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Designing a serious Virtual Reality game for neuro-rehabilitation: Improving usability, relevance and meaningfulness through iterative, user-centered approach

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"Science and everyday life cannot and should not be separated."

— Rosalind Franklin

Abstract

After a stroke, a large number of patients suffer from neurological and physical after-effects. Among the most frequently observed impairments are a loss of trunk control and a lack of motivation. Yet, trunk control is a key indicator of functional recovery in neuro-rehabilitation. The objective of this project is therefore to improve patients' adherence and motivation in training this function, by means of a serious game on a Virtual Reality (VR) headset.
This work aims to explore different gamification strategies that can enhance therapeutic relevance, meaningfulness in assessing patient performance, and ease of use of a VR game in a rehabilitation context.
Specifically, the impact of simplifying certain steps, adding a visual score display, introducing a daily objective, and improving graphical rendering was studied in relation to these operational goals.
Once these elements were implemented, a user-centered testing process was carried out to collect both qualitative and quantitative feedback. After testing the game by playing, participants would fill out a semi-structured interview along with a System Usability Scale (SUS). The results showed that the new features led to an increase of approximately 20% in the SUS score with respect to previous testing sessions, rising from 72.73/100 to 87.5/100. This progression is explained by a reworking of the game's playful aspects, which contributed to greater user engagement.

Après un Accident Vasculaire Cérébral (AVC), un grand nombre de patients subissent des séquelles neurologiques et physiques. Parmi les troubles les plus fréquemment observés, figurent une perte du contrôle du tronc ainsi qu'un manque de motivation. Or, le contrôle du tronc constitue un indicateur clef de la récupération fonctionnelle en neuroréhabilitation. L'objectif de ce projet est donc d'améliorer l'adhérence et la motivation des patients dans l'entraînement de cette fonction, au moyen d'un *serious game* sur un casque de Réalité Virtuelle (VR).
Ce travail vise à explorer différents leviers de ludification susceptibles d'augmenter la pertinence thérapeutique, le caractère significatif pour l'évaluation des performances du patient, ainsi que la facilité d'utilisation d'un jeu en Réalité Virtuelle dans un contexte de rééducation.
En particulier, l'impact de la simplification de certaines étapes, de l'ajout d'un affichage de score visuel, de l'introduction d'un objectif quotidien, ainsi que de l'amélioration du rendu graphique a été étudié par rapport à ces objectifs fonctionnels.
Une fois ces éléments implémentés, une démarche de tests centrée sur l'utilisateur a permis de recueillir des retours à la fois qualitatifs et quantitatifs. Après avoir testé le jeu, les participants remplissent une entrevue semi-structurée, ainsi qu'une System Usability Scale (SUS). Les résultats ont montré que les nouvelles fonctionnalités ont conduit à une hausse d'environ 20% du score SUS par rapport aux tests menés antérieurement, passant de 72,73/100 à 87,5/100. Cette progression s'explique par une maniabilité accrue du système de par la refonte des aspects ludiques, ayant favorisé une meilleure adhésion des testeurs.

Dopo un ictus, un numero significativo di pazienti presenta esiti neurologici e fisici persistenti tempo dopo l'evento. Tra i disturbi più frequentemente osservati si annoverano la perdita del controllo del tronco e ridotta motivazione. Tuttavia, il controllo del tronco rappresenta un indicatore fondamentale del recupero funzionale nel contesto della neuroriabilitazione. L'obiettivo di questo progetto è dunque quello di incrementare l'adesione e la motivazione dei pazienti nell'allenamento di tale funzione, mediante l'utilizzo di un "serious game" sviluppato per visore di Realtà Virtuale (VR).
Questo studio si propone di esplorare diverse strategie di "gamification" in grado di aumentare la rilevanza terapeutica, la significatività nella valutazione delle prestazioni del paziente e la facilità d'uso di un gioco VR in un contesto riabilitativo.
In particolare, è stato analizzato l'impatto della semplificazione di specifici passaggi, l'aggiunta della visualizzazione del punteggio, l'introduzione di un obiettivo giornaliero e il miglioramento della resa grafica, in relazione agli obiettivi operativi sopra citati.
Successivamente all'implementazione di tali elementi, è stato condotto un processo di testing centrato sull'utente, al fine di raccogliere feedback sia qualitativi che quantitativi. Al termine della sessione di gioco, i partecipanti hanno compilato un'intervista semi-strutturata accompagnata dalla System Usability Scale (SUS). I risultati hanno mostrato un incremento di circa il 20% nel punteggio SUS rispetto alle sessioni di test precedenti, passando da 72.73/100 a 87.5/100. Tale miglioramento è attribuibile a una rielaborazione degli aspetti ludici del gioco, che ha favorito un maggiore coinvolgimento degli utenti.

Glossary

Virtual Reality (VR): A simulation that can be interacted with using a Virtual Reality headset.

Meta Quest 3: Virtual Reality headset developed by Meta.

LLUI: The Lake Lucerne Institute.

Cereneo: Neuro-rehabilitation clinic located in Vitznau, near by the LLUI office.

ZHAW: The Zurich University of Applied Sciences.

KSW: The KantonsSpital Winterthur, a canton hospital located nearby Zurich.

Reaching Game: Name of the serious game developed within the AdaptVR project, under scrutiny here.

Extrinsic Feedback: Information provided by an external source about the performance or outcome of a movement, often used to guide future improvement.

Intrinsic Feedback: Sensory information received naturally during or after performing a movement, such as proprioception, vision, or tactile sensation.

Motor Learning Principles: A set of concepts describing how motor skills are efficiently acquired over time. Key principles include repetition, feedback, variability of practice, and progression from simple to complex tasks. [1]

Activities of Daily Living (ADL): Everyday tasks essential for independent living.

Gamification: The integration of game-design elements in non-game contexts to increase user engagement and motivation.

Unity: Software used for developing the Reaching Game on the Meta Quest, in C#.

Scenes: In the Unity game engine, individual sections of a game, each containing its own GameObjects and being loaded or switched during game flow.

GameObject: The fundamental Unity object representing objects in a scene.

Texture: A pattern applied to the surface of a GameObject in Unity to give it graphical complexity.

Build: The process of compiling a Unity project into a standalone application on the Virtual Reality headset.

Play Mode: A simulation mode in the Unity Editor that allows developers to test and interact with the game or application without building the full executable.

Thermal throttling: Automatic reducing of a graphical system's performances to avoid the overload of the GPU.

Study design: Methods and procedure used to collect the data needed.

System Usability Scale (SUS): A standardized questionnaire used to evaluate the usability of a system or product.

Semi-Structured Interview: A qualitative research method allowing flexibility of answers while maintaining focus on core topics.

Performance Score (PF): Result, in percents, of the equation allowing to compute the user's score in the Reaching Game.

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Motivation

The choice of this internship was the result of careful consideration. I had to ask myself not only what I wanted to do, but also what I wanted to gain from this final internship. Indeed, it was important for me to work where I could offer something and get something in return. Upon reflection, three expectations of this internship stood out:

1. Working in a field which has always appealed to me and in which I was sure that I would appreciate the project: biomedical engineering. I thus started by looking into biomedical projects, between my field of competences and medicine.

2. Once I knew where to orientate my research, I understood that I did not want to work for six months on a project I did not believe in. At this time, I found the internship offer of AdaptVR, and after looking into it, was convinced that the project was something useful, that could have a real impact on people's life, in a cutting-edge field that lays a new path for rehabilitation and therapy. I applied for the internship.

3. During the interview, I discovered that the project would let me put into practice and further develop my learnings from the EPFL semester. Indeed, the work done here is at the interface between hardware development and performance computations learnt at EPFL, and software development learnt through all semesters of my studies, but never deepened.

By the time I received the acceptance letter, I had had time to reflect on these three requirements, and I accepted the internship.

1

Introduction

1.1 Presentation of the laboratory

Every second, the human heart pumps blood and pushes it to the brain. This allows brain cells to receive the oxygen and glucose they need to function properly, supporting processes such as thought, movement, sensation, and coordination. But if it occurs that - because of a blocked artery or bleeding - the supply to tissues freezes, the deprived brain area degenerates, stops functioning, and the linked neurological functions are lost. This is what happens during a cerebrovascular accident, or stroke, for 15 million people each year around the world. [2]
Strokes are a leading cause of death. By the time blood circulation is successfully restored (if it can be), cell death has usually already occurred, and patients often experience a wide range of post-stroke impairments and compromised functions, from diminished senses such as smell or speech to severe motor control deficits and cognitive dysfunction. [3]
Similarly to the case of other conditions affecting the central nervous system, such as Multiple Sclerosis, Spinal Cord Injuries, Parkinson's or Alzheimer's diseases, the neuro-rehabilitation required is laborious, long, and has an important socio-economical impact. [4]

In this context, the Lake Lucerne Institute (LLUI), based in Vitznau, Lucerne, Switzerland, is a non-profit institute conducting independent research on neuro-rehabilitation, neuro-nutrition and neuro-psychology. In collaboration with the Cereneo clinic for neurology and rehabilitation, also located in Vitznau, the various researches aim to understand better neurological diseases and their different impacts on the patients.
Within LLUI, the Therapy Sciences group - founded in 2023 - focuses on neuro-rehabilitation through the development of tele and novel rehabilitation technologies. [5] Indeed, high-dose, high-intensity movement therapy of patients is encouraged to promote the recovery of autonomy in Activities of Daily Living (ADL), and traditional occupational therapy could benefit the support of assistive devices enabling patients to engage in more autonomous rehabilitation. [6]

1.2 Presentation of the project

1.2.1 Context of the project

Two of the key components that strongly impact the recovery of patients seen in the clinic are at the core of the focus here. The first is trunk control. In fact, research has not only shown a strong correlation between trunk control and functional independence, but also identified it as a strong predictor of both motor and functional outcomes. The second is the motivation of patients, which can be negatively affected by the complexity and duration of their recovery. [7]

The following project, called AdaptVR, emerged from a collaborative effort between the Therapy Sciences Lab and the Zurich University of Applied Sciences (ZHAW). It consists of the development of a serious Reaching Game on a Virtual Reality (VR) headset. The game's objective is twofold. First, to address the aforementioned factors by leveraging gamification through a Virtual Reality platform to support patient engagement in rehabilitation, and by integrating motor learning principles on this same platform to encourage high-quality movement therapy. Secondly, to explore the potential of VR in this context. Various projects linked to AdaptVR are detailed in Appendix 5.2.2.

Indeed, systematic reviews have revealed evidence for the statistically significant improvement in clinical outcomes from VR in comparison to conventional therapy; appearing to provide task-specific scenarios which can be easily adapted to patient's specific needs. [8]

In the case of trunk control, those reviews highlighted the improvement on balance and postural control allowed by the use of different Virtual Reality games during stroke rehabilitation, and even its superiority over conventional therapy alone.

In the case of motivation, research in motor learning and neuro-rehabilitation emphasizes the role of feedback mechanisms and adaptive strategies in optimizing patient outcomes. Studies have shown that timely feedback - both intrinsic and extrinsic - reinforces successful actions and enhances sensitivity to movement errors. It is the integration of these visual and auditory cues within VR-based exercises that can significantly boost patient adherence by highlighting progress and delivering rewards upon successful task completion. [9]

This sets the base and guiding principle for the development of the project. The Reaching Game should be an immersive Virtual Reality game, that relies on motor learning principles such as explicit and intrinsic feedback to increase the patient's implication in their own therapy, and encourage them to train their trunk and balance.

1.2.2 Presentation of the game

The game is currently being developed on the software Unity, and tested on the Meta Quest 3 Virtual Reality headset. This device is commonly used for home entertainment and accessible to the general public. This makes it particularly relevant, as the game will already be accessible to a broader population.

In the clinical context, AdaptVR includes a therapeutical chair called T-Chair (cf. 5.2.2), developed at ZHAW. Thus, this chair will not be part of the interests of this report, but it can be noted that the game has for now been developed to be played while sitting.

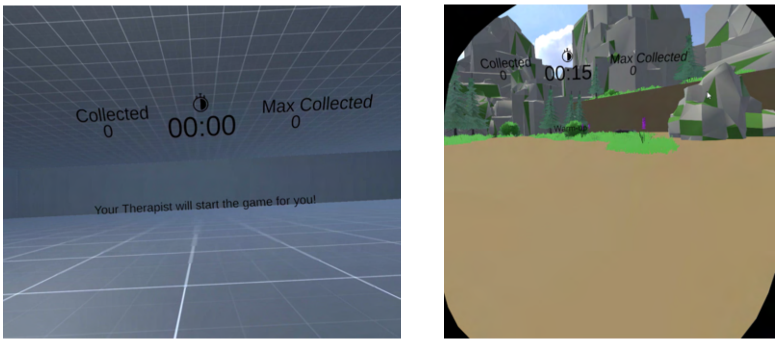
To start training, the patient will have to sit, and put on the VR headset. If they use the device in autonomy, they can control the settings of the games. If they are supervised by a therapist, the latter would be provided a tablet to control the settings, and decide when to start, pause or finish the game for instance. The set-up is depicted in Figure 1.1.

(a) Sitting position and VR headset

(b) Therapist control interface

Figure 1.1: Patient setup (a) and therapist interface (b)

From the outset, the patient is immersed in an engaging environment, in which they can see their hands moving in real time. Several virtual environments have been developed to stimulate them, such as a traditional Japanese room, or a forest, which can be chosen with the tablet. A plain environment called "Grey room" has also been designed to be as simple as possible, in order to avoid overwhelming sensitive patients with an excess of distractions. Examples of existing environments are shown in Figure 1.2.



(a) Grey room environment

(b) Forest environment

Figure 1.2: Examples of virtual environments available in the Reaching Game

Once the game is started, objects appear successively around the patient, who is encouraged by a Voice Assistant to activate their trunk to reach for them. The types of collectibles, paired up with the environment chosen, are also designed to be engaging and increase the patient's adherence: for instance sushi in the Japanese Room environment (cf. Figure 1.3).

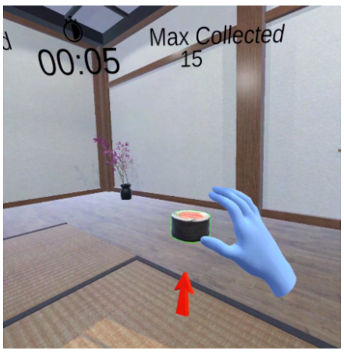


Figure 1.3: Visual of in-game sushi collectibles

The aim for the patient is, in a limited amount of time chosen in the settings (from 15 seconds), to reach the collectibles appearing gradually further and further away. For the time the user has the headset on, they can see the display shown in Figure 1.4. On this figure:
1: timer counting down the time left to play
2: amount of objects collected during the current game
3: maximum amount of objects collected by the user in one game
4: current instructions for the user to follow.

Figure 1.4: Visual of the display seen by the user

Using this link, a video of the game can help visualize better the user point of view.

1.3 Research question

1.3.1 Motivation of the internship

The objective of this internship is to develop the game into a usable and useful version to be used on patients long-term. Different requirements are thus expected to be fulfilled:

1. **Usability:** The therapist should be able to make their patient try the game without any external technical support.
2. **Relevance:** The prolonged use of the game should aim to provide significant added value to the recovery and neuro-rehabilitation of the patient, by encouraging adherence in an appropriate training session. [8]
3. **Meaningfulness:** The patient, as well as their clinician, should be able to assess the performance and progress of the patient by means of the feedback provided in the game.

Those three requirements set the path for the work and research done during this internship, guided by the following research question:
What are the key features that will make this serious game relevant, usable and meaningful, both to patients and therapists, in the context of stroke rehabilitation?
The six allowed months to answer this research question were distributed to find the aforementioned key features, set the priority on the most crucial ones, implement them, and observe how they meet the user requirements. The detailed Gantt chart of the internship is available in appendix 5.2.2.

This internship has been motivated around a clear deadline: the schedule of an on-site testing in the Rehabilitation Center of Valens, Switzerland in September 2025. During this testing, some headsets will be provided to therapists, who should be able to use the game during therapy with their patients. The presented work leads the path to meet the requirements before this delivery date.

1.3.2 Plan of report

To answer this research question, this report will first put under increased scrutiny the preliminary work done to define the choice of key features to implement: set the methodology of the project, and understand the state-of-the-art of the Reaching Game. Its code architecture and the results given by previous testing will be examined.
Secondly, the detailed process of implementing the various chosen features will be described, from a software, and then from a hardware point of view.
The usability testing process will then be itemized, from its organization to the results obtained and their analysis.
Finally, an outlook on the project, its limitations and next steps will be proposed.

2

Preliminary work: state-of-the-art of the project

The research question has been established with the deadline in mind: the on-site testing in Valens. "What are the key features that will make this serious game relevant, usable and meaningful, both to patients and therapists, in the context of stroke rehabilitation?"
To understand fully how to be able to answer it, an important preliminary work is necessary, to comprehend the state-of-the-art of the AdaptVR project. First, the game will be studied from the user experience, then the code perspective. Secondly, the study design and previous results obtained from testing sessions will highlight the point of advancement of the game's development, and the new challenges faced. In addition, a literature review will allow priorities to be set on the most crucial features to meet the objectives of the research question.

2.1 Methodology

Under the supervision of a research engineer, the AdaptVR project functions in iteration phases of six months each: an intern comes, discovers the Reaching Game and the state-of-the-art of the project, defines the limitations and priorities of the game, implements the major features to add, organizes testing sessions to gather user feedback and check the usability, and defines the new limitations and refinements required for the next iteration phase.
The renewing of students every semester brings periodically a new perspective on the Reaching Game and its usability. It enables the assimilation of a critical external view on the choices made previously, while the supervision of the research engineer keeps the development focus under a common thread and vision, centered around the integration of motor learning principles in a usable and useful game for the training of trunk control.
The proximity with the Cereneo clinic allows a tight collaboration with clinicians and their patients. Thus, once a version of the game has been fully implemented and tested with healthy participants, therapists put the AdaptVR team in touch with eligible patients. Patients willing to test the Reaching Game, and potentially benefiting of the training for their neuro-rehabilitation are selected.
This internship constitutes the third iteration phase of development.

2.1.1 Methodology of implementation

The entire implementation and development work has been carried out using the Unity software, in C#. This approach allows the project to be directed from both a software and hardware perspective.
After identifying the necessary additions and corrections through an in-depth analysis of the project and a literature review, the development phase began. The process started with soft-

ware coding, followed by several hardware-oriented optimizations.
Throughout software development, each implementation was regularly tested using the headset. Unity allows developers to connect the headset to the computer and use "Play Mode" to test their code in real time, by using the computer's processors. This feature enables rapid validation of functionality. Once a feature is fully implemented and confirmed to work correctly in play mode, a new build can be deployed to the headset for complete testing by letting the headset independently run the code.
As it will be discussed in Section 3.2, hardware-related features cannot be fully tested in Play Mode, since hardware-specific settings or behaviors - such as VR device configuration or performance optimizations - are only properly applied when the application is computed by the headset. [10]

2.1.2 Study design

2.1.2.1 Testers

Once all planned features were implemented and functioning, they were evaluated through a series of testing sessions. The initial testers were healthy participants, most of whom were unfamiliar with clinical environments. This step ensured that the implementations were intuitive and accessible for users with no prior experience with the game. In roughly half of cases, they had no experience with VR headsets at all.
After this initial validation, the updated version of the game was presented to therapists and patients. This group provided more informed and critical feedback, as they possess both theoretical and practical knowledge of neuro-rehabilitation.
The first priority was to confirm that the new features were usable. Subsequently, their usefulness was assessed, and more in-depth insights were gathered.

2.1.2.2 Testing procedure

An epitome of a testing session will be presented in Section 4.1, following the description of the features that were actually tested (see Chapter 3).
In general, each testing session lasted approximately one hour. For the first 40 minutes, participants explored and interacted with the game, with particular features being highlighted to them. During the remaining time, they completed a usability questionnaire in the form of a semi-structured interview, along with the System Usability Scale (SUS).

- **System Usability Scale**
  The usability of a system is a broad concept that encompasses multiple aspects of user interaction. According to ISO 9241-11:2018 [11], it is characterized by "effectiveness (the ability of users to complete tasks using the system, and the quality of the output of those tasks), efficiency (the level of resource consumed in performing tasks) and satisfaction (users' subjective reactions to using the system)". The System Usability Scale (SUS) provides a standardized and global measure of usability. It relies on statements about the product, which the tester will rate on a scale from 1 ("strongly disagree") to 5 ("strongly agree"). An equation then scores the usability on a scale from 0 to 100, providing a quick

measure of perceived ease of use, and overall satisfaction. [12] A detailed presentation of the SUS questions and its score calculation can be found in Appendix 5.2.2.

- **Semi-structured interview**
  Semi-structured interviews are commonly used in qualitative research, as in the case of this study. They rely on a flexible interview guide with open-ended questions, which helps orient participants toward specific topics under investigation while maintaining a conversational, collaborative format. This approach enables the collection of rich, detailed feedback, including participants' personal opinions and suggestions on inherently subjective matters. [13]
  The iterative nature of the project aligns well with this method: at each iteration phase, the interview can be completed and adapted to the latest version of the system and its newly added features.
  A variety of question types are employed, among which:

  – Binary questions, such as yes/no or two-option questions, typically followed by space to explain their choice.
    Example: "Were you more focused on visual or auditory input ? Why ?", with the choice between visual, auditory, or both.

  – Descriptive qualitative questions, where participants choose from a list of adjectives to describe a specific feature.
    Example: "What words would you use to describe the score displayed ?", with a list of adjectives proposed, the possibility to select one or more, or "other".

  – Rating scale questions, asking participants to evaluate a feature on a numerical scale.
    Example: "On a scale of 1 to 5, how do you think the voice assistant was (1 being not enough present and 5 being way too frequent, 3 the right amount) ?"

  – Open-ended questions, inviting participants to freely share additional suggestions or ideas.
    Example: "Do you have any other idea that we could design as an environment ?"

In the present context, the SUS offers a general measure of usability, whereas the semi-structured interview provides more specific insights into the Reaching Game.

2.2 Architecture of the game

Before diving deeper into the results of the iteration phase preceding the one introduced here, it is important to examine more precisely the game, its internal structure and the connection between each of its steps. The version presented here dates January 2025. The work of this internship comes directly on top of this version.
As mentioned in Section 1.2.2, it is strongly encouraged, using this link, to watch the video of the game, which will help picture the user point of view.

2.2.1 Game flow overview

On the software Unity - used as platform for the development of the Reaching Game, a game is organized in scenes, that articulate the different steps of the game. In this case, there are 5 scenes, one for each phase the patient goes through while playing. The game flow is illustrated on the state machine of Figure 2.1.

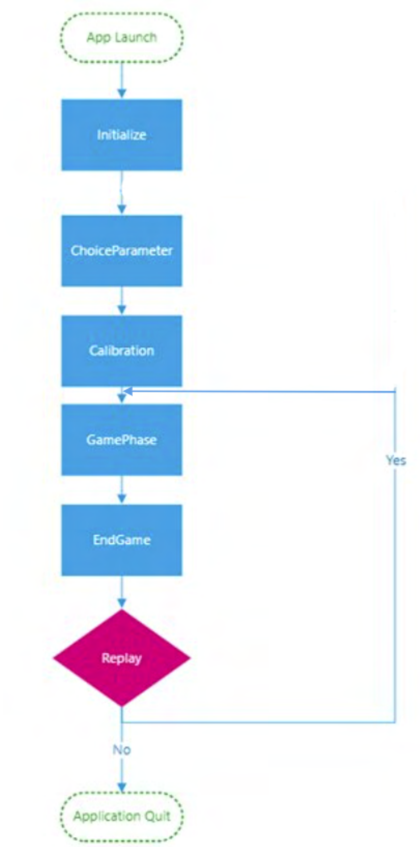


Figure 2.1: State machine of game flow

1. Initialization scene

When the patient puts on the headset, they land in an immersive environment (cf. Section 1.2.2). To enter the game, they then have to use a hand scanner, which is depicted in Figure 2.2.

Figure 2.2: Visual of the handscanner

As one turns their head, the hand scanner platform follows its movement. Once the user is ready, they must put their hand on the platform, while looking straight ahead, towards the red target also shown in Figure 2.2. They will have to hold this position for 4 seconds to complete this step. The purpose of the hand scanner phase is threefold. First, it helps users familiarize with the VR environment. They see what their hands look like in Virtual Reality and intuitively visually explore their surroundings. Second, it ensures that the patient is in the right position. They must sit upright enough for their head to be straight, and be able to face the red target ahead. It also encourages them to sit comfortably, so that they can hold this position with their hand on the hand scanner platform while looking in front of them instead of at their hand. Finally, this allows the code to pick up the patient's position in the 360-degree rotation. The rest of the game interface will be centered on this position.

2. ChoiceParameter scene

If the therapist is using the tablet (cf. Section 1.2.2), this scene allows them to choose the settings of the game (e.g. the duration). If the user is playing autonomously, they control the settings and a table appears in front of them so they can choose, and start the game themselves.

3. Calibration scene

Once the initialization step is cleared, the previously captured position is used to center the calibration scene. As illustrated by Figure 2.3, a cloud of red dots appears in front of the patient. The Voice Assistant instructs them to try to reach as many of those red dots as possible.

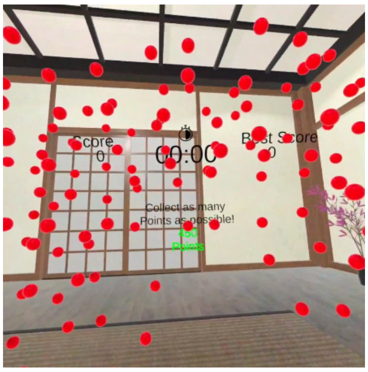


Figure 2.3: Visual of the calibration scene

From the user's perspective, this phase introduces the reaching task in Virtual Reality.
From a software perspective, it provides valuable information about the patient's reachable range. This range depends on individual body proportions but, more significantly on the patient's current physical condition and stage of neuro-rehabilitation. Impaired patients might face difficulties reaching in certain areas of space, often due to a lack of trunk control. [7]

4. Game phase scene

The core of the game has already been presented in Section 1.2.2. A complete session for now

includes ten difficulty levels: the patient starts at level 0, and evolves through the following ones based on their performance. The difficulty is increased by the gradual distance between the user and the placement of each collectible.
Only the very first level comprises two stages, the warm-up and the level itself.

- Warm-up phase
  Before the countdown starts, the Voice Assistant asks the patient to train and reach five collectibles for practice. This is useful for the patient to understand how to play. Meanwhile, the code computes the mean amount of time taken by the patient to collect each object, in other words the average amount of seconds between the moment the collectible appears and the moment it disappears after it is reached. This mean amount of time is saved as the "allowed time", and will be use for score calculation in 5. End Game scene.

- Game phase
  After the warm-up phase in the case of the first level, and when the replay button is pressed in the case of the other levels, the countdown starts. For the time given, the patient must reach as many objects as possible. If a collectible appears out of the reachable range for the patient, it disappears after six seconds. This avoids to block the game completely and keep the training going, and highlights which spatial areas the patient has difficulty to reach.

5. End Game scene

Once the countdown is over, the End Game scene starts. The display appearing in front of the player can be observed on Figure 2.4. On it, it can be noticed a score in percentage appears. This score is calculated based on two factors:

1. For 80%, the score depends on the Success Rate (SR): the amount of collectibles reached relative to the total amount of collectibles spawned during the level.

2. For 20%, the score depends on the Time Fraction (TF): the average time taken to reach each collectible during the level, relative to the allowed time, the average time taken to reach each collectible during the warm-up (cf. 4. Game phase scene).

This results in the following equation called Performance Function (PF):

$$PF = 100 \times (0.8 \cdot SR + 0.2 \cdot (1 - TF)) \tag{2.1}$$

where:

- $\text{SR} = \dfrac{\text{total grasped}}{\text{total spawned}}$

- $\text{TF} = \dfrac{\text{average time}}{\text{allowed time}}$

An adaptive difficulty algorithm has been implemented so that:

- if PF $<$ 60%, the level of difficulty of the next game is decreased

- if PF > 80%, the level of difficulty of the next game is increased
- else, the level of difficulty remains the same for the next game.

Figure 2.4: Visual of the End Game scene

2.2.2 Architecture of the code

The architecture of the code is quite similar to the game flow the user can witness when playing. It is divided into scenes, that each contain a main named manager, and codes referring to different objects in the scene named GameObjects (cf. Figure 2.5). For instance, in Calibration scene, the different GameObjects are the cloud of red dots to reach to calibrate, with the red dots themselves("CloudInit"), the sector where this cloud is placed ("SectorManager"), the code that checks what positions the user is able to reach ("HandTracker"). In addition, the "ReadyButton" is the button pressed by the player once they have reached all the red dots they could. All these GameObjects and scripts are coordinated by the main, called "SceneManager".

Figure 2.5: Scenes with their Game Objects of the Unity Project

One slight difference with the visible game flow (cf. Section 2.2.1), is the existence of an additional scene called Main Scene in the architecture of the code. While all the other scenes are only active when the patient is actually in them, the main scene is always active. It is loaded as the application is launched, and controls the launching of the other scene as showed in the Figure 2.6.

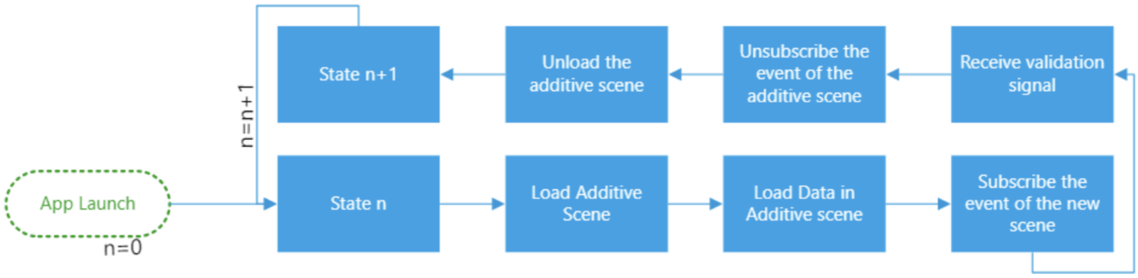


Figure 2.6: Load scene process

An events set up is used in the extra scenes to handle transitions. The Main Scene listens for these events, and when one of the added scenes is marked as done (for instance when the button Start is played after the 2. ChoiceParameter scene), it sends out a signal. The Main Scene catches that signal, unloads the current scene and moves on to the next one. This same setup works for every stage.

It is also used in the code as the manager of features that are constant in the game, e.g. the choice of environment and the Voice Assistant language and function that provides instructions and encouragements during the different scenes. These features, in addition to the performance function and the adaptive difficulty algorithm (cf. 5. End Game scene), happen to be part of an effort to integrate motor learning principles, as explained in the Section 1.2.1.

2.3 Choice of priority and road-map

After studying the architecture of the game, it is essential to study the results of the testing sessions gained from the version studied. Only this study of the full state-of-the-art permits understanding of the challenges faced. Once they have been understood, a literature review allows for selection of priorities and how to fix them.

2.3.1 Previous testing results

The version of the game presented in the previous sections was tested on different occasions by 20 healthy participants, therapists, and neuro-rehabilitation patients. These sessions revealed encouraging results: the Reaching Game was appreciated by the different groups of participants, and marked a score SUS of 72.73, evaluating the Reaching Game's usability as not only acceptable, but also good (cf. 5.2.2).

Several features on which the testers were interrogated showed a successful implementation. For instance, when asked to choose between a list of adjectives to describe the Voice Assistant, most participants picked meliorative ones, as can be seen in the graph Figure 2.7. Some patients did find it overwhelming, mostly complaining of the repetitiveness of certain encouragement comments.

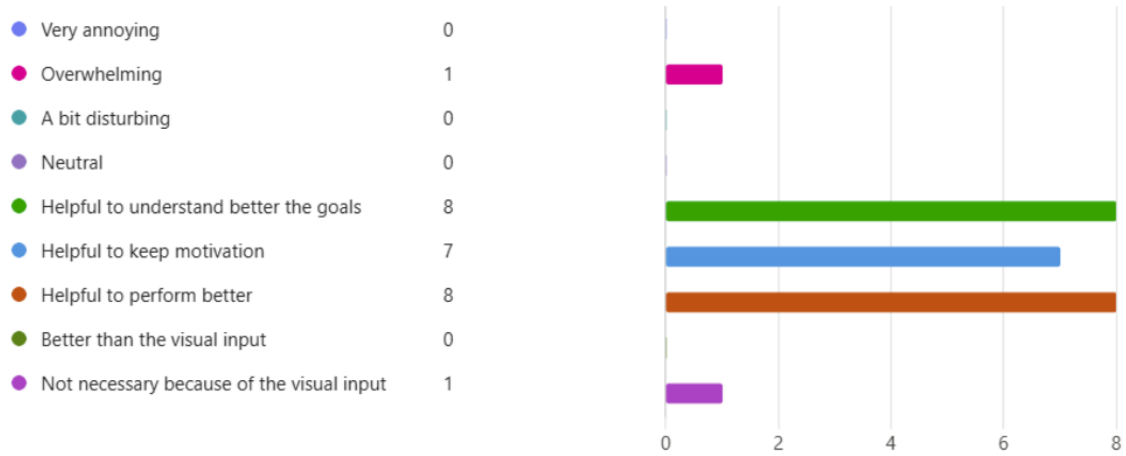


Figure 2.7: Words used by participants to describe the voice assistant

Similarly, participants judged the adaptive difficulty algorithm was operating well enough and adapted well to their performance, as they were asked "On a scale from 1 to 5, how much did you feel the difficulty increasing or decreasing across levels ?" (cf. Figure 2.8). The average rating given by the participants here conveys a balance between significant but still subtle increments, that provide a feeling of progress, while staying within the reach of the user.

Figure 2.8: Average score given by participants on how much they feel the difficulty increments

However, it also highlighted the limitations of certain features, and the lack of others.

- The initialization phase, as detailed in Section 2.2.1 requires the user to simultaneously hold their hand directly in front of them, on the handscanner platform (cf. Figure 2.2) and look straight ahead for four seconds. This counterintuitive posture, though just used to calibrate the user's position, caused difficulty for patients, and even some healthy participants testing the Reaching Game. Despite the instructions provided both visually and by the Voice Assistant, some participants simply did not understand what was expected. Others, in particular patients with motor impairments, struggled to maintain the position for the required four seconds.
  This difficulty likely contributed to lower the SUS scores. Indeed, during both game-play and follow-up discussions, many participants expressed frustration with this counterintu-

itive initialization step. This challenges the usability of the system.

- During the previous iteration phase, the Performance Function (PF) was developed and displayed directly as a percentage at the end of each level (cf. section 2.2.1). However, as shown in Figure 2.9, if a large part of the testers described the score display as motivating and meaningful, almost half thought it was hard to understand. It can be noted that in "other", some participants chose to describe the percentage as "confusing". Because the score did not allow the users to really understand their performance, this challenges the meaningfulness of the system.

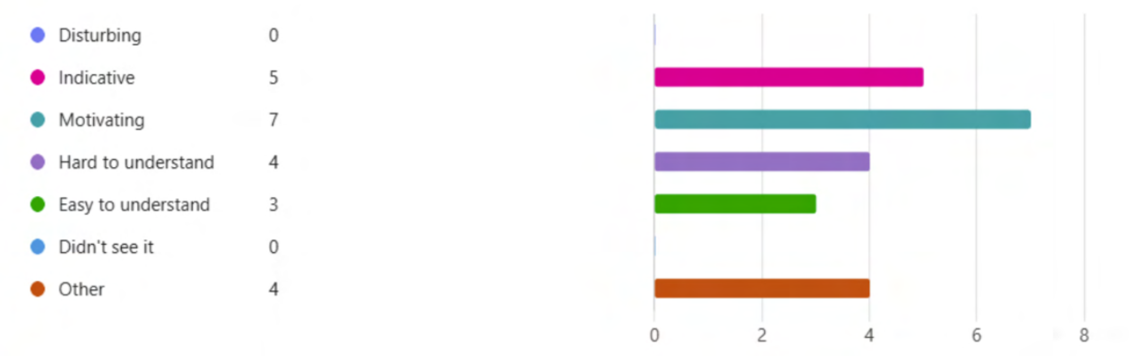


Figure 2.9: Participant feedback on the score display

- A closer analysis of the SUS responses reveals that the item significantly lowering the overall score is the statement: "I think that I would like to use this system frequently." Notably, 45.5% of participants either strongly disagreed, disagreed, or were neutral (see Appendix 5.2.2).
  This comes in contradiction with the fact most participants reported to have appreciated the game. One can thus question the features implemented to trigger the motivation and adherence of the user. Since one of the primary goals of the AdaptVR project is to boost motivation and adherence among neuro-rehabilitation patients, this discrepancy challenges the relevance of the Reaching Game itself.

- Finally, a major possible limitation of the game is the quality of images. If there is no question about it in the semi-interview, nor traces of mentions of it by participants, this has definitely been noticed by the developers. Indeed, it has been remarked that the edges of the virtual objects can shiver. This troubles the quality of the user experience once they notice it, and cause some noticeable discomfort, as several VR users testify *. Thus, this can challenge the usability of the system, but also decrease the motivation to play, and thus once again its relevance.
  It should be noted that this phenomenon is only noticeable when playing, and could not be shown in the videos of the game (link).

Once these major limitations of the AdaptVR have been established, solutions and priorities shall be set, using a literature search.

2.3.2 Literature work

To do so, the literature search started by a benchmarking of other video games.
First, neuro-rehabilitation games were studied. Indeed, other VR serious games exist for stroke rehabilitation. [14] [15] [16] [17] These games all differentiate from the AdaptVR project, as they focus on other aspects of physical therapy, like limbs training. However, as any serious game, they all have in common that one major aim of their use would be to spark motivation of neuro-rehabilitation patients.
Indeed, to be valuable to the user, serious games should rely on at least two of the three following "worlds": the world of play, the world of meaning, and the world of reality. This means that it should provide a playful experience to spark motivation, have a meaningful goal to spark focus and adherence, and/or join reality to bring real knowledge or training. [18]
In the context of therapy, it can be interesting to draw the patients out of the world of reality. Indeed, therapists observed that when immersed in another environment, patients can forget their disabilities or difficulties, and perform better than usual. Consequently, this Reaching Game should rely mostly on the worlds of play and meaning.
In this sense, some non serious games that find an audience among similar age groups as stroke patients were studied.

World of play: gamification and feedback

To rely on the world of play means that gamification principles should be added. This means that the training should be disguised as a game.
Notably, games such as "Candy Crush" offer a wealth of feedback mechanisms: visual effects, sounds, haptic responses (vibrations), verbal reinforcements, and frequent reward systems including coins, bonuses, and level-ups. This rich feedback ecosystem has been shown to be particularly engaging for users, greatly increasing their adherence and motivation to play. [19]
Indeed, games that provide such multi-sensory feedback would tend to drive motivation and increase return rates. Similarly, Nintendo Wii games have demonstrated success in neuro-rehabilitation settings. They also offer auditory, visual, and haptic feedback through their remotes, contributing to user immersion and sustained use. [20]
However, the Reaching Game aims for a different purpose than distraction: neuro-rehabilitation. This is why it also relies on another World:

World of Meaning: setting of objectives

Games that incorporate clear goals and representation of progress can create strong user identification and immersion.
In certain Wii games, players are represented by expressive avatars that react to success or failure, enhancing player attachment and emotional engagement. [20]
One significant gap in many VR rehabilitation games, however, is the limited use of score display. Yet, the presence of a score can set short and long term objectives, which are essential for motivating users, especially in clinical settings, where long term adherence is crucial. This important aspect should not be ignored while developing the Reaching Game.
Research has shown that certain types of score displays can significantly affect motivation. One study found that verbal feedback and tangible rewards like coins were the most effective to en-

courage the players. [21]
In Candy Crush, progression is structured around both immediate and long-term goals. Similarly, rehabilitation success depends on frequent, consistent training. Designing a system that encourages patients to return daily is key. However, this requires tailored patient profiling, which can be complex in a limited amount of time as in the present case. As a compromise, the game could propose objectives on a shorter term, renewed at each session.
Nevertheless, despite the effectiveness of multiplying the types of feedback, as done in Candy Crush, this method can be criticized for bringing about complexity and an overload of signals. [19]. This raises an important consideration: simplicity is key to be understood by all users, especially for rehabilitation games. Indeed, studies on educational serious games have shown that the score display directly influences the quality of the next performance. The user will want to play better to receive the reward they were promised. [22].

Another important factor that can negatively affect user motivation in VR environments is motion sickness, also known as cybersickness. This condition, characterized by symptoms such as nausea, dizziness, and disorientation, [23] is attributed to diverse causes. Different hypothesis include low image quality, lags, low frame rates (FPS), [24] or gender dependency [25].
To mitigate this, one approach to consider would be the use of mixed reality, which could help acclimate patients to the VR environment in a more gradual and less overwhelming way. This could be particularly beneficial for users unfamiliar with immersive systems. However, a technical review revealed that mixed reality features are still under active development and currently incompatible with the version of Unity used in this project. [10] Thus, mixed reality implementation would require more time than this internship offers.
Instead, an actionable and immediate solution is to enhance visual fidelity and performance, which remains a well-established factor in reducing motion sickness. Improving rendering quality, increasing frame rates, and minimizing latency are all feasible within the current development environment and can significantly enhance user comfort and motivation.

2.3.3 Final choice

Keeping in mind the final aim to ensure the Reaching Game would be increasingly relevant, usable and meaningful, this literature search highlighted which limitation fixes and added features could help reach that goal. The finality of this work is to build a road map containing the key implementations which the project would benefit of, while being doable in a limited period of six months.
In this sense, the road map illustrated on Figure 2.10 has been chosen. As it will be detailed, this internship consisted of a preliminary work phase, which has just been presented, followed by a software development phase during which the initialization phase was simplified, and the score display reworked. Then, some optimizations on the quality of image were reviewed through some hardware development, and finally, the new implementations were tested during sessions, and a refinement of the features based on the results obtained was started.

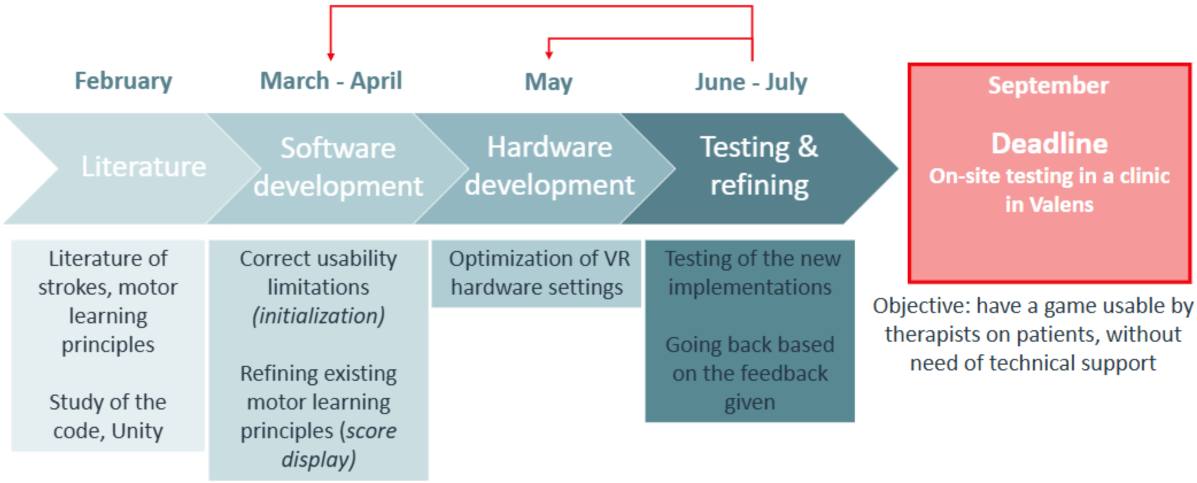


Figure 2.10: Road map of the presented master thesis

3

Development

The aim of this internship is to address the following research question: "What are the key features that will make this serious game relevant, usable and meaningful, both to patients and therapists, in the context of stroke rehabilitation ?"
Now that the key challenges to tackle in the project have been emphasized, the following section outlines the processes implemented to mitigate them, first from a software, then hardware perspective. As explained in the Methodology Section 2.1.1, Unity enables the control of both software logic and hardware integration within a single development environment.

3.1 Software development

It was shown in the previous sections (cf. Section 2.3), that the complexity of the initialization phase reduces the usability of the Reaching Game, while the lack of score display and objective constitute an obstacle to the motivation and will to play of the users. As patients' adherence and usability are the whole reason for being of the Reaching Game, it is important to correct those limitations.

3.1.1 Usability corrections

As explained in the Section 2.3.1, the initialization phase (cf. Section 2.2.1) is counterintuitive because it requires holding a position of the hand and looking in another place. In addition of the difficulty of use, this phase is situated at the very beginning of the game flow. This means that even before starting to play, the user can be frustrated to struggle passing a step, which would then demotivate them, and decrease the perceived usability of the Reaching Game. For a reminder of Section 2.2.1, this phase's purpose is to:

- Familiarize the user with the VR environment.
- Ensure they are in the right position: they should sit up and have their head as straight as possible.
- Pick up their position in the 360-degrees rotation within the code, to center the rest of the game around it.

It can be noted that if the user struggles to understand what they should do and pass this step, it also becomes less efficient to familiarize them to VR.
The initialization scene was changed to increase its intuitiveness and simplicity, while still making sure the user is allowed to explore the VR environment, they are in an appropriate position to start playing, and their rotation is collected.
Practically, this means that the system should require for the user to sit upright and look in front of them. Only once one can make sure they are in that position, the 360-degree rotation

of the trunk and head (supposedly henceforth aligned) can be collected, and the game started. The choice of implementation was thus to delete the hand scanner of the to-date initialization phase, presented in the State-of-the-art, Section 2.2.1. Instead, the new initialization would be such that: the user is asked to sit up and look straight ahead. Once they kept that position for a few seconds, a simple "Start" button appears in front of them, at a fixed position. They can start the game whenever they are ready, and the rest of the game will be centered around the position of the button.
The flow chart of the code monitoring this phase is depicted in Figure 3.1.

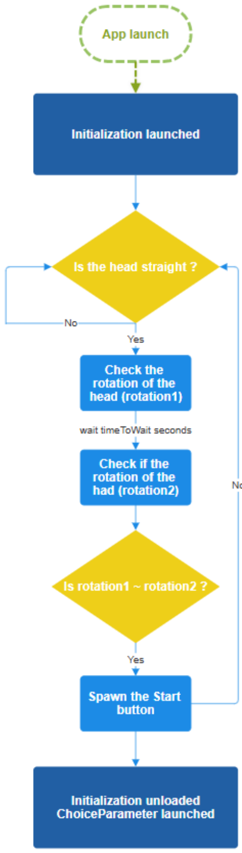


Figure 3.1: State machine of the script controlling the initialization process

The position of the head is actually checked through the position of the camera, captured by sensors internal to the headset. As the headset is fixed on the head, it will be assumed that the position of the head corresponds to the position detected by the sensors of the headset.
The script proceeds by checking if the position of the head is approximately perpendicular to the x and z axis (cf. Figure 3.2), with an angle tolerance of 8 degrees.
The system first checks the rotation (in rotation1) of the camera (and thus the head) around the y-axis. It then waits for a duration defined by timeToWait (in seconds) and checks the rotation again (in rotation2). If the two measurements differ by no more than ±5 degrees, the Start button is spawned in front of the user, approximately at mid-trunk level. If the difference exceeds this threshold, the system re-evaluates the head's position along the x and z-axes, and the timeToWait countdown restarts.

Figure 3.2: Reference axes for head position tracking

Once the Start button is pressed, the Initalization scene is unloaded and the ChoiceParameter scene is loaded, respectively to the process shown in Figure 2.6. To have a more representative idea of what this means for the user, it can be noted that the maximum range of motion of human head, for healthy participants, is approximately [26]:

- For the x-axis: 60 degrees for the neck extension and 50 degrees for the neck flexion.
- For the z-axis: 45 degrees for the lateral bending.
- For the y-axis: 80 degrees for the neck rotation.

The determination of timeToWait was based on the need of a balance between a position that could be easily held for this precise amount of time, and a Start button that should not appear too quickly, for instance while the user is still looking around while exploring the VR environment. It was thus fixed at 5 seconds. The Figure 3.3 shows the resulting display of this implementation.

3.1.2 Enhancement of meaningfulness

It was seen in the previous testing results of Section 2.3.1, that the score display as a simple posting of the PF in percents (cf. equation 2.1) was judged as "hard to understand" by a many participants (cf. Figure 2.9). This causes a decrease in the meaningfulness of the Reaching Game, both for patients and therapists, as it reduces their access to the good and complete comprehension of their performance.

Indeed, the score display is a major feature of every game, and constitutes a crucial feedback for the player, as it [27]:

1. Motivates them to keep playing, which is one of the main purpose of the Reaching Game (cf. Section 1.2.1)
2. Directly influences the next performance of the user, which is also extremely important, since the final goal is for the patients to get better, meaning enhance their performance.

Three requirements for an efficient score display were extracted during the benchmarking conducted in the literature search, detailed in Section 2.3.2:

1. **Be clear, understandable by everyone, intuitive**
   It can be noted that the mean age of stroke patients, and thus of the target audience here, is 74 years old. [2]

2. **Be indicative**
   It should constitute a good indicator for the therapist and patient of the latter's performance.

3. **Constitute a reward**
   To be a valuable element of motivation, it should provide the patient with a feeling of accomplishment (cf. Section 2.3.2).

It is perfectly translated by the distribution of Figure 2.9 that either the user understands the percentage, either they are not sensitive to it, and do not find it clear. It should be noted that the PF formula 2.1 is never given to the user within the game: they are never given the information of how their score was calculated. One hypothesis is that, because most of testers were healthy participants with scientific background and therapists, they were familiar to figures and percentages, and thus could understand it with more ease. In this sense, it would also be logical to assume that the Performance Function (PF) directly displayed as a percentage is indicative to therapists. Most of those who tested the game did confirm this.
Therefore, the PF should still be given as a percentage, but completed with a more universal and understandable-by-everyone posting. Of course, one direct solution is - like in many games - an illustrative representation of the score.
Two options were thereby examined. The first would be a stars ranking, with one, two or three stars appearing alongside the PF. The second would be a gauge filling up with respect to the amount of percents of the PF. Both options come with benefits and drawbacks, listed in the Table 3.1.
This comparison allowed us to opt for the stars ranking. Indeed, it appeared to be less inconsistent than the gauge, that would fill up and empty out in a counterintuitive way in between each level. Moreover, the stars ranking can always constitute a reward: even if the PF is low, at least one star can appear to encourage the user. On the other hand, an almost unfilled gauge could discourage a patient that struggles, and lead to abandonment. The implementation of this display was done in two phases. First, a proof of concept was coded in a few steps:

- The design was imported as GameObject (cf. Section 2.2.2), from the Unity Asset Store. This store allows to import free or charged designs for GameObjects within a Unity project. The GameObject was placed in the EndGame scene.

- A script was attached to the GameObject, activated when the EndGame scene is loaded. The code calls the result of the PF, calculated in another script:

  - if $PF \geq 90\%$, three stars appear
  - if $PF \in [80\%, 90\%]$, two stars appear
  - else, one star appears.

  This choice was made in order to always let at least one star appear, to reward the user regardless of their performance and avoid discouragement. However, by playing continuously, they should notice that they are rewarded better if they improve their performance.

- The script positions the stars centered, in between the timer and the PF percentage display in the EndGame scene (cf. Figure 3.3b).

Once the draft was tested and discussed internally, the feature was refined, and positive feedback was added to increase its interactivity and reward value (cf. Section 2.3.2). In this way,

- an animation was added so that each star would appear successively
- feedback sound was added every time one star appears

Table 3.1: Comparison between stars ranking and gauge

Criteria	Stars Ranking	Gauge
Clarity	Clear and intuitive	Could be clearer: just a visual translation of score percentages
Consistency	Always a positive feedback	May appear inconsistent: gauge fills/unfills unpredictably between levels
Motivational Value	Functions as a reward: reinforces positive progress (cf. Section 2.3.2)	Not perceived as a reward
Indicative value	Not precise	Very precise if can be understood
Communication of Progress	Easy to understand, encourages continued effort	Can be confusing and lacks emotional engagement

3.1.3 Enhancement of relevance

In the previous testing results 2.3.1, though they appreciated the Reaching Game, testers did not express particular enthusiasm to "use the system frequently", as asked in the SUS. This challenges the very relevance of the game, as it is supposed to stimulate adherence of neuro-rehabilitation patients in their own therapy.
The literature review of Section 2.3.2 showed that long-term motivation is sparked through several ways in games, and very efficiently by setting objectives. However, setting long-term objectives within the game to users would require a personal profiling. This would mean they could create a personal profile on the game's app, which would store their advancement from one session to the other. Although this implementation is part of the global road map of this project, it is not part of this internship's, as it would be very intensive in time and work. As a consequence, a compromise was made and a system of "daily objective" was conceived, with no need for personal profiling.
The principle of this daily objective relies on the star score display implemented in the previous Section 3.1.2. The idea would be to have a certain amount of those stars to collect on one session. After each level, in the EndGame scene, a counter increments with the number of stars received based on the score. This encourages the patient to keep playing and making efforts in the training until they reach this objective.
To implement this daily objective, three features had to be coded, mainly integrated within a script called StarCounter:

1. **Adaptive algorithm**:
   The objective should adapt to the user's abilities. Indeed if it is too easy, the absence of challenge may cause boredom; if it is too hard, the unattainability of the objective could cause weariness. In both case, this would lead to a decrease of motivation. Presently, it adapts to the score obtained by the user in the first level.
   It was coded in StarsCounter, called by the StarDisplayController, in which the stars score ranking is controlled. The script checks if the level is the first. If it is the case, the objective is set with respect to the score of the first level, according to Table 3.2:

   Table 3.2: Daily objective in number of stars based on the Performance Function

Performance Function range (in %)	Objective in number of stars to collect
$[90, 95[$	20
$[80, 90[$	15
$[70, 80[$	10
$[0, 70[$	5

   Once the objective is set, it should not be modified for the rest of the game, during any of the ten levels.

2. **The cumulative counter**:
   The function of this counter would be to store the number of stars already collected, and increment it for each new star collected.
   This was also implemented in the StarsCounter script. Every time the EndGame scene is loaded, the StarsCounter script is activated too. It calls the StarDisplayController script to check how many stars are displayed. As each star appears, the counter is incremented by one.

3. **Instructions to inform and remind the patient of the objective**:
   Using the Voice Assistant (VA), and a visual display in the EndGame scene, instructions and reminders of the daily objective, its principle, the number of stars already collected and left to collect for the day are given regularly. Indeed, after the first level, the objective of stars is set, and the VA explains that one, two or three stars are distributed after each level, based on the performance. It states that "For today", there is a certain number of stars to collect. When only ten or five stars are left to collect to reach the objective, the VA reminds it and encourages the user to keep playing to reach it.
   Concurrently, during every EndGame scene, a visual counter is displayed next to the usual text. The final result is shown on Figure 3.3b.

(a) Initialization scene (b) Score display

Figure 3.3: Visual of the new implementations

For now, this implementation is just a proof of concept, and should be visually refined. It still gives a good idea of what a "daily objective" could look like with a few additional corrections and implementations.

It can be noted that indirectly, it could solve the issue of the monotony of the Voice Assistant's comments tackled in Section 2.3.1. Indeed, it replaces repetitive comments with new instructions and encouragements, and focuses the attention of the user on a different goal.

3.2 Hardware development

Eventually, after crucial issues internal to the game were addressed, more global ones should be treated. Indeed, as further detailed in the Section 2.3.2, the quality of the images could constitute a serious matter in the long term, as it may be the cause of discomfort, and might even be linked to motion sickness.

When putting on the headset, one can notice that the edges of the virtual objects, and most importantly the ones in the background, shimmer.

If users came to notice and be disturbed by these shimmering edges, it could put a stop to the smooth usage of the game. In this case, it could strongly limit, and even decrease the usability of the Reaching Game, and consequently its relevance. Unfortunately, this phenomenon is noticed only when putting on the headset, and thus could not be displayed in this report.

Fortunately, the quality of images can be monitored through Unity. Indeed, the user interface offers a control of different hardware settings that can influence the image quality.

First a description of the hardware architecture of the headset will be given, followed by the selection of major hardware settings to optimize for image quality enhancement. Finally, the cost of the changes made, in terms of power consumption for instance, will come under close scrutiny.

3.2.1 Hardware architecture

3.2.1.1 Architecture

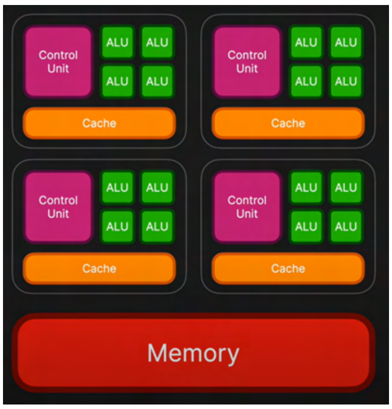
Like any computer capable of real time rendering of complex, high-resolution images, the Meta Quest 3 - used during the development of the Reaching Game, is equipped with a Central Processing Unit (CPU), but also a Graphics Processing Unit (GPU). Their respective architectures are broadly represented on Figure 3.4, and described hereunder. [28]

- The CPU is the primary component, the "brain" of a computer. It is responsible for executing all types of computation tasks necessary for the operation of the system and the applications. [29] It is composed of units named cores. Each of these cores itself contains subsections:
  - Arithmetic Logic Units (ALUs), responsible for processing tasks as calculations and logical operations, that function simultaneously,
  - The control unit, responsible for coordinating the various operations by regulating the transmission of data between the CPU and the other components of the computer system,
  - The cache, a high speed small volatile memory, responsible for temporary storage of data.

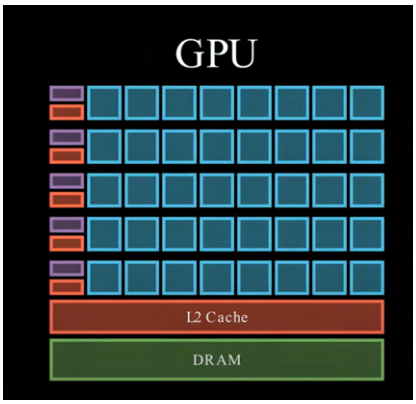
  Each core of the CPU treats the computations sequentially and fast, and functions independently from the others. Thus the cores can function in parallel.

- On the other hand, GPU's were invented to process images, where each pixel demands its own computation operations (based on its individual color, light intensity, texture). This requires the ability to do a bigger quantity of less demanding, more repetitive computations in parallel, as an image contains thousands of pixels. A GPU is composed of [30]:
  - Threads of Arithmetic Logic Units (ALUs) too, much more lightweight and simplistic than the CPU's,
  - The control unit, functioning under a "Single Instruction, Multiple Data" (SIMD) model, responsible for sending the same instruction across multiple data points,
  - A cache too.

  The GPU is the processor of images in the headset. The headset works like any other screen: it displays a certain amount of images, called frames, every second. The more images every second, the more the video seems fluid.



(a) [28]



(b) [30]

Figure 3.4: CPU (a) and GPU (b) simplified architectures

The Table 3.3 summarizes the differences between CPU's and GPU's, their modes of operation and purposes. Here, the latency is the delay between an instruction and the beginning of its processing. The throughput is the amount of data that can be processed per unit of time.

The VR headset used during the development of the Reaching Game is a Meta Quest 3. Its technical documentation states [31] it is equipped with a Qualcomm Snapdragon XR2 Gen 2 chip [32]. On it are integrated both an eight-core CPU, and an Adreno 740 GPU. [33]

Table 3.3: Comparison between CPU and GPU architectures

Category	CPU	GPU
Function	General-purpose processor that handles most of the computer's core tasks	Specialized processor designed for massively parallel operations
Processing	Executes tasks sequentially (serial execution)	Executes tasks concurrently (parallel execution)
Design	Fewer, more powerful and complex cores	Many simpler, lower-power cores optimized for parallel workloads
Emphasis	Low latency and quick response time	High throughput and efficient parallelism

3.2.1.2 Performance equations

The process described in Appendix 5.2.2 obtains the equation 3.1, which links the frame rate FPS to the clock frequency of the GPU f_{GPU}, the number of pixels on each of these frames P, the cost C in number of operations required to render each of these pixels.

$$\frac{1}{\text{FPS}} \propto P \cdot C \cdot t_{\text{GPU}} = \frac{P \cdot C}{f_{\text{GPU}}} \tag{3.1}$$

with:

- FPS: the frame rate, framing frequency, or number of Frames Per Seconds the GPU can process
- P: the number of pixels per frame
- C: the average Cost in number of cycles needed to render each pixel
- t_{GPU}: the clock cycle time of the GPU, or duration of a clock cycle
- $\frac{1}{t_{\text{GPU}}} = f_{\text{GPU}}$: the clock frequency of the GPU

3.2.2 Possible optimizations

The GPU is the processor responsible of the graphics. Thus, optimizing its performance metrics, listed in the previous Section 3.2.1.2, should directly optimize the quality of the images. The changes were made with the help of the Unity documentation. [10]

1. Frame rate FPS

The most obvious parameter to change to increase the quality of images would be the frame rate FPS. Indeed, processing more images every second would make the video look smoother. By default, it is set to 72 Hz, but can be changed to 60, 90, or 120 Hz through Unity. To start, increasing the FPS to 90 Hz was tried out.

2. Eyes texture resolution Scale S

The number of pixels P appearing on each frame is also a variable which can be monitored from Unity. Increasing P would automatically make each frame more precise and appear "sharper", rendering a higher resolution. This number depends on a factor called Eyes texture resolution S, as shown through equation 3.2:

$$P = 2WHS^2 \tag{3.2}$$

where:

- P: number of pixels per frame
- $W = 1680$: width of each frame (in pixels)
- $H = 1760$: height of each frame (in pixels)
- S: eyes texture resolution scale factor

It can be noted that in the VR headset, for each image, two frames are actually displayed: one for each eye. This is why the number of pixels should be doubled in the aforementioned equation. By default, S is equal to 1, setting the default number of pixels to near 6 millions. S can be modified in a range of 0.8 to 1.5 on Unity. Increasing it to 1.5 was tried out, thus multiplying the defaults number of pixels by 1.5^2.

3. Rendering cost of each pixel C

Finally, internal settings on Unity were changed to enhance the quality of images and tone down the shimmering of the objects' edges described in Section 3.2. The anisotropic filtering mode was set to `ForceEnable`. This should improve the sharpness of textures viewed by adding more details on the pixels at steep angles of objects. This means more operations for the rendering of pixels placed at steep angles. The `masterTextureLimit` was set to `0`, enabling full-resolution textures on every pixel across the entire scene. This means on each pixel, the textures were rendered at high-resolution. Additionally, the `lodBias` was increased to `2.0`, which delays the transition to lower-detail models. Indeed, by defaults, upon a certain distance, objects are rendered with less precise mesh, providing less details. Increasing the `lodBias` maintains higher geometric and texture details over longer distances. These adjustments seemingly improved image clarity and edge stability in VR rendering, but raised the GPU usage per frame by increasing the cost of each pixel rendered. The Unity documentation states that the increase of cost depends on the frame rendered, but in the worst case, it can be estimated to a 50% increase.

Different try-outs with different changes made to these three metrics were made. Every time, one metric was changed individually, keeping the others to default level. Then, they were tried out by pairs. Finally, the three of them were tested together. The detail of each try-out are given in the Table 2.

While developing the game, and implementing the try-outs, a student developer is permanently exposed to the VR environment. This makes it hard to perceive the changes obtained from each try-out. Still, the perceived change for each try-out is described in Appendix 5.2.2. A more objective perception of the changes was expected from the testing sessions with healthy participants external to the project (cf. Section 4.2.2). However, the testing sessions format, limited in time, only enables participants to compare two versions. Thus, the choice was made to let them test one control "default" version with the untouched default hardware settings as control test, and another "optimized" version with the set of changed settings that seemed to have enhanced the quality of image, and reduced the shimmering of edges. The optimized version presented to testers was the **G**.

Table 3.4: Try-outs detailed with each change labeled

Label of try-out	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**
Metrics changed	Default	S	FPS	FPS, S	C	C, S	C, S, FPS	C, S, FPS
FPS [Hz]	72	72	90	90	72	72	90	120
S	1.0	1.5	1.0	1.5	1.0	1.5	1.5	1.5
Cost Increase	1	1	1	1	1.5	1.5	1.5	1.5

Nevertheless, these changes come at a certain cost. The process to calculate this cost in terms of power consumption, battery life and temperature increase of the headset is detailed in Appendix 5.2.2. It should be duly noted that these computations are only estimations, based on simplifications. The results were summarized in the following Table 3.

Table 3.5: Computation of the estimated variation of power consumption, battery life and temperature increase for each change of performance metrics

Try-out	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**
Power Increase (%)	—	125%	25%	181.25%	50%	237.5%	321.875%	462.5%
Battery Life [h]	2.4	2.1	2.3	1.9	2.25	1.8	1.67	1.5
Temperature [°C]	37	—	—	—	—	—	41	—

The results correspond to what could have been expected: increasing the number of pixels on each frame, the frame rate, or the number of operations required to render each pixel all imply more demand on the GPU. Thus, the GPU frequency increases, and the power consumption with it. Try-outs **B**, **C** and **E** highlight that increasing the number of pixels per frame is the most impactful change on the power consumption. Besides, increasing the power consumption also decreases the time the battery takes to discharge: the battery life. In between the control try-out, and try-out **H**, which has the most power consumption increase, near one hour of battery life is lost.

Furthermore, as it will be developed in the Section 4.2.2, these results do correspond to the observations made while playing in the different versions. Indeed, for instance the increase of GPU solicitation and thus power consumption in version **H** is such that the game starts bugging and the images lag. This behavior is indicative of thermal throttling, a phenomenon where the GPU automatically reduces its performance in response to excessive heat. It is a protective mechanism to prevent overheating and potential damage to the components, implemented by Meta and detailed in the technical documentation. As the system reaches its thermal limits, it scales back clock speeds or power draw, resulting in lower performance, which can manifest as stuttering, reduced frame rates, or lag during game play, as observed in the present case. [34] The increase of temperature of the headset itself is also felt while playing.

4

Usability testing

After understanding the challenges of the project, selecting solutions and implementing them, a new session of usability testing is imposed to verify the efficiency of the new features. The goal of this chapter, in reference to the research question "What are the key features that will make this serious game relevant, usable and meaningful, both to patients and therapists, in the context of stroke rehabilitation ?", is to check that the new version of the Reaching Game shows improved relevance, usability and meaningfulness.
After described the procedure of the testing sessions led, the results obtained will be detailed and analyzed.

4.1 Procedure

The complete methodology of testing was justified in the Section 4.1.
A dozen of testers, all new to the Reaching Game, participated to the session. Among them, 10 are healthy participant, 1 is a therapist, and 1 is a patient.
The new version of the game's usability was verified with the healthy participants before presenting it to the therapist and the patient. It shall later be tested again with other therapists and patients.
A testing session lasts about an hour. The tester is introduced to the Virtual Reality headset and the background of the project.
They are first prompted to play in a version of the game with only the software implementations (and no hardware optimization) activated. Once they put on the headset, they are presented the different environments and encouraged to explore the Virtual Reality world by looking at their hands, and around them.
The game is then started and they are invited to play, only supported by the instructions within the game.
The healthy testers complete the ten levels, and the patients are left to play as far as they are able to and their health state allows. This is to explore all the difficulty increments and the full implementation of the objective of stars (cumulative counter, visual and Voice Assistant instructions).
In the case of the healthy participants and therapists, after reaching the tenth level, a new session is started, and they are asked to play as they judge an impaired patient would be capable of. The goal is to notice how the difficulty levels and the position of collectibles adapts to their performance.
Only in the case of the ten healthy participants, they were then asked to pay an increased attention to the background of the virtual environment. They were given the time to do so,

before a version of the game with the additional hardware optimizations (try-out **G**, cf. 3.2) was presented. They were free to give their impressions, but not informed of what had changed. After testing the game, testers were asked to fill the questionnaire, still composed of the SUS and the semi-structured interview. It was completed with respect to the one presented in the previous testing sessions (cf. Section 2.3.1), to verify the efficiency of the new implementations, and was organized according to the following plan:

1. Information about the participant are asked, such as prior experience with video games, or the type of participant (healthy participant, therapist, cause of the neurological disorder for patients).

2. A score display investigation is lead, asking about the perceived meaningfulness of the Performance Function (cf. Section 2.2.1) displayed as a Stars ranking and a percent, but also the objective of stars to collect implemented (cf Section 3.1.2).

3. Questions about the adaptive difficulty algorithm, the perceived increments of difficulty and adaptation to one's performance.

4. Impressions on the Voice Assistant and the different instructions and comments

5. The quality of the game, and the differences noticed between the two versions presented.

6. Comments on the existing Virtual Reality environments, and suggestions of new ones.

4.2 Results and analysis

After the previous testing session, which results were presented in the Section 2.3.1, the score SUS was evaluated to 72.73.
After the testing of this new version, it was evaluated to 87.5.
This evolution is very encouraging. Indeed, according to these results, the usability of the device went from "good" to "excellent" (cf. Appendix 5.2.2). In fact, the participants, though they did have some critics and remarks, developed in hereunder, all showed enthusiasm and satisfaction. It should still be noted, to put in perspective this evolution, that the healthy participants tend to be more familiar to Virtual Reality. In addition to their health state, this lets them perceive the game as more usable as a patient or a therapist who knows the clinical reality, would.
Moreover, the only patient already testing the game was not able to fill the questionnaire. The presented results thus contain only answers from the therapist and the rest of the healthy participants.
The results presented here should thus be interpreted with greater caution, as they should still be verified by testing with patients and therapists, more familiar to the clinical reality.

4.2.1 Feedback on software implementations

Thanks to the testings, feedback on both already existing, untouched during this internship, and newly implemented or refined software features was collected.
On the features already existing, similar results as in the previous testing sessions were collected.

This shows that despite the lack of patients testing the new version of the Reaching Game for now, the collected results so far are comparable to the previous ones, and quite reliable.
For instance, the evaluation on difficulty increments, which indicates how at ease the participants were with the difficulty of the game, scarcely changed. In average, they rated the feeling of difficulty increments at 3.88/5 in the previous testing, and at 3.10/5 in the present one.

On the newly modified or implemented features, new feedback was gathered on:

1. The Initialization scene

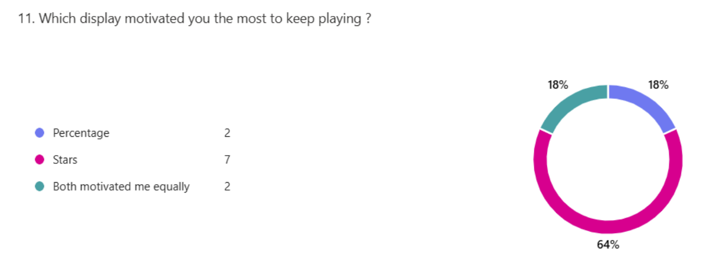
This feedback was collected similarly as previously, by the observation of how the testers managed this step.
This time, none of them struggled to pass it. Even the patient testing the game, despite a language barrier (did not understand english and thus the instructions), managed intuitively to position right on their chair. This may have influenced the observed increase in the score SUS. In this case, this translates a successful usability enhancement through this correction.
It was still observed however, that the Start button sometimes appears far from the user, which can be impractical.

2. Score display

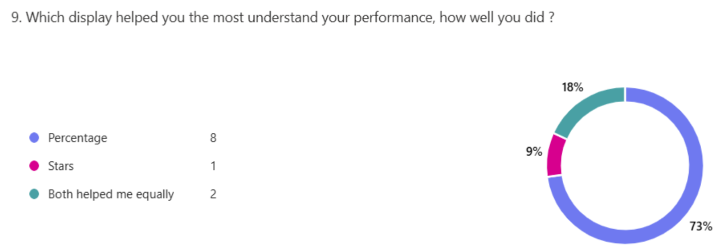
This time, only one participant considered the score display "hard to understand", as shown in Figure 4.1.

Figure 4.1: Adjectives used to describe the score display

The results showed that the global understanding of the score, and thus the motivation induced by the score display was enabled by the stars ranking, while the precise indicative value of the score was provided by the display of the PF in percents. Indeed, to the question "On a scale of 1 to 5 (1 being not at all, 5 being extremely), how motivating did you find the score display ?", testers answered an average grade of 4.30. Most of them said that the display that motivated them to keep playing is the Stars ranking, while the one that helped them the best understand their performance was the percentage, as shown in Figure 4.2.
The graphical score display definitely convinced some participants, since it was even sometimes asked to add graphical score feedback while playing, like a gauge filling up for instance.



(a) Choice of testers on preferred motivational score display



(b) Choice of testers on preferred indicative score display

Figure 4.2: Answers of testers on the stars and percentage score displays

3. Objective of stars

It can be seen on Figure 4.3 that most participants said to have understood well the principle of the objective of amount of stars to collect, and that it adapted well to their performance.

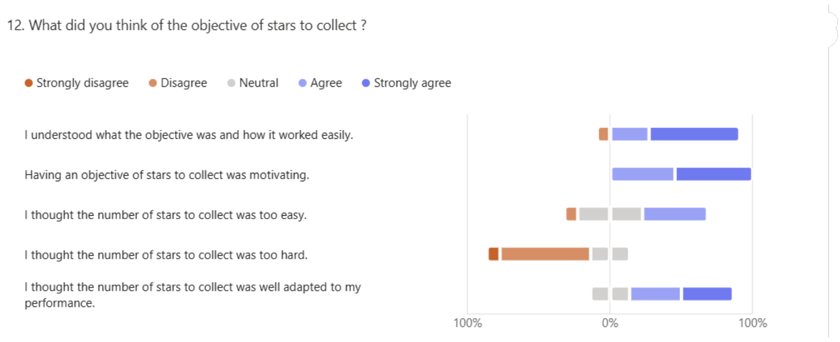


Figure 4.3: Feedback obtained on the daily objective implementation

However, they did mostly think the objective was too easy to reach. However, it must be remembered that if healthy patients might think this objective is easy, it might not be the general case of neuro-rehabilitation patients. This will have to be studied in further clinical testing sessions. In any case, contrarily to the answers given in the previous testing session, 100% of the participants answered "neutral", "agree" (for 70% of them), or "strongly agree", to the affirmation "I think I would like to use this system frequently.", in the SUS questionnaire. This enhancement may be attributed to this objective, which would in this case completely fulfill its purpose.
It also seems that the new Voice Assistant instructions implemented with this daily objective may have distracted the testers that found it repetitive. Indeed, no tester complained of it being too repetitive or overwhelming this time.

4.2.2 Feedback on hardware implementations

In addition, feedback was collected on the hardware optimizations for the enhancement of image quality tried out. In the control version, the quality of image was rated 3.73/5. As shown in Figure 4.4, the shimmering of edges did not disturb the testers, although they did notice a change on the optimized version. The enhancement of quality on the optimized version, in the question " On a scale of 1 to 5 (1 being not at all, 5 a lot), how much do you think the quality of images was enhanced between the two versions ?" was rated 3.18/5. This means there is an actual change, but one can wonder how noticeable it really is.

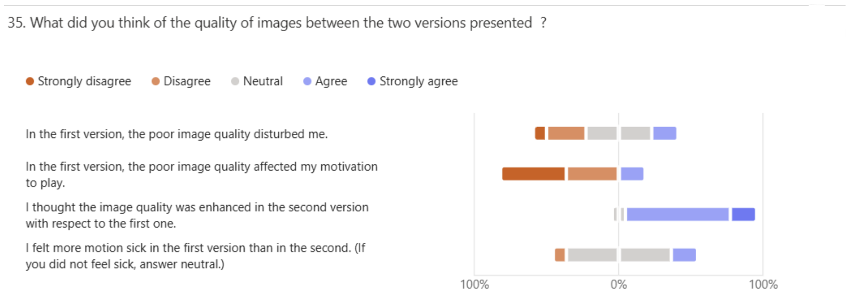


Figure 4.4: Feedback obtained on the quality of images of both version presented

In open questions, participants testified that they were not particularly focused on the quality of the images, but more on the game.
And effectively, when searching the internet for solutions to this problem, posts on forums show that the people that do notice and complain about the issue are regular users of the Meta Quest 3, or even developers in some cases.*
One participant did notice lags while playing in the optimized version. This is most likely due to thermal throttling, a risk detailed in Section 3.2. This is counterproductive, and the complete opposite effect than desired when optimizing the images quality, once again, this risk was detailed in Section 3.2.
Another, while playing on the optimized version, did complain about the headset being too hot, causing headaches.
Moreover, it should be noted that there is a strong chance that the questions in the semi-structured interview may have biased the answers of the participants. Indeed, instead of randomizing the test of each version, adjectives used to qualify both versions, as seen in Figure 4.4, clearly betrayed that the second version was supposed to have enhanced image quality with respect to the first. This should be thought through in advance and avoided for the incoming testing sessions, in order to keep the feedback collection reliable and dependable.

4.3 Refining post-testing

In conclusion, in order to prepare the game for the on-site testing in Valens, the end of this internship will be dedicated to bringing small corrections to the new features, sharpen the visual display of the objective of stars, and correct the position of the Start button for instance.
In the case of hardware optimizations, before continuing the research, it would be valuable to

check if the patients using the game on a longer term do notice the shimmering effects and the issues on the quality of images.
If so, less demanding hardware optimizations could be brought to the game, in order to avoid cases of thermal throttling. Then, they may be tested in the form of A/B testing for instance, showing the two versions to two separate groups of testers to compare unbiased feedback. [35]
In the immediate priority of the testing in Valens, it can be drawn from the testing sessions that the work of this internship did participate in increasing the usability (as shown by the SUS score), the meaningfulness (as shown by the increased comprehension of the testers' own performances), and the relevance (as shown by the increase of the motivational value of the game) of the Reaching Game. Of course, the development of this game still requires work and implementations, detailed more in depth in Section 5.2.

5

Conclusion: outlook on the project

This work was introduced by a problem: preparing a neuro-rehabilitation serious game for an on-site testing. The game was functional, but presented limitations that prevented it from fulfilling the three crucial requirements of usability, relevance and meaningfulness of the game. The goal of this internship was thus to answer the research question "What are the key features that will make this serious game relevant, usable and meaningful, both to patients and therapists, in the context of stroke rehabilitation ?"
First, a preliminary study of the project, its methodology, and previous testing results were collected, and a literature review was conducted. This allowed the building a road map with clear objectives of implementation:

- For the sake of usability, refine the initialization scene, as it was too counterintuitive and difficult to use, and enhance the quality of images which could risk disturbing the users if it was not.

- For the sake of meaningfulness, implement new ways to display the score, as percentages are not clearly understood broadly enough by public users.

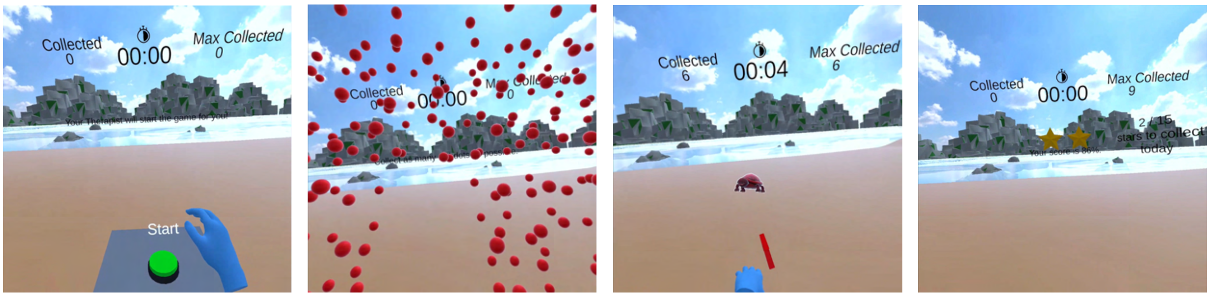
- For the sake of relevance, increase the motivational value of the game, by setting objectives to the player, which will increase their adherence.

During a development phase, technical work was done to refine and implement those features.
Eventually, testing sessions with an appropriate study design were carried out, in the aim of verifying the effects of those implementations, and whether or not they do fulfill their purpose. Although they may require corrections and further testing sessions with clinically familiar testers, those implementations did seem to have had a positive impact on the usability, meaningfulness and relevance of the Reaching Game.
Thus, to the research question, one may answer that the use of a score display, a daily objective, and as for the initialization scene simple steps with clear instructions allowed to a serious game to be made relevant, meaningful and usable for neuro-rehabilitation.

5.1 New state-of-the-art and discussion

The game has been changed with respect to the one studied in the Preliminary work Chapter 2, which video's can be found on this (link). A new outlook of the game can be found using this link, Despite all the implementations, the game flow remains as illustrated in Figure 2.1. The user still goes through the same 5 scenes presented in Section 2.2.1. However, the initialization and endgame scene have changed, as shown on the new flow of the Reaching Game, Figure 5.1.

Indeed, the initialization scene has been simplified, and the EndGame scene has been added a Stars ranking based on the value of the score, and a cumulative counter of the number of stars collected since the beginning of the game: the daily objective.



(a) Initialization scene (b) Calibration scene (c) Game play scene (d) EndGame scene

Figure 5.1: New game flow of the Reaching Game

The testing sessions highlighted that, if they still require some corrections, these software developments did fulfill their purpose of augmenting the users' ease of use, motivation and understanding of the game.
Furthermore, quality optimizations have been implemented. According to the feedback given, they do visually reduce the shimmering of the objects edges, that could disturb the user in the previous versions. However, the testing sessions raised the question of how noticeable the shimmering of the edges was in the first place, and how much the optimizations really influenced the user experience. The work accomplished here lays the first stone to tackle the issue of quality of image, but requires further testing and investigation.

5.2 Next steps

Indeed, the project is close, but not completely ready. It requires refinements and sharpening corrections, developed in Section 4.3. Once these will be done, the game will be considered fully ready for the on-site clinical testing.
After the feedback of this testing will be gathered, just like at the beginning of this internship, a new road map will have to be planned.
In the meantime, from this iteration, avenues for the further development work were already thought of.

5.2.1 Software work

- To simplify usability, a tutorial could be implemented before starting the game. This would enable the user to grasp more clearly the goals of the game, and provide them with a support to understand better the different features of the game, like the visual display that follows them through all the scenes.
- To increase the meaningfulness through the strike of motivation, fixing objectives to patients in the long term will be a game-changer. For this, personal profiling will have to

be implemented, adding memory within the application of the game on the Meta Quest 3. The idea would be that when a user leaves the game, they can come back to where they were thanks to a personal profiling. This way, two major additions could be developed.
First, long-term objectives could be fixed for patient, meaning unlocking collectibles or environments, and allowing to show an advancement. For instance, features like a "streak" could be added, meaning an objective in number of consecutive days the patient has trained with the game. This would motivate daily practice.
Besides, long-term performance analysis could be provided, such as evolutionary graphics. This would provide the therapists with a precise follow-up of their patients, but also help the latter visualize their own evolution.
In order to really spark motivation, these evolutionary graphics could only be shown at the beginning of each session. This would push the patient to do better than last time, and re-immerse them in the therapy session. It would also reduce discouragement after a difficult training.

- Instead, at the end of the session, accomplishment could be shown. As explained in the literature review (cf. Section 2.3.2), the game aims to immerse the patient, to rely on the worlds of play and meaning. However, at the end of the training session, they could be brought back to the world of reality in an enthusiastic way. An example would be to analyze the metrics and performance of the patient, and compare it to an achievement of the real world. For instance, "Congratulations, you have burnt as many calories as a 2-hour hike !". Another simple example would be the display of the daily amount of time played. This would add a feeling of accomplishment, and help the patients re-anchor in the world of reality.

5.2.2 Hardware work

The case of the quality of images is slightly different.

- Further testing sessions should be dedicated to checking how disturbing the quality of images is for users. On long-term usage, there is a strong chance that this would be noticed more. The semi-structured interview should be modified to avoid all biasing, as observed during the present session. Instead, the possibility of A/B testing format should be scrutinized, to randomize the versions and feedback (cf. Section 4.2.2).

- Another major idea could be to implement a mixed reality, transparent environment. As developed in the literature work of Section 2.3.2, this could avoid the issue of motion sickness, cause by the virtual environments. This way, patients that are prone to motion sickness would still be able to benefit from motivational aspects and training from the Reaching Game.

Appendix 1: System Usability Scale

The System Usability Scale (SUS) provides a standardized and global measure of usability. It relies on statements about the product, which the tester will rate on a scale from 1 ("strongly disagree") to 5 ("strongly agree"). The ten statements the user has to rate are shown in Figure 2. [12]

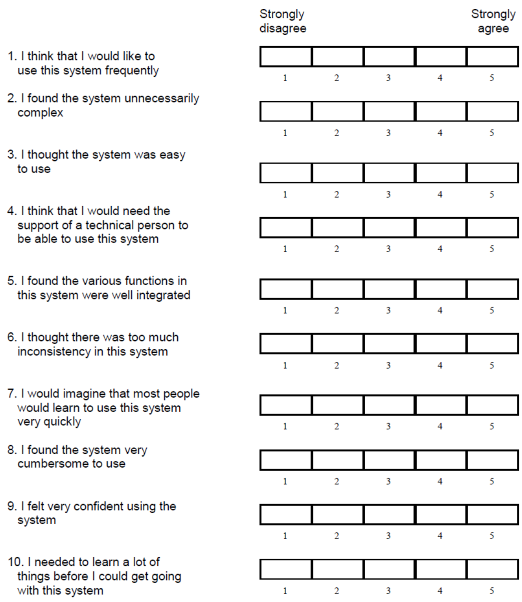


Figure 2: SUS questionnaire

To calculate the SUS (System Usability Scale) score, for odd-number items, the score contribution is the scale position minus 1. For even-number items, the contribution is 5 minus the scale position. Finally, the total sum of these score contributions is multiplied by 2.5 to obtain the overall SUS score.
The formula can be expressed as:

$$SUS = 2.5 \times \sum_{i=1}^{10} C_i$$

where:

$$C_i = \begin{cases} \text{Scale Position} - 1, & \text{for items } 1, 3, 5, 7, 9 \\ 5 - \text{Scale Position}, & \text{for items } 2, 4, 6, 8, 10 \end{cases}$$

To obtain the SUS score of the complete testing sessions, the average score given by participants was computed.
The results can be interpreted according to a scale provided in SUS documentations [36], and reprinted in Figure 3.

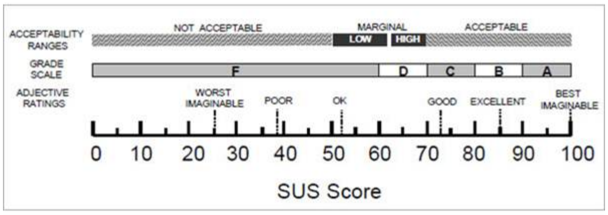


Figure 3: Rankings of SUS scores

As recommended [12], after testing the Reaching Game, and prior to any debriefing or discussion, participants were asked to fill the SUS and provide their immediate reactions to each item, rather than overthinking their responses.

Appendix 2: AdaptVR project within the Holoteach project

The Holoteach project, which the AdaptVR is part of, does not only include the development of the Reaching Game in itself, although every other research work is linked to the game.

1. **Therapeutical chair**
   The exercises are planned to be conducted in the clinic using an innovative therapy chair developped in ZHAW, showed in Figure 4 With a movable seat, the seat of the chair slides according to the trunk movements. This adds difficulty for the reaching task and increases the training value, by challenging and supporting trunk muscles activation and movements. A security belt should be integrated for safety. This user study is conducted without the use of the movable seat as it is not available at the moment.

Figure 4: Therapy of a participant on the therapy chair

2. **MetaReachValidation**
   This project aims to validate the accuracy of the Meta Quest 3 VR device in measuring reaching finger position in a 3D space using a reference standard, in a therapeutically relevant scenario. The final aim is to measure the error of position tracked by the VR headset, with respect to reality.

3. **Cognitive mode**
   Within the AdaptVR project, another mode has not been studied during this internship. The Cognitive mode is another mode of the Reaching Game in which the user is asked to reach specific collectibles with a specific hand. This aims to increase the training value of the game by augmenting its difficulty, and adding cognitive challenge to patients suffering of neglect, meaning their brain does not process information on certain areas of space.

Appendix 3: Performance equations and hardware computations

A CPU's performance equation can be generalized as hereinbelow [37]:

$$T = N_{\text{instr}} \cdot \text{CPI} \cdot t_{\text{CPU}} = \frac{N_{\text{instr}} \cdot \text{CPI}}{f_{\text{CPU}}} \tag{1}$$

with:

- T: the performance, or time taken by a program
- N_{instr}: the number of instructions executed
- CPI: the average number of clock Cycles Per Instruction
- t_{CPU}: the clock cycle time of the CPU, or duration of a clock cycle
- $\frac{1}{t_{\text{CPU}}} = f_{\text{CPU}}$: the clock frequency of the CPU

As seen in the previous Section 3.2.1.1, the GPU's functioning is quite similar to a CPU's. Indeed, the main difference in their modes of operation is CPU process sequentially, and GPU in parallelism. It can be seen that a CPU or a GPU - processing respectively a program or a frame, with each having respectively a certain number of instructions or pixel to execute; is equivalent.
Therefore, it is possible to find equivalence between each of the variables. Each of them is listed in the Table 1.

Table 1: Equivalence of performance metrics between CPU's and GPU's

Concept	CPU	GPU	Meaning
Performance	T	$\frac{1}{\text{FPS}}$	Amount of time taken for a program or frame to be processed
Number of instructions	N_{inst}	P	Amount of instructions or pixels in a program or frame
Instruction cost	CPI	C	Amount of cycles needed to render each instruction or pixel
Clock time	t_{CPU}	t_{GPU}	Time taken to complete one clock cycle
Clock frequency	f_{CPU}	f_{GPU}	Number of clock cycles completed per second

It should be duly noted that as a GPU functions with threads of ALUs activated simultaneously (cf. Section 3.2.1.1), a factor of proportionality should be added to the equation with respect to the CPU's equation 1. However, it is known that this factor depends on the internal architecture

of the GPU and the number of ALUs threads, which is constant. [30]
Therefore, this still allows to obtain the equation 2, which links the frame rate FPS to the clock frequency of the GPU f_{GPU}, the number of pixels on each of these frames P, the cost C in number of operations required to render each of these pixels.

$$\frac{1}{\text{FPS}} \propto P \cdot C \cdot t_{\text{GPU}} = \frac{P \cdot C}{f_{\text{GPU}}} \tag{2}$$

with:

- FPS: the frame rate, framing frequency, or number of Frames Per Seconds the GPU can process
- P: the number of pixels per frame
- C: the average Cost in number of cycles needed to render each pixel
- t_{GPU}: the clock cycle time of the GPU, or duration of a clock cycle
- $\frac{1}{t_{\text{GPU}}} = f_{\text{GPU}}$: the clock frequency of the GPU

Different try-outs with different changes made to these metrics intervening in the GPU frequency equation were made. Every time, one metric was changed individually, keeping the others to default level. Then, they were tried out by pairs. Finally, the three of them were tested together. The detail of each try-out are given in the Table 2.
The table of each try-out can be found hereinbelow:

Table 2: Try-outs detailed with each change labeled

Label of try-out	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**
Metrics changed	Default	S	FPS	FPS, S	C	C, S	C, S, FPS	C, S, FPS
FPS [Hz]	72	72	90	90	72	72	90	120
S	1.0	1.5	1.0	1.5	1.0	1.5	1.5	1.5
Cost Increase	1	1	1	1	1.5	1.5	1.5	1.5

For each try-out, the following changes were observed and wrote down while developing them:
B: Very slight increase of details on edges of objects close.
C: Increased smoothness of the movements with the hands, slight too.
D: Very slight increase of details on edges of objects close and increased smoothness of the movements with the hands, slight too.
E: Increased details on the objects (for instance the grass in the Mountain environment), less shimmering of edges, particularly of far away objects.
F: Increased details on the objects, less shimmering of edges in general.
G: Increased details on the objects, less shimmering of edges in general, smoother movements.
H: Increased details on the objects, less shimmering of edges in general, but lags and bugs while playing, in particular in environments with a bigger amount of GameObjects, like the Japanese Room.
Moreover, these changes come at a certain cost. Following assumptions and equations were gathered to estimate the cost of power consumption and the decrease of time the battery can last while playing, called battery life.

- The variation of dynamic power consumption of the GPU was assumed equal to the variation of GPU frequency, as the dynamic power consumption of a processor is given by:

$$P \propto \alpha \cdot C \cdot V^2 \cdot f \tag{3}$$

  where:

  - α: switching activity (probability a node changes per clock cycle),
  - C: capacitance load,
  - V: supply voltage,
  - f_{GPU}: clock frequency

  and the capacitance load, voltage and switching activity may be considered constant with respect to the clock frequency. [38] Thus:

$$\Delta P \propto \Delta f_{\text{GPU}} \tag{4}$$

  where:

  - ΔP: variation in power consumption,
  - Δf_{GPU}: variation in GPU clock frequency.

- To estimate the impact of increased GPU usage on battery life in the Meta Quest 3, accordingly to its technical documentation [34], a battery capacity of $B = 36\,\text{Wh}$, a baseline system power draw of $P_{\text{base}} = 13\,\text{W}$, and a baseline GPU power consumption of $P_{\text{GPU}} = 2\,\text{W}$ were assumed. GPU power increases were then modeled as

$$\Delta P_{\text{GPU}} = x \cdot P_{\text{GPU}},$$

  and the total system power becomes

$$P_{\text{total}} = P_{\text{base}} + \Delta P_{\text{GPU}}$$

  The new battery life T was then calculated for each increase of power consumption, using

$$T = \frac{B}{P_{\text{total}}}.$$

- The GPU's clock frequency can then be expressed by reordering equation 3.1, which relates performance demands to clock speed:

$$f_{\text{GPU}} \propto P \cdot C \cdot FPS \tag{5}$$

  Nonetheless, any GPU has a maximum clock frequency at which it can function, and this limit cannot be exceeded. According to the official Meta documentation [34], the GPU in the Meta Quest 3 has a maximum frequency of 599 MHz. If the system is asked to exceed this limit through the increase of performance metrics, the device will engage in thermal throttling: reducing the clock speed, decreasing resolution, or lowering frame rate to stay within safe operating limits. As a result, the visual quality or smoothness of the VR experience may degrade, even if the software continues requesting higher performance.

- Additionally, increased computational load is expected to raise the internal temperature of the device. This temperature rise will be measured directly using the integrated thermometers embedded in the Meta Quest 3 headset, allowing to monitor thermal behavior in real time and correlate it with GPU load and performance limits.

The increase of power consumption and temperature of the headset and decrease of battery life were summarized in the following Table 3. The variations were all computed with respect to the default settings version. It should be duly noted that these computations are only estimations. They are based on simplifications. Indeed, the Meta Quest 3 documentation precises that the GPU frequency is incremented by levels. This means according to the usage of GPU, the headset varies the level of GPU clock frequency. [34] Moreover, the capacitance load for instance in equation 3 was considered completely constant according to the demand on the VR headset, which is not entirely true, but the dependency is difficult to estimate. However, these assumptions were made in order to obtain a general idea of the changes. Besides, they were confirmed by the observations noted when playing, that came in correlation. The optimized version presented to testers was **G**.
The value of temperature was collected twice. Once playing for 10 minutes on the default version, then for the same time on the optimized one. Between the usage of the two versions, the headset was turned off and unused for 30 minutes, to make sure the temperature increase would not be due to a lingering usage.

Table 3: Computation of the estimated variation of power consumption, battery life and temperature increase for each change of performance metrics

Try-out	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**
Power Increase (%)	—	125%	25%	181.25%	50%	237.5%	321.875%	462.5%
Battery Life [h]	2.4	2.1	2.3	1.9	2.25	1.8	1.67	1.5
Temperature [°C]	37	—	—	—	—	—	41	—

Appendix 4: Gantt chart and cost of the internship

Gantt chart
The Gantt chart used during this internship is presented on Figure 5. It corresponds to a week-by-week precised version of the road map showed on Figure 2.10.

Cost estimate of the Master's thesis project

1. **Financial costs**
   The financial costs of this internship include

   - the gross salary (1000 CHF monthly)
   - the accomodation covered by the laboratory (780 CHF monthly)
   - the material used: a computer for developing with a Nvidia Gefore RTX GPU, and a Intel Core i9 CPU (about 1150 CHF), an Android tablet (about 300 CHF), a Meta Quest 3 (540 CHF). The Unity version used is free.
   - travel reimbursements: a testing session, at the beginning of the internship was organized at the Kantonsspital Winterthur (KSW), a hospital near Zurich, to let patients and therapists test the game. The trip was done in train (25 CHF).

   Adding every item, the estimated financial cost of the project to the laboratory is 12,695 CHF.

2. **Time investment**

   - a biweekly one-hour meeting with the supervisor (research enginner) was organized
   - a weekly one-hour project meeting with another intern and the laboratory director
   - additional time for training by the supervisor was taken at the beginning of the internship, estimated at about 10 hours.

   Assuming the internship lasted 26 weeks, this adds up to a total cost of a total 49 hours, namely about 1h53min per week.

3. **Space usage**

   - a desk place in open-space was used for most of the internship
   - a bigger laboratory with free space was used to conduct the testing sessions with healthy participants

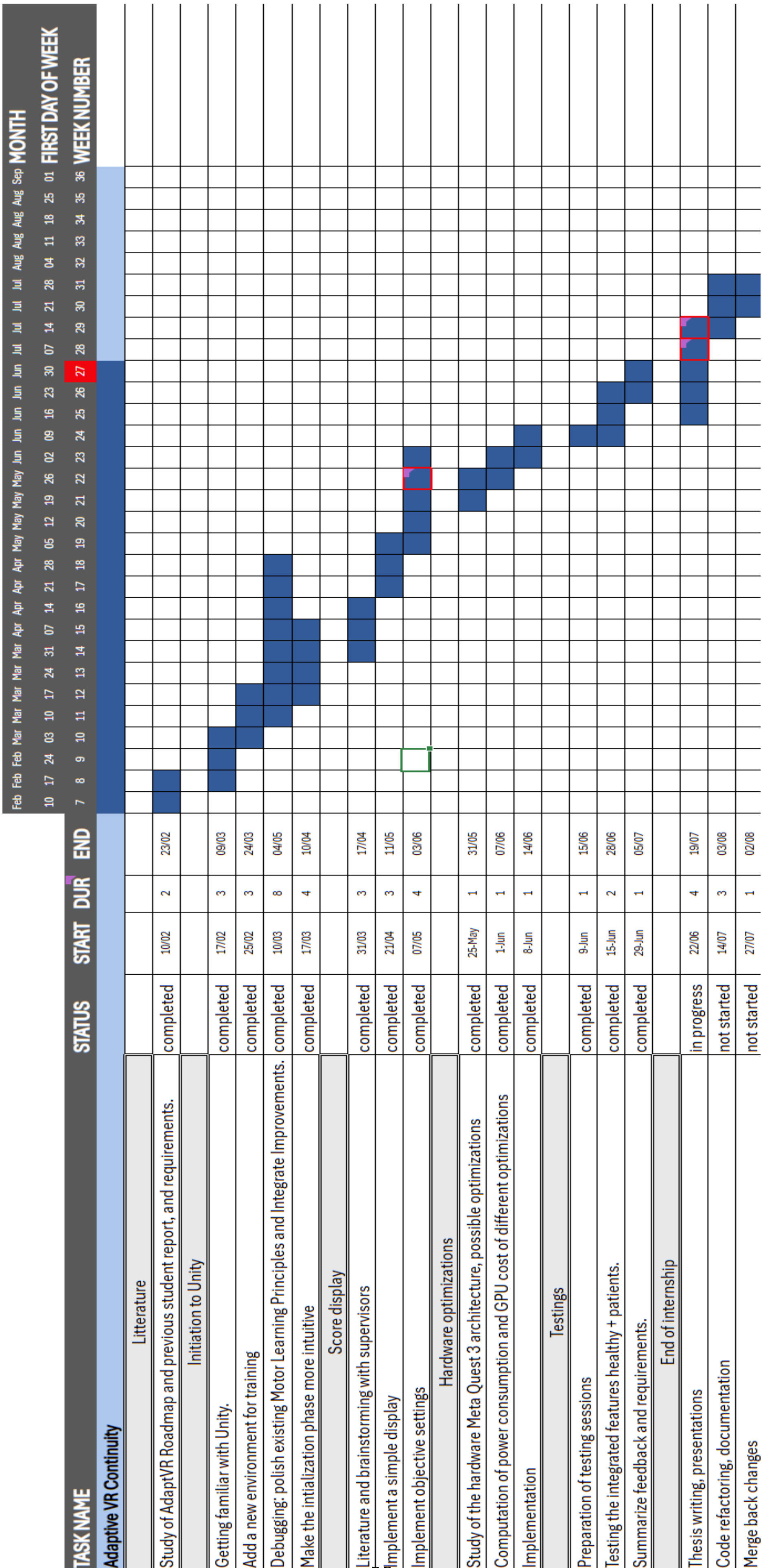


Figure 5: Gantt chart of the presented internship

Appendix 4:

I. Analysis of environmental and societal impact of your project

1. **Personal footprint**

   - home-work-home trips: walking
   - utilization of VR headset (5h/day), computer with internet (8h/day), tablet (1h/day) lights always on in office (8h/day),
   - business trip: 5 trips to the clinic (10 km), trip to the hospital in Zurich (60 km) in train and bus

   For the electronic devices, it was assumed that the computer's power is 100 W, the tablet's around 30 W and the VR headset's about 200 W[*], and the led lights in the office area used around 50 W.[*] Then, it was estimated that 0.37 kg of CO_2 are emitted per kWh of electricity generated.[*] Thus, this consumption is estimated to 104.79 kg of CO_2 for the 127 days of the internship.
   For the trips, it was estimated that 47g of CO_2 are emitted per passenger kilometer using the bus. [*] Thus, about 10.3 kg of CO_2 were emitted for trips.
   This results in a total of 115 kg of CO_2 emitted during 6 months, so 230 kg per year, which is 4% of the individual recommendations.[*]

2. **Reducing initiatives**
   Initiatives were taken to for each, give impact of reducing

   - use the public transports instead of the LLUI car
   - turning off lights in the morning (about 4h)
   - turning off headset when unused
   - turning off computer when unused

   This avoided to emit approximately 36.2 kg of CO_2. It is however not to forget that the project aims for people to use an electronic device, the VR headset, which would increase individual carbon footprint.

3. **Ethical aspects of LLUI**
   The internship took place in a small research institute in Vitznau LLUI, which benefits from a flat hierarchy and strong proximity between staff and leadership. Employees and interns have direct access to the CEO and HR for any concern, whether professional or personal, such as housing or interpersonal issues. This promotes a responsive and supportive environment. The institution provides housing to students near the laboratory, significantly reducing commuting emissions and supporting local living. Indeed, the institute is located in a small village where few accomodation, and thus unaffordable ones

for students are offered. Social cohesion is actively encouraged by the hierarchy through regular events like team bonding activities, or for instance Eastern and Christmas celebrations. Within the Therapy Science group, team bonding through a two-day hiking retreat and weekly coffee breaks reinforces psychological well-being, by allowing every member to feel included in the social life of the team.
From an ecological standpoint, the location in a small village naturally limits commuting impact, and internal practices show a positive, though informal, approach to sustainability. Advantages like access to a free gym reflect attention to health and well-being. There is a close follow-up on interns' progress and mental health. However, formalized policies on diversity, disability inclusion, and harassment prevention were never explicitly observed or communicated during the internship. The institution could improve by publishing its commitments to sustainability and social responsibility, and implementing training or visible protocols addressing workplace equity, diversity, and mental health. These steps would help transition from informal goodwill to a structured, accountable strategy.

4. **Utility of the project**
   Within the strategy of LLUI: The Lake Lucerne Institute (LLUI) and the Therapy Science group are deeply committed to developing neuro-rehabilitation technologies adapted to home rehabilitation. This project aligns directly with their strategy to integrate patient-centered, motivational therapy solutions. By leveraging consumer-grade VR and gamification, this work advances LLUI's mission of scalable, intensive, and autonomous neuro-rehabilitation. It demonstrates the viability of low-cost, accessible therapeutic tools that can be deployed clinically and potentially at home.

   With respect to the users: Although this project is not governed by the Swiss Human Research Act, ethical standards were strictly followed. All participants of testing sessions gave informed consent in line with Swiss and European data protection policies. Data collected during testing was anonymized, securely stored, and used exclusively to improve system usability and relevance, as explained with complete transparency in the consent forms.
   Critics might argue that the use of VR in this context is redundant: effective rehabilitation methods already exist. However, real-world barriers persist: patients frequently experience low motivation and poor adherence, while therapists face increasing caseloads. Many patients would prefer to recover at home, especially after discharge. This project directly addresses these issues by enhancing user engagement through gamified feedback, adaptive difficulty, and goal-setting. This paves the way for more autonomous, at-home therapy.
   In its current state, VR-based rehabilitation remains more accessible to wealthier individuals, due to the cost of hardware and internet requirements. Yet, by designing for simplicity, scalability, and compatibility with commercially available consumer headsets, this project hopes to contribute to the future democratization of digital rehabilitation tools, eventually making them accessible to a broader population.
   Moreover, the environmental footprint of traditional therapy must not be ignored. Many patients must rely on private transportation to reach clinics, especially in rural or less-connected areas, like Vitznau in the canton of Lucerne. By enabling therapy from home,

this VR solution offers a low-energy alternative that substitutes significant car-based carbon emissions with minimal electricity use.

Ultimately, the improvements made during this project increased the game's usability and moved it a step closer to being reliably usable by patients of all backgrounds and abilities, independently, and from the comfort of their homes.

Personally: Research in biomedical technologies is always rewarding, as it offers the opportunity to create tools that have tangible impact on people's lives. This project was especially meaningful because it addressed stroke rehabilitation, a matter that concerns millions globally and where every improvement can directly enhance someone's recovery journey. Knowing that one's work contributes to solving such an widely spread health issue added a deep sense of purpose in this internship.

What particularly made the experience powerful was the direct connection to the field: regular contact with therapists and patients brought clarity to the real-world problems being tackled. It shifted the focus from abstract technical challenges to concrete needs. One striking example was a patient who had lost motivation, was far from home, and emotionally low. Trying the game, she became newly engaged in therapy and expressed a willingness to train again. Seeing that kind of immediate impact reaffirmed why this work matters.

This internship also provided a high degree of autonomy, with freedom to shape development priorities within a road map full of ideas. This required constant balance: between creativity and practicality, innovation and feasibility, and what was ideal and what time allowed. Learning to prioritize what was most crucial, especially under time constraints, was a valuable exercise in decision-making and autonomy.

Another key learning was how to accept feedback, even when it was difficult. During user testing, some comments may be tough to hear, especially when they concerned features a lot of efforts were put in. But these moments teach how to detach from the work emotionally, embrace constructive criticism, and see it as a way to improve. Overall, this internship not only strengthened technical skills, but also reinforced the motivation to keep working where something useful to society can be constructed.

5. **Positive and negative impacts of the project**

The project's most positive impact lies in its potential to reshape stroke rehabilitation, shifting it from clinics to patients' homes. This approach supports autonomy, reduces the burden on therapists and cuts the carbon emissions associated with traveling to therapy sessions by car. Thus, the modest energy consumption of a VR headset could effectively replace fossil fuel-powered transportation, providing an overall environmental benefit.

The system is built on commercially available consumer hardware which supports reuse, repair and eventual remanufacturing. Its reliance on Unity and modular code design also means that future improvements can be implemented through software updates, extending the product's useful life without the need for new hardware.

However, a new concern emerged during this particular iteration of development. Improving visual quality to reduce motion sickness and enhance the user experience implied here increasing GPU performance. This caused to raise the power consumption and reduced the battery life of the headset. This is problematic, and particularly for long therapy sessions as frequent recharging shortens the lifespan of the hardware, generates more e-waste and discourages patient use. Furthermore, higher energy demands undermine the sustainability argument, particularly if the technology is used by many people.

To address this, future iterations could explore optimizations techniques such as dynamic resolution scaling: adapting image quality in real time based on user motion or scene complexity; edge rendering: focusing detail only where the user is looking; and mitigating the frame rate to a certain threshold.

Although some materials used in current VR hardware are not recyclable, extending the lifetime of devices and minimizing performance overhead are realistic and necessary steps towards reducing environmental impact. The project's modular and scalable design also makes it suitable for use in various clinical contexts, or even for other conditions such as Parkinson's disease or spinal injury, thereby increasing its societal and ecological value.

II. Propose sustainable engineering solutions

During my internship, I worked on optimizing image quality through hardware-based settings for a VR headset. However, as explained previously, a significant ecological and societal challenge was then observed: these improvements resulted in higher GPU and overall system power consumption, directly affecting battery life and increasing the device's electrical energy demands. This is problematic in the broader context of global energy constraints and the urgent need to reduce consumption due to environmental concerns and limitations in energy production capacity over the coming years.

To address this, a systematic evaluation framework should be established, where each optimization is tested individually to quantify its exact contribution to both power consumption and perceived image quality. This task requires designing and executing a series of controlled experiments, including energy profiling, image fidelity characterization, and user experience testing. Due to the subjective and user-specific nature of visual quality assessment, additional metrics should be used as in this work, such as MSE (Mean Square Error) and PSNR (Peak Signal to Noise Ratio), as in other examples *.

Therefore, the implementation of A/B testing protocols was proposed in Section 4.3, showing different optimized (or not) versions to separate groups of testers to compare unbiased feedback. The combination of those two approaches would help quantify trade-offs between visual quality and energy consumtion.

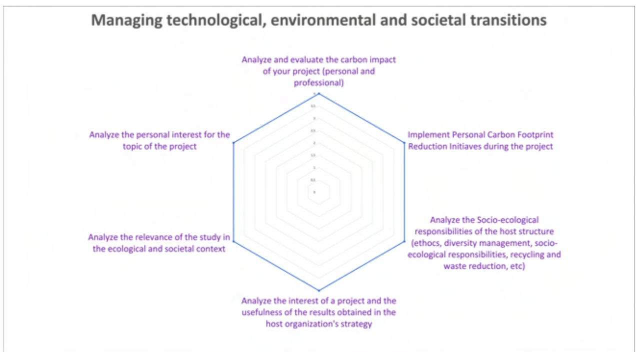


Figure 6: Managing technological, environmental and societal transitions

Appendix 5: Fiche-archive

1. Identité de l'élève: Raphaëlle Claude Michèle Braha Dahan
2. Filière Nanotech
3. Année universitaire 2024-2025
4. Titre du stage: Designing a serious Virtual Reality game for neuro-rehabilitation: Improving usability, relevance and meaningfulness through iterative, user-centered approach
   Période: 3 février 2025 au 31 juillet 2025
5. Institut: Lake Lucerne Institute (LLUI)

   Figure 7: Logo of LLUI

   Adresse postale: Lake Lucerne Institute AG Rubistrasse 9 6354 Vitznau
6. Responsable du stage: Marwen Mokni, marwen.mokni@llui.org
7. Tuteur école: Marianne Weidenhaupt
8. Description du stage: "Therapy Science Labs envisions a future where rehabilitation is intelligently and continuously adapted to meet the individual needs of each patient. Our mission is to make rehabilitation ubiquitous, with personalized interventions guided by data from ongoing assessments and multiple data streams, spanning the entire rehabilitation journey—from the hospital and inpatient care to home-based therapy. Join our team and support two ongoing projects exploring trunk control in stroke survivors and validating a portable measurement device. You'll work with cutting-edge technologies, including 3D optoelectronic motion tracking, electromyography, and VR movement tracking. Your tasks will involve recruiting participants, conducting measurements, and processing and analyzing data. Gain hands-on experience in every stage of scientific research, from data collection to analysis. Be part of an exciting opportunity to contribute to meaningful advancements in rehabilitation science. You will build upon the work of highly talented students, bringing a VR exercise closer to real-world application with patients and therapists. You will be also enhancing our understanding of therapeutic exercise effects and

support clinical decision making in the longer run. This role offers you the opportunity to directly test your developments with recruited patients, allowing you to refine the product based on real-life feedback. Your tasks: • Literature search (10%) • Participant recruitment (30%) • Participant measurements (30%) • Data processing and analysis (20%) • Scientific reporting (10%)"

9. Moyens mis à disposition: 1 ordinateur portable, 1 ordinateur avec GPU, logiciel Unity
   Encadrement additionnel: Directeur de Therapy Science Christoph Bauer, christoph.bauer@llui.org

Bibliography

[1] Martina Maier, Belén Ballester, and Paul Verschure. "Principles of Neurorehabilitation After Stroke Based on Motor Learning and Brain Plasticity Mechanisms". In: *Frontiers in Systems Neuroscience* 13 (Dec. 2019), p. 74. DOI: 10.3389/fnsys.2019.00074.

[2] Institut du Cerveau. *L'Accident Vasculaire Cérébral (AVC)*. https://institutducerveau.org/fiches-maladies/laccident-vasculaire-cerebral-avc. Accessed July 2, 2025.

[3] Geetha Poomalai, Suhas Prabhakar, and Nalini Sirala. "Functional Ability and Health Problems of Stroke Survivors: An Explorative Study". In: *Cureus* 15 (Jan. 2023). DOI: 10.7759/cureus.33375.

[4] Stefan Strilciuc et al. "The economic burden of stroke: a systematic review of cost of illness studies". In: *Journal of Medicine and Life* 14 (Sept. 2021), pp. 606–619. DOI: 10.25122/jml-2021-0361.

[5] Lake Lucerne Institute. *Research*. Accessed July 2, 2025. URL: https://www.llui.org/research/.

[6] Peter Langhorne, Julie Bernhardt, and Gert Kwakkel. "Stroke rehabilitation". In: *The Lancet* 377.9778 (2011), pp. 1693–1702. ISSN: 0140-6736. DOI: https://doi.org/10.1016/S0140-6736(11)60325-5. URL: https://www.sciencedirect.com/science/article/pii/S0140673611603255.

[7] Mandy Scheermesser et al. "Therapists and patients perceptions of a mixed reality system designed to improve trunk control and upper extremity function". In: *Scientific Reports* 14 (Mar. 2024). DOI: 10.1038/s41598-024-55692-4.

[8] Silvia Bargeri et al. "Effectiveness and safety of virtual reality rehabilitation after stroke: an overview of systematic reviews". In: *eClinicalMedicine* 64 (Oct. 2023), p. 102220. DOI: 10.1016/j.eclinm.2023.102220.

[9] Belén Ballester et al. "Counteracting learned non-use in chronic stroke patients with reinforcement-induced movement therapy". In: *Journal of NeuroEngineering and Rehabilitation* 13 (Aug. 2016), p. 74. DOI: 10.1186/s12984-016-0178-x.

[10] Unity Technologies Documentation. *Virtual Reality Overview*. https://docs.unity3d.com/540/Documentation/Manual/VROverview.html. 2015.

[11] *ISO 9241-11:2018 – Ergonomics of human-system interaction – Part 11: Usability: Definitions and concepts*. Standard. Geneva, Switzerland: International Organization for Standardization, 2018.

[12] John Brooke. "SUS: A quick and dirty usability scale". In: *Usability Eval. Ind.* 189 (Nov. 1995).

[13] Melissa DeJonckheere and Lisa Vaughn. "Semistructured interviewing in primary care research: a balance of relationship and rigour". In: *Family medicine and community health* 7 (Mar. 2019), e000057. DOI: 10.1136/fmch-2018-000057.

[14] Isabela Alves Marques et al. "Virtual reality and serious game therapy for post-stroke individuals: A preliminary study with humanized rehabilitation approach protocol". In: *Complementary Therapies in Clinical Practice* 49 (2022), p. 101681. ISSN: 1744-3881. DOI: https://doi.org/10.1016/j.ctcp.2022.101681. URL: https://www.sciencedirect.com/science/article/pii/S1744388122001499.

[15] Michael Bressler et al. "A Virtual Reality Serious Game for the Rehabilitation of Hand and Finger Function: Iterative Development and Suitability Study". In: *JMIR Serious Games* 12 (2024). ISSN: 2291-9279. DOI: https://doi.org/10.2196/54193. URL: https://www.sciencedirect.com/science/article/pii/S2291927924000631.

[16] Gauthier Everard et al. "A Self-Adaptive Serious Game to Improve Motor Learning Among Older Adults in Immersive Virtual Reality: Short-Term Longitudinal Pre-Post Study on Retention and Transfer". In: *JMIR Aging* 8 (2025). ISSN: 2561-7605. DOI: https://doi.org/10.2196/64004. URL: https://www.sciencedirect.com/science/article/pii/S2561760525000301.

[17] "Motion Rehab AVE 3D: A VR-based exergame for post-stroke rehabilitation". In: *Computer Methods and Programs in Biomedicine* 151 (2017), pp. 15–20. ISSN: 0169-2607. DOI: https://doi.org/10.1016/j.cmpb.2017.08.008. URL: https://www.sciencedirect.com/science/article/pii/S016926071730113X.

[18] Pr Richard Wetzel. *Conference on serious games and immersive rehabilitation apps.* https://lnkd.in/eZnsxyMD. 2025.

[19] Ana Carla Amaro, Ana Veloso, and Lidia Oliveira. "Social games and different generations: A heuristic evaluation of Candy Crush Saga". In: Dec. 2016. DOI: 10.1109/TISHW.2016.7847791.

[20] Naveed Anwar et al. "Virtual Reality Training Using Nintendo Wii Games for Patients With Stroke: Randomized Controlled Trial". In: *JMIR Serious Games* 10.2 (2022). ISSN: 2291-9279. DOI: https://doi.org/10.2196/29830. URL: https://www.sciencedirect.com/science/article/pii/S2291927922000630.

[21] Hao Fang et al. "Reward Feedback Mechanism in Virtual Reality Serious Games in Interventions for Children With Attention Deficits: Pre- and Posttest Experimental Control Group Study". In: *JMIR Serious Games* 13 (2025). ISSN: 2291-9279. DOI: https://doi.org/10.2196/67338. URL: https://www.sciencedirect.com/science/article/pii/S2291927925000248.

[22] Zhongqi Liu et al. "The impact of feedback elements in serious games on nursing learning outcomes: A systematic review and meta-analysis". In: *Nurse Education Today* 150 (2025), p. 106689. ISSN: 0260-6917. DOI: https://doi.org/10.1016/j.nedt.2025.106689. URL: https://www.sciencedirect.com/science/article/pii/S0260691725001248.

[23] NHS. *Motion Sickness.* Accessed: 2025-07-03. National Health Service. 2023. URL: https://www.nhs.uk/conditions/motion-sickness/.

[24] Jialin Wang et al. "Effect of Frame Rate on User Experience, Performance, and Simulator Sickness in Virtual Reality". In: *IEEE Transactions on Visualization and Computer Graphics* 29.5 (2023), pp. 2478–2488. DOI: 10.1109/TVCG.2023.3247057.

[25] Kay Stanney, Cali Fidopiastis, and Linda Foster. "Virtual Reality Is Sexist: But It Does Not Have to Be". In: *Frontiers in Robotics and AI* Volume 7 - 2020 (2020). ISSN: 2296-9144. DOI: 10.3389/frobt.2020.00004. URL: https://www.frontiersin.org/journals/robotics-and-ai/articles/10.3389/frobt.2020.00004.

[26] Arockia Arockia Doss et al. "A Comprehensive Review of Wearable Assistive Robotic Devices Used for Head and Neck Rehabilitation". In: *Results in Engineering* 19 (Sept. 2023), pp. 1–14. DOI: 10.1016/j.rineng.2023.101306.

[27] Wai Ying Chung et al. "Give it a second try? The influence of feedback and performance in the decision of reattempting". In: *Cognition* 248 (2024), p. 105803. ISSN: 0010-0277. DOI: https://doi.org/10.1016/j.cognition.2024.105803. URL: https://www.sciencedirect.com/science/article/pii/S0010027724000891.

[28] Tech Prep. *CPU and GPU Architectures*. https://www.techprep.org/courses/cpu-gpu-architectures. Course material. Tech Prep, 2024.

[29] Andreas Burg. *Digital Systems Design*. Course material. 2024.

[30] Simon Oz. *Modern GPU Architecture / GPU Programming*. 2024. URL: https://www.youtube.com/watch?v=whPSD8sdx-0&t=47s.

[31] Meta Platforms, Inc. *Meta Quest 3 – Mixed Reality Headset*. 2025. URL: https://www.meta.com/ch/fr/quest/quest-3/.

[32] Wikipedia contributors. *List of Qualcomm Snapdragon Systems on Chips – Snapdragon XR series*. 2025. URL: https://en.wikipedia.org/wiki/List_of_Qualcomm_Snapdragon_systems_on_chips#Snapdragon_XR_series.

[33] Wikipedia contributors. *Adreno*. Accessed July 2, 2025. 2025. URL: https://fr.wikipedia.org/wiki/Adreno.

[34] Meta Platforms, Inc. *Technical developper documentations*. Accessed July 2, 2025. URL: https://developers.meta.com/horizon/develop/.

[35] Federico Quin et al. "A/B testing: A systematic literature review". In: *Journal of Systems and Software* 211 (2024), p. 112011. ISSN: 0164-1212. DOI: https://doi.org/10.1016/j.jss.2024.112011. URL: https://www.sciencedirect.com/science/article/pii/S0164121224000542.

[36] Aaron Bangor, Phil Kortum, and James Miller. "Determining What Individual SUS Scores Mean: Adding an Adjective Rating Scale". In: *J. Usability Stud.* 4 (Apr. 2009), pp. 114–123.

[37] Bina Ramamurthy. *Fundamentals of Computer Design*. Lecture slides. Course: CS506. 1997.

[38] Marilyn Wolf. *Computers as Components*. Course material.