors liquids. The patient then would need to pour these liquids on a larger beaker in order to create a potion.

The difficulty on this task would be to raise the number of liquids to mix, the size of the main beaker to pour liquids into, and input an order to pour the liquids in order to respect a particular sequence.

2.5 SUMMARY

We presented a series of VR tasks to test the patient's physical and cognitive abilities divided into two categories: **Atomic tasks** (Head task, Arms task, Fingers task) and **Atomic mixed tasks** (Pick and Place task, Pointing task, Painting task). These tasks range from simple movements such as controlling an object with the head or hitting a moving object with the arms, to more complex tasks that require the patient to perform multiple actions and use their cognitive abilities. The difficulty of the proposed tasks shall increase as the patient progresses through the study.

It is important to note that, to the best of our knowledge, no articles or studies have been found that specifically address tasks developed for the ICU context. Consequently, the majority of the tasks were conceived and designed for the ICU context. Some of these tasks were inspired by articles that presented activities and games in different contexts.

3

PROPOSED APPROACH

In this chapter, it is going to be presented the proposed approach that is estimated to be followed by. With an overview of all the architecture needed to complete this project, a better and a more organized system can be deployed. With this, the goal is to evaluate constrained user's ability to interact with VR applications. So we propose an IVR computer application, sketching and explaining its architecture.

3.1 SYSTEM ARCHITECTURE

The main inputs for the system are the settings and choices by the **Supervisor**, as well as the **User** task inputs in form of body movement, cognitive abilities and biometric data.

The system is made up from two main modules: **Interpreter** and **VR-based Application**.

Interpreter module is where the **Immersive platform scene and tasks** will be created and implemented. Without this, it would not be possible to create and build an executable to be ran on the VR devices.

VR-based Application module is where the **Immersive platform scene and tasks** will be executed. This allows the **User** to have a device where he can interact and perform tasks on. Note that this module serves mainly to allow the application to be processed on, as well as, having a mediator in between the **Interpreter** and the **User**. It is also in this module that the main interactions with **Supervisor** will occur.

Figure 6 shows the system architecture in a diagram so that it is possible to have a better overview of the overall system.

There is also one alternative architecture based on using a support device, such as a laptop, in order to swift the work load and the monitoring to that device. This alternative architecture is represented in Figure 7.

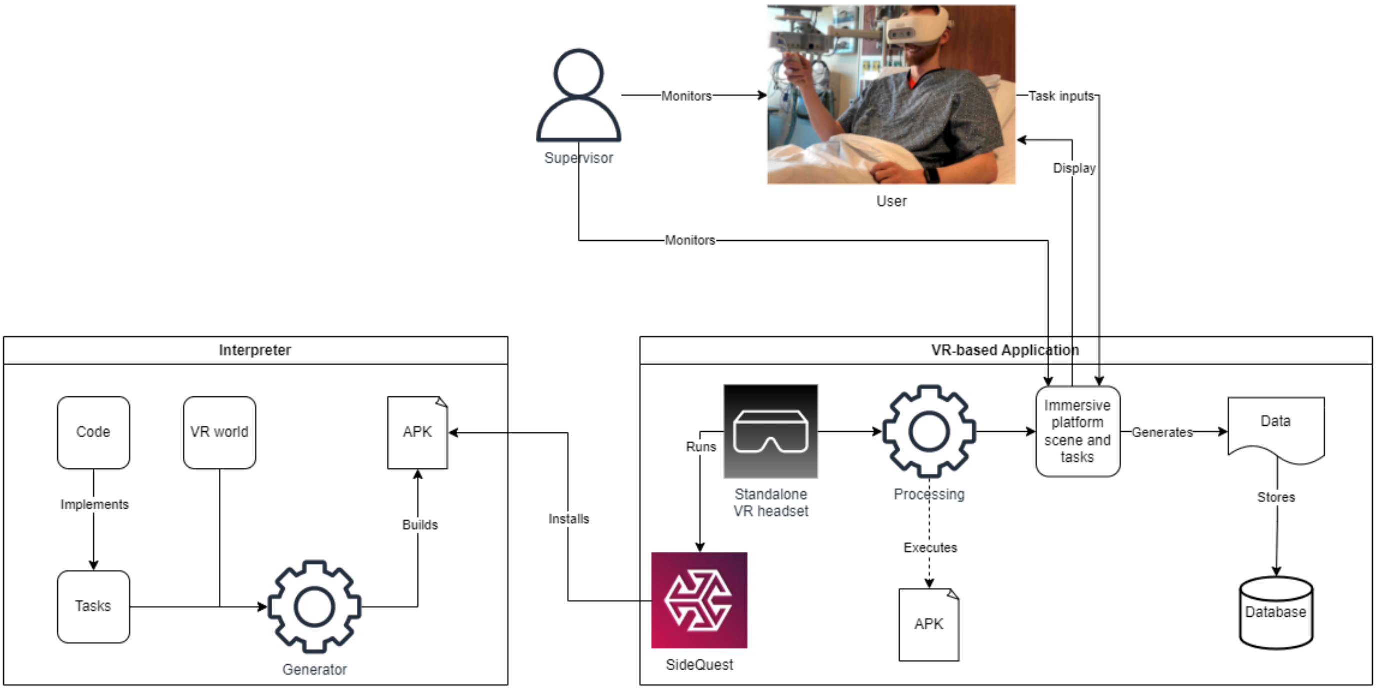


Figure 6: Proposed architecture for the system.

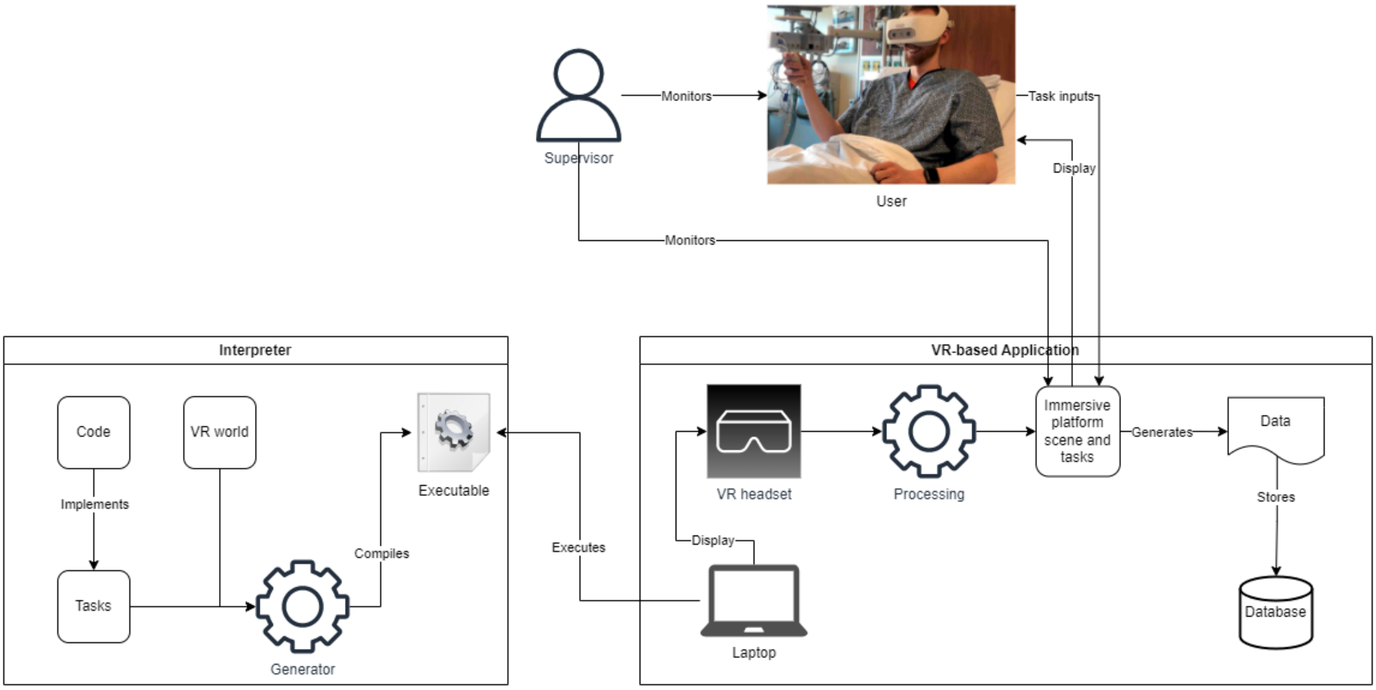


Figure 7: Alternative architecture for the system.

3.1.1 *Software Architecture*

In order to better understand the **Code**, **Tasks** and **VR world** modules of the proposed system architecture in Figure 6, a software architecture was designed. Figure 8 represents a diagram of the proposed software architecture.

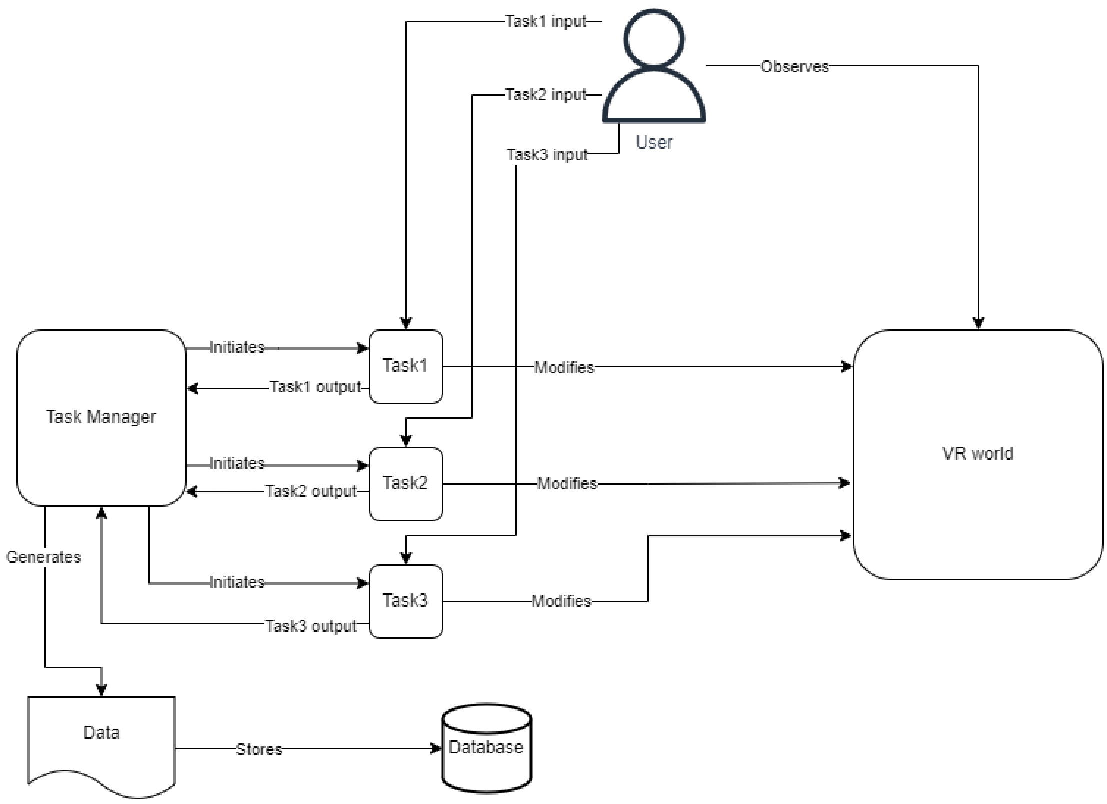


Figure 8: Proposed software architecture for the system.

It shows two main components: **Task Manager** and **VR world**.

The **Task Manager** module represents an entity controlling all tasks that will be implemented. This entity is essential to better organize the procedure so that the tasks can be initiated consecutively. This allows that **Task1**, for example, can be executed before the other tasks. This means that, if a patient ends up not being able to complete a certain task, it can be easily skipped to a different task. It also simplifies editing the task's order, so that if it ends up observing many patients with trouble on the first few tasks and not on subsequent tasks, the task's order can be switched accordingly.

The **VR world**, on the other hand, it is also one of the main modules. It is composed by all the 3D models that contains a scenery and also it is where the tasks will be shown on.

For example, a VR world can include a room with plants, some couches in a cosy and relaxing environment. It also includes visual for the tasks so that the patient knows what to do and where to begin.

3.1.2 *Deployment Architecture*

To better understand the way in which software systems, applications, and infrastructure components are organized, configured, and managed throughout their life cycle, a deployment architecture was designed and proposed. Figure 9 represents a diagram of the proposed deployment architecture.

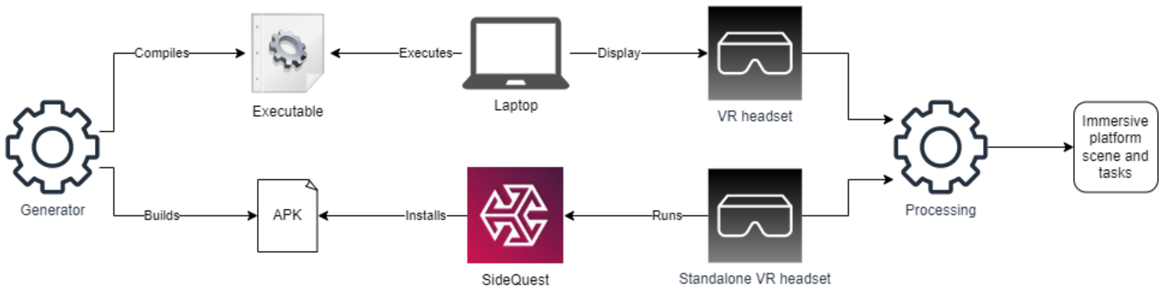


Figure 9: Proposed deployment architecture for the system.

Note that there is two ways of deploying the system. One is using the laptop device in order to support the execution of the application. The second one is using the VR standalone capabilities in order to execute the application. This uses the **SideQuest** third-party software that allows users to install .apk files on their VR headset. This has the requirement of having a VR device that support a standalone feature.

3.1.3 *Data Architecture*

In order to have a deeper understanding how the data flows through the system, a data architecture was designed and proposed. It allows to represent the way the data is managed and structured. Figure 10 illustrate a diagram of the proposed data architecture of the system.

The main entity on this architecture is the **Immersive platform scene and tasks** because it is where the important data is going to be generated. This data is related to the completion of the tasks as well as the variables to be tracked on each task, such as the levels achieved by the user.

For this data to be better visualized, is also proposed to transfer the data from the local **Database** to a **Database server** hosted just for the purpose of storing this information. This

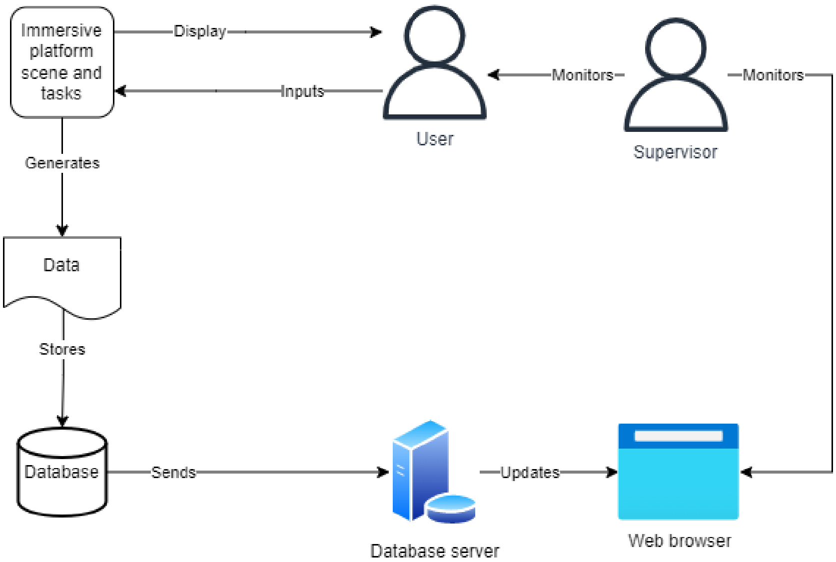


Figure 10: Proposed data architecture for the system.

data is then updated to a **Web browser** where the main supervisor can better visualize and monitor all the information related to the user.

4

DEVELOPMENT

Before starting the development of the planned tasks, some basic concepts were settled and aesthetics were thought and implemented in the VR world.

After an initial creation of the VR world, some elements were edited to make it acceptable in the ICU context. For example, the letter size was adjusted so that it can be better read. It was concluded that the size of the letter initially created were allegedly too small for the ICU patients to read. So, for better and more clear reading, the size of the letters were increased.

The models and colors were adjusted based on feedback from specialists in the field. To maintain a cozy and cheerful atmosphere in the room, the colors were changed to vibrant and lively hues. The decision to create a room, as opposed to another scenario, was arbitrary but driven by the need for a space that promotes comfort, familiarity, and reduces overstimulation.

Figures 11a, 11b and 11c shows some examples of text that will be displayed to guide the challenges proposed to the ICU patients.

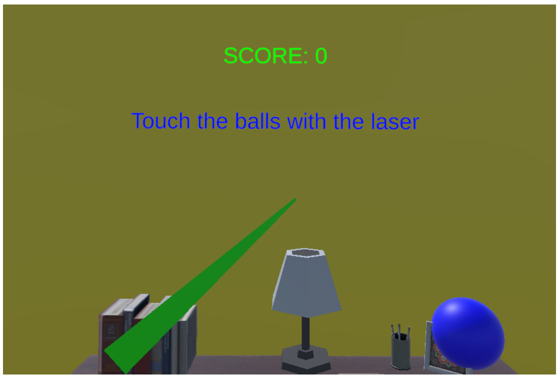
In Figure 11a, another extra element can be seen called **SCORE**. This element is a counter incremented, one by one, as the task is being completed. For example, each hit to the targets on a task adds 1 point to the score, so if the score is currently at 0, it will be increased to 1.

Another element that was later added on was a timer so that if the patient is not being able to complete a certain task, the game can still keep running automatically and the next task shown.

Figure 12 represents the Head-up display (HUD) that will be shown to the user so that he can be aware of the time remaining for the conclusion of the task.

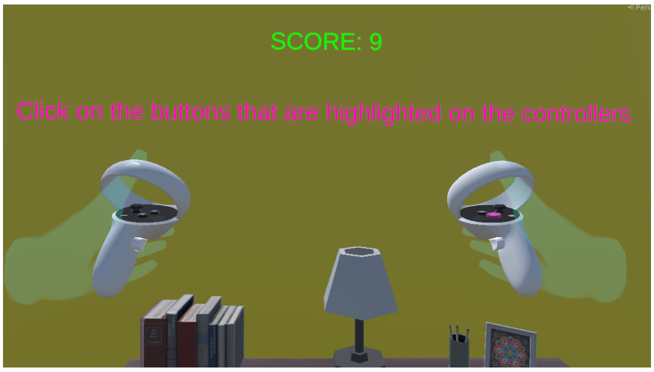
As it is shown in Figure 12, the timer image is going to be subsequently consumed until there is no HUD image left, representing the end of the task. This timer duration is set to be one minute, but can be adjusted later on, depending on the patient tests.

This timer allow for a better control over the tests without the active intervention of a helper. This is especially useful for when using the standalone version of the VR devices, that is, without a laptop supporting/running the application.



(a) Head Task.

(b) Arms Task.



(c) Fingers Task.

Figure 11: Text guides of the tasks.

Figure 12: A representation of the timer on the HUD.

4.1 DEVELOPED TASKS

In the context of this Master's Project, a total of 8 tasks were implemented and tested on different types of patients. It is these tasks that will now be detailed.

4.1.1 *Head Task*

The Head Task is the first and one of the most important basic tasks. Since this task only needs the head movements to be completed, it is completion is very important because the subsequently task will have this type of head movement in order to complete them. So this task is the base of all the others atomic tasks (first atomic level).

Figure 13 shows an example of the task developed. The blue ball represents the target and the user has to touch it with the green laser. This green laser is attached to the head, so whenever the user moves the head it also moves the laser accordingly. After this, it will spawn harder targets on higher and wider positions so that it is possible to measure the max reach of the head movement for the user playing it.

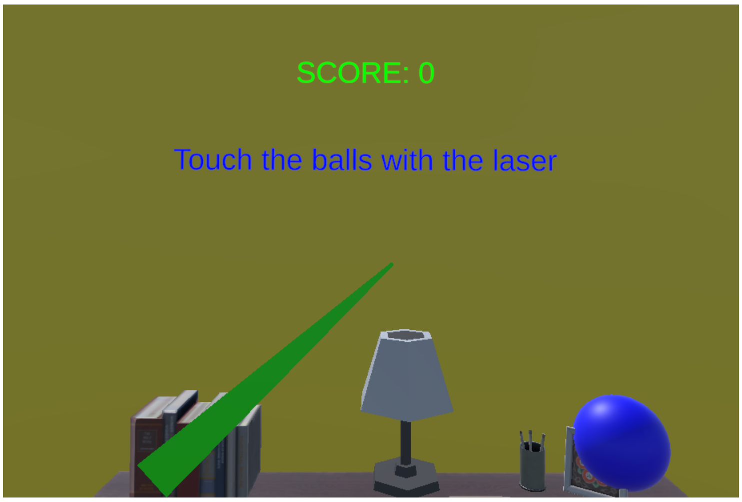


Figure 13: The developed Head Task.

4.1.2 *Arms Task*

The second task is called Arms Task and it allows to understand if the user has mobility of the arms. This task requires some head movement (like it was mention previously) and also the movement of the arms. Subsequently tasks will also have this atomic task in the base of them but since this one is already using an atomic task (Head Task) behind it, it is consider as a second layer of the atomic level, assuming the previous one was on the first layer level.

Figure 14 shows an example of the task developed. The red ball is the target that needs to be touched. The user needs to simply move his arms to touch the ball. After this, another target appears on the left side in order to test the left arm as well. When this is done, subsequently harder targets will spawn on harder positions, such as, on a more higher and wider positions. With this, it is possible to conclude on how far the user can reach the targets using his arms.

Figure 14: The developed Arms Task.

4.1.3 *Fingers Task*

The third task is called Fingers Task and its objective is to test whether or not the user can press the different buttons on the controllers. Since on the later on tasks it will be asked to press specific buttons to interact with the task, it is one of the important atomic tasks since without completing this one, the subsequently tasks will be harder to complete. This task is consider as a second layer of the atomic level. It is consider the same layer as the previous task because this one does not need any type of arms movement, but it always need the head movement to look around.

Figure 15 shows an example of the task developed. Notice that there is a highlighted button on the right controller which is the task's target. The user is asked to press each highlighted button until the task is complete.

4.1.4 *Pointing Task*

The fourth task is called Pointing Task and its purpose is to understand whether or not the user has the precision to point at a certain target. This task is consider as a third layer of the atomic level because it also requires some arm movement. So, and because it

Figure 15: The developed Fingers Task.

requires previous done atomic tasks, it should be in a higher level layer. Furthermore, since subsequently task will require precision motion, this task is also considered atomic.

Figure 16 represents an example of the task developed. The purple ball is the target that needs to be touched with the pink laser. Note that the laser is coming out of the user's hands (first the right hand and eventually the left hand) and the user has to point it, or touch it, to the ball. After touching it, the ball/target will get subsequently smaller and in different positions. After this, it is replicated, with the same ball size and positions, to the left side of the room and the laser is moved to the left hand.

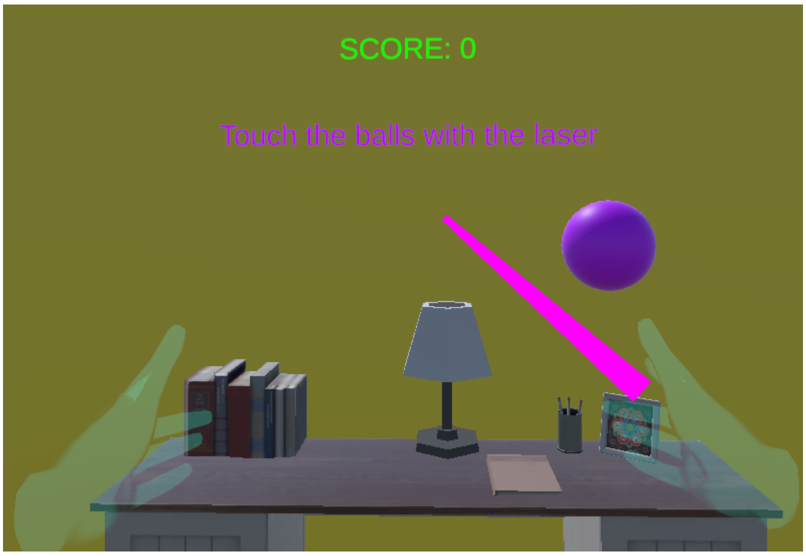


Figure 16: The developed Pointing Task.

4.1.5 *Pick and Place Task*

The fifth task is called Pick and Place Task, and its objective is to understand if the user is able to transport an object from one place to the other. Since this task includes doing more than one movement tested on the previous tasks, it is not considered an atomic task and therefore it is considered a normal primary task.

Figure 17 shows an example of the task developed. The green ball on top of the right pedestal is the target and it is required that the user picks it up and place it on the left pedestal. After this is done, the ball and the pedestals will decrease in size.

Figure 17: The developed Pick and Place Task.

4.1.6 *Point and go Task*

The sixth task is called Point and go Task, and it allows to understand if the user is able to have the precision to point at one place and click on a button to teleport into it. This task is also not considered an atomic task due to include concepts/movements from the atomic tasks mentioned previously.

Figure 18 shows an example of the task developed. Note that the big blue circle zone on the right side of the figure is the target and it is required that the user uses the left controller analog to teleport to this zone. It can also be seen, on the left side of the figure, the trajectory line or preview of the teleport being done when the user holds the left analog stick. After teleporting to the first zone, another zone is shown in a different place so that the user is forced to look and move around.

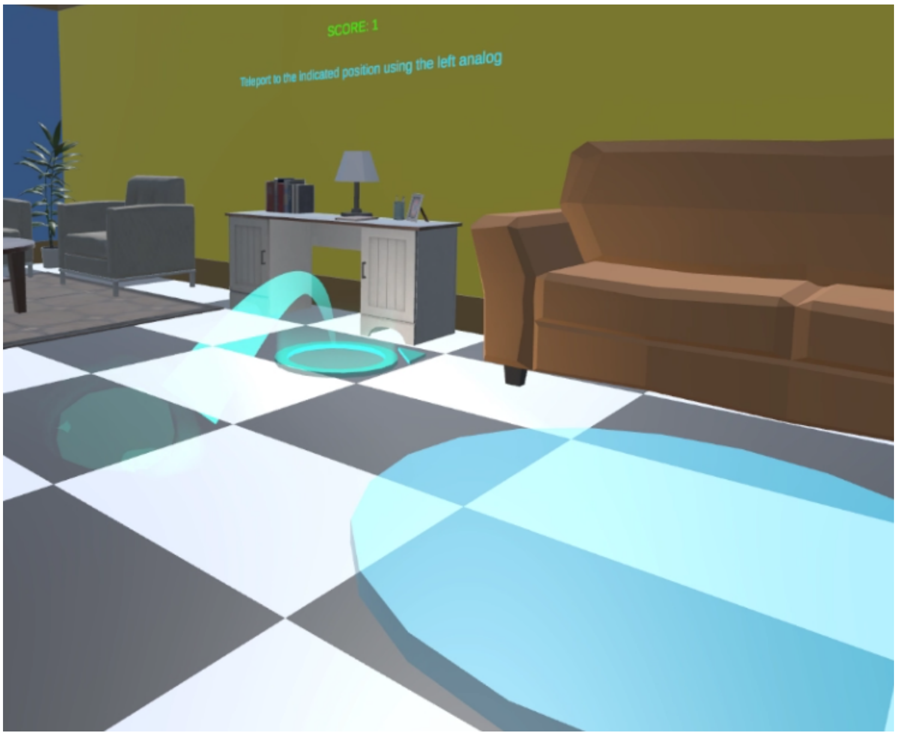


Figure 18: The developed Point and go Task.

4.1.7 *Painting Task using free hands*

The seventh task is called Painting Task using free hands, and its objective is to test if the user is able to clear a painting using his own hands. It will be asked for the user to lay down the controllers and use the hands to complete the task.

Figure 19 represents an example of the task developed. The target is the painting on the right side of the figure and it is required for the user to clean the yellow paint that it is on it.

4.1.8 *Pick and Place Task using free hands*

The eight and final task is called Pick and Place Task using free hands, and its purpose is to test the same task done before but now using the free hands method. Similar to the Pick and Place task, it will be asked for the user to pick the ball from one pedestal to the other but using his own hands.

Figure 20 shows an example of the task developed. The light green ball is the target that the user has to pick it up and pass it to the left pedestal on the figure.

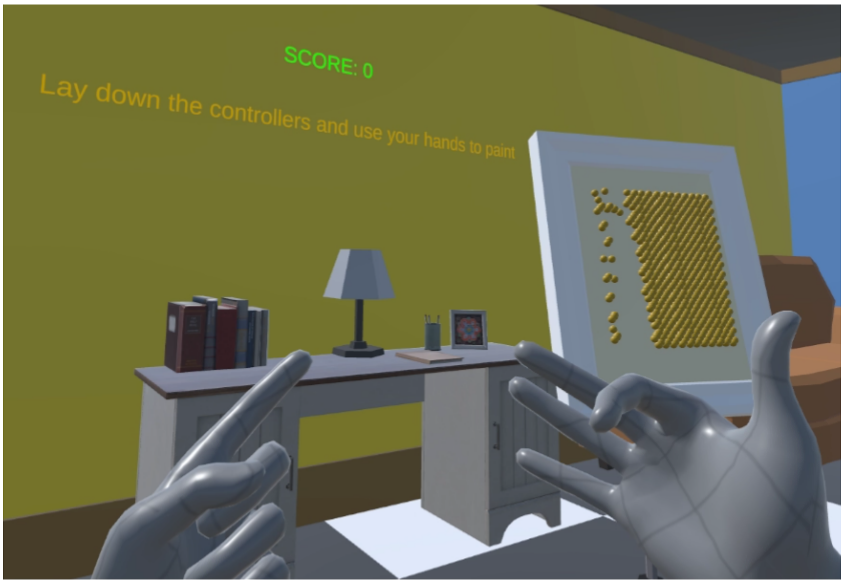


Figure 19: The developed Painting using free hands Task.

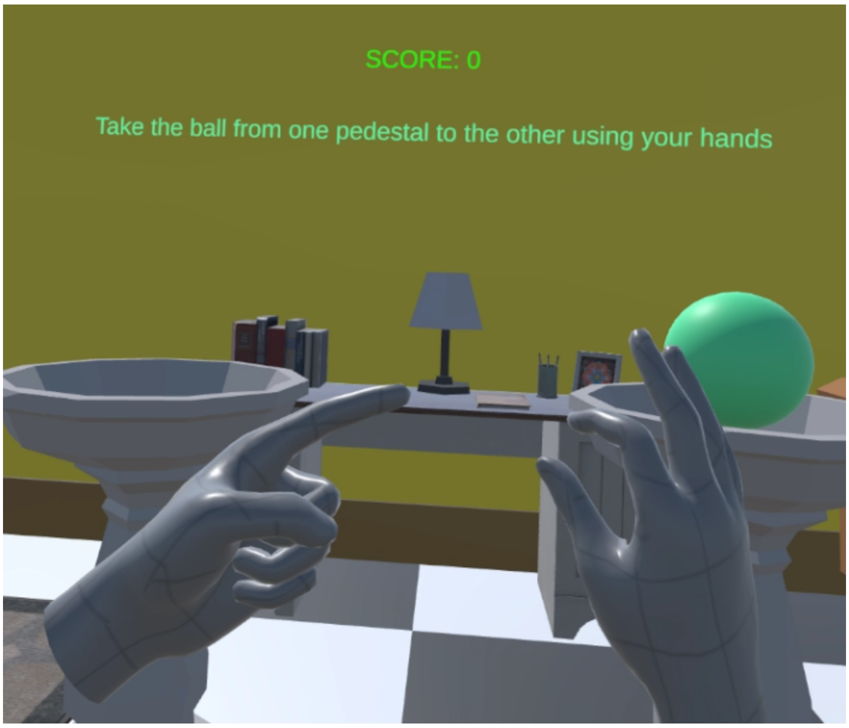


Figure 20: The developed Pick and Place using free hands Task.

4.2 TOOLS

The application was developed using a software called *Unity* which is a cross-platform game engine developed by *Unity Technologies*. The editor version used on the development of this project was the '2022.2.19f1'. It is also to be noted that all the 3D models used in this project were taken from the official Unity Asset Store.

The device used to test the application was the *Oculus Quest 2*, a VR headset developed by *Reality Labs*, a division of *Meta Platforms*. The resolution employed for testing was 4128 x 2096 pixels, with a refresh rate set at 72 Hz. The hand tracking method was implemented using the official SDK downloaded from the Meta Quest website.

4.3 DATA GATHER

In order to better gather and organize several user's data and performance, an application called *Cognitive3D* was used.

Cognitive3D is a software company that provides spatial analytics solutions for virtual, augmented, and mixed reality applications. Their platform collects and analyzes data on user behavior in 3D environments, providing insights into how users interact with products, environments, and training simulations.

This software was used for tracking the performance of each patient in order to conclude which targets were completed, how many time it took and overall progression of the test.

Figure 21 shows a small example of one of the parts of the code written using the cognitive3D module.

As shown in Figure 21, the following line:

```
new Cognitive3D.CustomEvent("(Task 1) Looked at target " + i).Send();
```

allows to initiate an event to cognitive3D application. This sends data to its cloud or it is stored on the computer if there is no active internet connection. It will automatically upload the buffer stored on the local computer to the cloud once there is a internet connection available.

Once a test is done to an user, its data is easily seen on the cognitive3D software. Figure 22 represents an example of some of the data gathered.

Note that all the data gathered here was then transported to an Excel sheet for further analysis and conclusions.

```
// Check if the ray hits the object
if (Physics.Raycast(ray, out hit))
{
    // If the ray hits the object, disable it
    if (hit.collider.gameObject == gameObject)
    {
        if (flag) {
            flag = false;   // flag para controlo de concorrência

            gameObject.SetActive(false);
            ScoreManager.incScore();

            if (i == positions.Length)
            {
                new Cognitive3D.CustomEvent("(Task 1) Looked at target " + i).Send();
                //gameObject.SetActive(false);
                lineRenderer.enabled = false;
                taskController.Task1Completed();
            }
            else
            {
                gameObject.transform.localPosition = positions[i];
                new Cognitive3D.CustomEvent("(Task 1) Looked at target " + i).Send();
                i++;
                gameObject.SetActive(true);
            }

            flag = true;
        }
    }
}
```

Figure 21: An example of a code using the cognitive3D module.

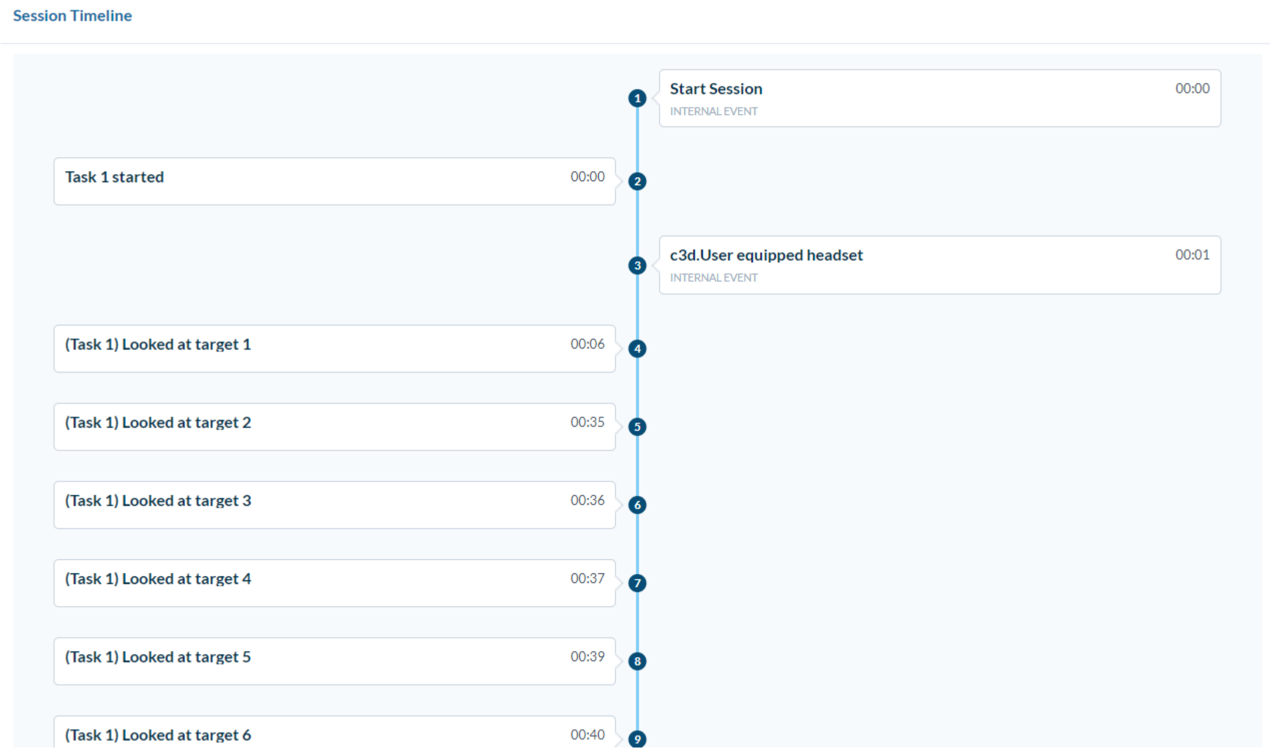


Figure 22: Small example of the data gathered on the cognitive3D website.

5

ASSESSMENT

In order to evaluate the performance of a patient, it is necessary to identify the parameters to track (i.e., the variables that should be measured) to analyze the user performance in each task.

A total of three interventions were conducted to evaluate and test the application. The first intervention involved two participants, while the second and third interventions each included eight participants. It is worth noting that the third intervention tested different versions of the application, with the initial part remaining consistent to ensure that valid conclusions could still be drawn.

The first intervention served primarily as an application test and was conducted at home. The second and third interventions took place at a day care center. Unfortunately, due to the limited time available between the development of the app and the completion of this dissertation, it was not possible to conduct tests in the ICU environment. While this presented a challenge, it did not prevent us from conducting similar tests with elderly individuals. Elderly individuals are still considered part of the constrained user group, which is within the scope of this thesis.

5.1 METRICS (PARAMETERS TO MEASURE)

In this context, the most important variables to track are:

- Total time for completing a task.
- Time for completing each target of a task.
- Number of times a task was done correctly (Score).
- Number of times a task was done incorrectly (Errors).
- Total time for completing all tasks.

In practice, it is not always possible to evaluate all variables for each task. For example, the most basic tasks can not be done incorrectly, so the fourth parameter will not be computed. In fact, it will only be tracked the number of errors done for the third task (Fingers Task).

5.2 EXPERIMENT SETUP

With the objective of understanding the overall performance of the different type of users, a total of three experiments were executed. The sequence of the tests and the numbers was based on the amount of resources available at the time.

5.2.1 *First Experiment*

The initial experiment was conducted on a smaller scale in a local environment, involving only two users. This approach allowed us to address potential issues, gain valuable experience, and better prepare for a more realistic scenario.

To assess the proposal and the prototype developed, and to analyze its performance, a module called *Cognitive3D* was used to monitor and structure all the data gathered from the user input.

In order to better understand the variables and the impact the outside factors have on the completion of the tasks, the execution of the test was split in two major scenarios: *User is sit down* or the *user is lying down*. Figure 23 and 24, collected during the actual experiment, illustrate properly those two scenarios.

Figure 23: User sitting down.

Figure 24: User lying down.

Since these two patient's situations will probably affect his performance and the overall results, it was decided that the experience should be duplicated to track both scenarios and executed two times to replicate a real ICU environment.

The experiment was conducted involving people outside the ICU but it was performed pretending the real context. This means that the movements were restricted in order to better simulate the ICU context. The first experiment conducted involved actually two users: User1 is 26 years old and has some experience with VR technology, and User2 is 60 years old and has no experience with VR technology.

Table 2 and 3 display the processed data taken from *Cognititve3D* module during the activities. Figure 25 shows a part of overall data that it is being monitored.

Session Events

Event Details

Scene: ICU_Tasks_Scene (Version 3)

Total Events Duration: 00:00

Total Events Completed: 25

EVENT NAME	DURATION
c3d.sessionStart	0.00s 00:00
(Task 1) Looked at target 1	0.00s 00:16
(Task 1) Looked at target 2	0.00s 00:17
(Task 1) Looked at target 3	0.00s 00:19
(Task 1) Looked at target 4	0.00s 00:19
(Task 1) Looked at target 5	0.00s 00:21
(Task 1) Looked at target 6	0.00s 00:22
(Task 2) Touched on target 1	0.00s 01:06
(Task 2) Touched on target 2	0.00s 01:08

Figure 25: A sample of the total data registered on *Cognitive3D*.

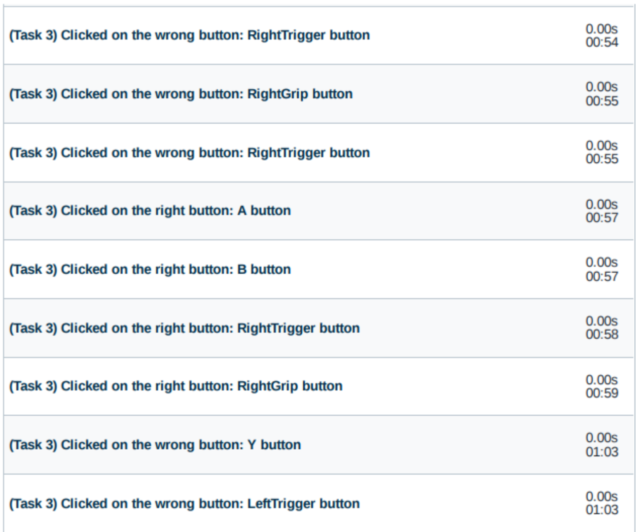
Note that the default timeout for each target is 60 seconds. This is to prevent a patient getting stuck on a task that he can not complete. This can be noticed on Figure 25 when the user looked at target 6 and then waited 60 seconds for the timeout to occur and eventually the start of the task 2. This explains why the user touched the target 1 in the task 2 only at 1 minute and 6 seconds.

Notice that the Fingers Task targets represent each individual button to be pressed. This means that the target number can easily be replaced by the button name. Table 1 establishes the correspondence between target numbers and button identifiers.

Targets	1	2	3	4	5	6	7	8
Buttons	A	B	R. Trigger	R. Grip	X	Y	L. Trigger	L. Grip

Table 1: Controller's buttons that is representing each target's number.

On top of registering correct actions (when the user presses the due button), the wrong actions are also monitored. If the user presses a button that is not, currently, the right one, an event is launched and registered at *Cognitive3D*. Figure 26 represents an example of when a user pressed wrong buttons.



(Task 3) Clicked on the wrong button: RightTrigger button	0.00s 00:54
(Task 3) Clicked on the wrong button: RightGrip button	0.00s 00:55
(Task 3) Clicked on the wrong button: RightTrigger button	0.00s 00:55
(Task 3) Clicked on the right button: A button	0.00s 00:57
(Task 3) Clicked on the right button: B button	0.00s 00:57
(Task 3) Clicked on the right button: RightTrigger button	0.00s 00:58
(Task 3) Clicked on the right button: RightGrip button	0.00s 00:59
(Task 3) Clicked on the wrong button: Y button	0.00s 01:03
(Task 3) Clicked on the wrong button: LeftTrigger button	0.00s 01:03

Figure 26: A sample of the total data of *Cognitive3D* about the error events.

Note that in the context of the present experiment, some users did not press any wrong button, but this does not mean that in the ICU context there will be no errors. It is estimated that the ICU patients will click in many wrong buttons by accident or even because they do not know which button to press.

5.2.2 *Second Experiment*

The second experiment was conducted on a day care center with 8 people. This time, the experiment was much closer to the real ICU patients due to these users being more elderly. Some of which also have mental problems which can influence the performance of the test.

It is important to note that besides this experiment, it was also tested a Mini-Mental Status Examination (MMSE) at the same time in order to further correlate the variables analyzed. Based on a study (Park et al., 2012), this simple but effective examination allows to better understand if the user has cognitive dysfunction as this is associated to mortality in the elderly.

The results taken from this second experiment will be presented and discussed at section 5.3.

5.2.3 *Third Experiment*

This third and last experiment was also conducted on the same day care but this time on a improved and final version of the application developed as well as the experience learned from previous tests. It was tested to another 8 different people. Note that the MMSE was also performed on these users as well.

The results taken from this third experiment will be presented and discussed at section 5.3.

5.3 RESULTS AND DISCUSSION

In this subsection the results so far collected will be analyzed and possible conclusions will be drawn.

5.3.1 *First Trial Results*

User is sit down

To better understand how each target is influencing on the outcome of a task, the individual targets time were also collected and recorded for posterior analysis.

Figure 27 details, for each one of the three tasks proposed, the time taken by each User to complete each specific target.

Note that the initial time of the first target is longer than the rest of the targets. This is mainly because of this task being the first that is introduced to the user. So it will take more time for the user to get used to the environment, as well as the game mechanics and

User ID	Task	Targets completed	Total time	Errors	Score	Total time (all tasks)	Total time (all tasks with timeouts)
User 1	Head	6/8	23s (-timeout)	-	20/24	61s	138s
	Arms	6/8	20s (-timeout)	-			
	Fingers	8/8	18s	0			
User 2	Head	6/8	26 (-timeout)	-	14/24	83s	180s
	Arms	4/8	12 (-timeout)	-			
	Fingers	4/8	45	22			

Table 2: Data gathered on sitting down users.

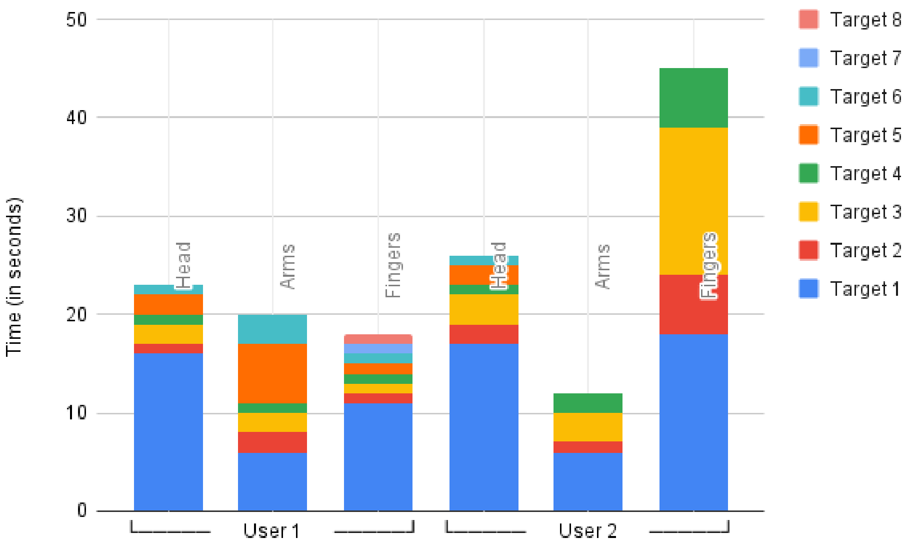


Figure 27: Targets and Completion Times in Scenario 1.

guides. Fingers Task time also contains a longer time for the first target. This is due to the task having small differences in relation to the previous ones. The time for the subsequent tasks is expected to be shorter, due to the initial adaption to the challenge proposed, as is demonstrated by the graphic in Figure 9. User1 was the fastest in this third task, as in the previous ones, due to his age and experience with VR tools; however User2 demonstrated a performance surely closer to the ICU patients.

Notice that Targets 7 and 8 on the **Head Task** and **Arms Task** have no time associated. This is because it was unable to be completed for the reason that the user could not reach it therefore could not complete these targets.

User is lying down

User ID	Task	Targets completed	Total time	Errors	Score	Total time (all tasks)	Total time (all tasks with timeouts)
User 1	Head	0/8	0s (-timeout)	-	12/24	32s	137s
	Arms	4/8	12s (-timeout)	-			
	Fingers	8/8	17s	0			
User 2	Head	0/8	0 (-timeout)	-	12/24	75s	180s
	Arms	4/8	25 (-timeout)	-			
	Fingers	8/8	50	39			

Table 3: Data gathered on lying down users.

Figure 28 plots the total time and times of the respective targets that each User took to complete the second and the third tasks.

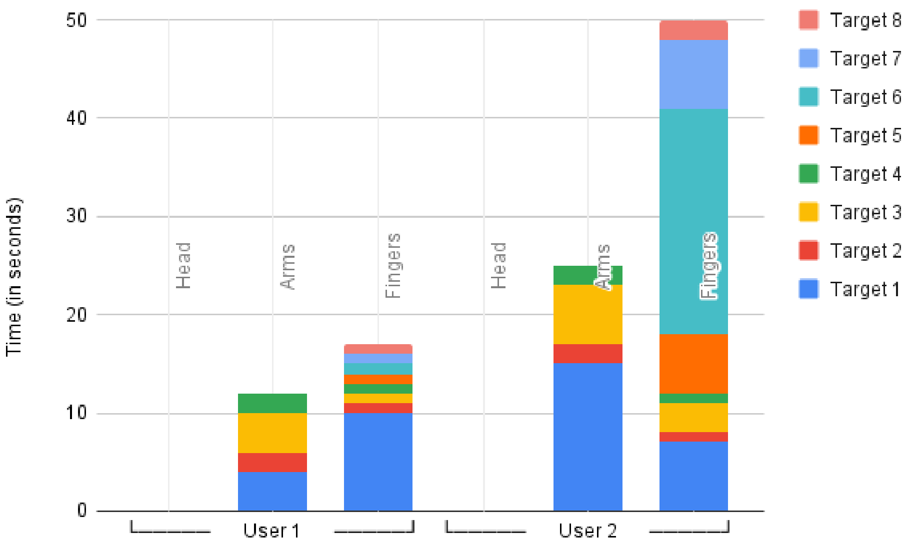


Figure 28: Targets and Completion Times in Scenario 2.

As it can be seen in Figure 28, the **Head Task** was not possible to execute while lying down. This was due to the fact that the targets spawn first close to eye level (assuming the standing/sitting position). So while lying down, the target really gets out of eye and head position, resulting in the impossibility of completing the target and eventually the task.

There are targets in this task that would, most likely, be able to be completed, but since the approach of showing the targets to the user is spawning the second target after the first one is completed, the user could not try to complete the latter targets. This may be changed in the future to better analyze the limitations of each patient in the ICU.

5.3.2 *Second Trial Results*

The second results are divided into two categories: The people who tested the first version of the application which consisted in 3 tasks; And the people who tested the second version of the application which consisted in 8 tasks. Note that the second version of the application include the first 3 tasks of the first version, so it is possible to place together the data of these two interventions to better and more firmly conclude some results.

It is also noted that there was some positive correlations when the data was analyzed with only 8 people but, it was decided to conclude with all 15 people. The reason why 15 people and not 16 as said before (8 people on first experiment and 8 on the second) is because one of the user that tested in the first experiment, also tested the second one, which was more advanced. This was interesting to see if the performance would be much better than the other users which it actually end up being true (user *A256* end up having much better score on second run of experiments).

It is also to be noted that, in this second results, all the test were made sitting down, leaving the laying down part for future work.

Table 5 represents the first results of tests done to the first 8 users.

After this results, another set of users were tested but this time with an improved version. Note that this version has increased number of targets on the first tasks, as well as more tasks implemented. But, in order to have more number of people to analyze, it is only shown the performance of the first 3 tasks.

Table 6 represents the data processed from the second experiment.

As it can be seen, the user *A256* was the only user that was on both experiments and as such, it had an noticeable increase of score on the second round of experiments. This could mean that being able to have some experiment or have at least a first try at VR can help understand and be more natural at doing task and perform them better. Since for most of the users, this was their first time trying out VR, most of them if not all of them have a harder time to adapt and interact with this new technology. This was noticeable while doing the tests as the users were very scared to take actions or even moving the head or looking around.

It is to be noted that this 16 tests were aggregated in two test sessions, with the first session being tested on a 3-task application, and the second session on a improved 8-task application. Since only 8 users were tested on each application version, it was decided to merge the first 3 tasks (since they were the same) and analyze the correlations with a higher number of users for a stronger conclusion.

5.3.3 *Variables Correlations*

After analyzing and organizing the data gathered from all users, it was time to correlate them with the data given through MMSE.

Table 4 shows the Pearson correlations coefficients of the variables measured. Just to clarify, the columns variables *Score* and *Total Time* represents the score and total time of all tasks without any timeouts mentioned previously. And on the rows, all of the variables were gathered by a specialized person and are self explanatory. Only needs to be noted the BMI acronym stands for Body Mass Index and was calculated by taking the person's weight in kilograms and divide it by the square of height in meters.

	Score	**Total Time**
Sex	-0,032	0,065
Age	-0,423	-0,420
Scholarship	0,127	0,087
MMSE_score	0,312	0,040
Height_cm	-0,055	-0,143
BMI	0,155	0,186
Body_fat_percentage	0,171	-0,006

Table 4: Pearson correlations coefficients.

As it can be seen, most of the correlations are close to 0, which indicates no correlation at all. But there are some of them that are almost closer to 0.5, which means that they have some correlations but not that strong correlated. The negative values means that they are negative correlated, which means that when one variable raises, the other one decreases.

The "Age" variable exhibited a negative correlation of approximately -0.42. While this correlation isn't particularly strong, it does suggest that age inversely affected both the "Score" and "Total Time". Specifically, as age increased, both "Score" and "Total Time" decreased. The interpretation of the "Total Time" variable is nuanced: when there are no timeouts, a user who did not complete any tasks would register 0s for "Total Time". Evaluating using the variable that accounts for timeouts is problematic, as a large number of users reached a timeout due to the increasing difficulty of tasks at later levels, leading to a convergence in time values. This means that a direct relationship between increasing age and decreasing time isn't as straightforward as one might expect. In this context, the decreased time is understandable, given that unfinished tasks result in shorter times recorded for the variable.

The *MMSE_score* exhibited a modest correlation with the *Score* variable, suggesting that cognitive ability is related to user performance. While the results aren't as robust as desired, these preliminary indicators point out some research avenues worth further exploration.

5.3.4 *Qualitative Analysis*

While a User Experience (UX) survey was not integrated into the testing procedures, an overall analysis of the UX can still be derived from personal opinions.

The majority of users expressed satisfaction with their experience experimenting with VR technology, particularly as it was their first encounter with such a novel technology. One user even described it as an amazing experience and expressed excitement about trying it again in the future.

However, a few users reported feeling a bit queasy after spending 1 to 2 minutes in the test. Despite this, they persevered and completed the full test. Additionally, nearly half of the users admitted to harboring reservations about trying and experimenting with VR. Many were hesitant to move their heads around, possibly due to unfamiliarity with the technology, resulting in them mostly remaining stationary during the test.

This highlights the importance of conducting a pre-training session to allow participants to acquaint themselves with VR glasses and controllers before progressing to the actual test.

6

CONCLUSION

In this Master's Project, we embarked on a comprehensive journey to evaluate the ability of constrained users, particularly those with physical disabilities or cognitive impairments, to interact with virtual reality applications. The investigation delved into the realm of virtual reality systems, scrutinizing their adaptability and applicability for these unique user groups. A first objective of this Master's project was to establish a set of guidelines to design VR applications that cater to the distinct abilities and needs of individuals facing cognitive and physical challenges.

Some experiments were conducted in settings designed to mimic the real-life constraints experienced by patients in an Intensive Care Unit (ICU). User actions and behaviors were meticulously recorded, scrutinizing the impact of age, experience with VR technology, and cognitive abilities on their performance.

In the first experiment, it was observed a notable variation in user performance based on age and familiarity with VR technology. It was apparent that prior experience with VR technology could lead to improved user performance, while age exhibited a negative correlation with performance. The data collected indicated that some tasks were especially challenging for users, reinforcing the importance of designing user-friendly VR applications for individuals with cognitive and physical limitations.

In the second experiment conducted, it was further investigated the impact of age, experience, and cognitive abilities. The inclusion of an improved VR application with more tasks provided a broader perspective. A significant improvement in user performance in the second trial, especially for the user with previous exposure to VR technology, highlighting the potential benefits of familiarity and practice.

Additionally, it was explored correlations between user characteristics and their performance in VR tasks. While the correlations were not overwhelmingly strong, the project findings suggest that cognitive abilities, as measured by the MMSE, are related to user performance in virtual reality applications. This shows the importance of considering the cognitive capabilities of users when designing VR applications for individuals facing cognitive challenges.

The research carried on along this Master's work underscores the need for more extensive studies, particularly in real ICU settings, to validate our findings and draw more conclusive results. The complex interplay of factors affecting user performance in VR environments calls for continued exploration.

In conclusion, this project provides a foundation for future research and application development in the realm of virtual reality for constrained users. Designing VR applications that account for cognitive and physical limitations holds promise in improving the quality of life for these individuals, and this thesis paves the way for more inclusive and accessible VR experiences.

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ADDITIONAL TABLES

This section presents supplementary tables that provide further details and data related to the research. These tables are not included in the main text to maintain readability but are important for a comprehensive view of the results.

User ID	Task	Targets completed	Total time	Errors	Score	Total time (all tasks)	Total time (all tasks with timeouts)
A270	Head	6/8	41s (-timeout)	-	18/24	118s	178s
	Arms	4/8	19s (-timeout)	-			
	Fingers	8/8	58s	28			
A238	Head	6/8	47s (-timeout)	-	14/24	92s	165s
	Arms	8/8	45s	-			
	Fingers	0/8	0s (-timeout)	8			
A239	Head	1/8	2s (-timeout)	-	10/24	68s	180s
	Arms	6/8	27s (-timeout)	-			
	Fingers	3/8	39s (-timeout)	35			
A242	Head	6/8	54s (-timeout)	-	20/24	148s	173s
	Arms	6/8	41s (-timeout)	-			
	Fingers	8/8	53s	14			
A243	Head	2/8	57s (-timeout)	-	12/24	138s	156s
	Arms	8/8	36s	-			
	Fingers	2/8	45s (-timeout)	13			
A245	Head	1/8	25s (-timeout)	-	5/24	71s	180s
	Arms	0/8	0s (-timeout)	-			
	Fingers	4/8	46s (-timeout)	18			
A246	Head	6/8	34s (-timeout)	-	15/24	88s	180s
	Arms	7/8	36s (-timeout)	-			
	Fingers	2/8	18s (-timeout)	6			
A256	Head	6/8	50s (-timeout)	-	15/24	145s	180s
	Arms	7/8	60s (-timeout)	-			
	Fingers	2/8	35s (-timeout)	19			

Table 5: Data gathered on the first experiment.

User ID	Task	Targets com-pleted	Total time	Errors	Score	Total time (all tasks)	Total time (all tasks with timeouts)
A271	Head	0/10	0s (-timeout)	-	3/30	12s	180s
	Arms	0/12	0s (-timeout)	-			
	Fingers	3/8	12s (-timeout)	6			
A272	Head	1/10	55s (-timeout)	-	5/30	108s	180s
	Arms	0/12	0s (-timeout)	-			
	Fingers	4/8	53s (-timeout)	21			
A256	Head	10/10	57s	-	26/30	137s	150s
	Arms	12/12	53s	-			
	Fingers	4/8	47s (-timeout)	37			
A273	Head	2/10	57s (-timeout)	-	13/30	161s	180s
	Arms	8/12	58s (-timeout)	-			
	Fingers	3/8	46s (-timeout)	5			
A274	Head	1/10	9s (-timeout)	-	10/30	108s	180s
	Arms	8/12	46s (-timeout)	-			
	Fingers	1/8	53s (-timeout)	12			
A275	Head	1/10	6s (-timeout)	-	2/30	40s	180s
	Arms	0/12	0s (-timeout)	-			
	Fingers	1/8	34s (-timeout)	14			
A276	Head	1/10	5s (-timeout)	-	16/30	125s	180s
	Arms	9/12	60s (-timeout)	-			
	Fingers	6/8	60s (-timeout)	19			
A277	Head	5/10	60s (-timeout)	-	19/30	179s	180s
	Arms	8/12	59s (-timeout)	-			
	Fingers	6/8	60s (-timeout)	73			

Table 6: Data gathered on the second experiment.