

# **Development of biofeedback-based Virtual Reality therapies, research of efficiency and presence**

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Ph.D. Thesis

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DEVELOPMENT OF BIOFEEDBACK-BASED VIRTUAL REALITY  
THERAPIES, RESEARCH OF EFFICIENCY AND PRESENCE

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# Abstract

This Ph.D. thesis focuses on developing and evaluating biofeedback-based Virtual Reality (VR) therapies, particularly their effectiveness in rehabilitation settings. The primary aim is to design VR-based serious games that engage patients in activities such as breathing exercises and memory improvement programs, targeting individuals with post-COVID syndrome, memory issues, and pulmonary disorders, while also aiding in stress reduction. The final goal was to identify best practices for VR rehabilitation. The research began with a comprehensive review of existing technologies designed for individuals with cognitive impairment. Out of 132 studies, a total of 23 studies were analyzed to understand the strengths and limitations of technologies such as VR, mobile devices, and wearable assistive technology in addressing cognitive challenges. Findings show that these Information Technology (IT) solutions offer a cost-efficient alternative to clinical therapies and provide innovative methods for assessing memory functions. In the first phase, a comparison was made between visualization devices, such as mobile phones, tablets, monitors, and VR headsets, to evaluate their impact on rehabilitation. The experiment included 33 healthy participants who engaged in indoor cycling while watching a beach cycling video on various devices. User experience, engagement, and heart rate were measured, revealing that VR head-mounted displays (HMDs) provided the most immersive experience, with 68% of the participants rating them highest for attractiveness and effectiveness. Larger monitors were also preferred for their comfort. A VR version of the Corsi-Test, a spatial memory assessment tool, was developed. This VR-based version, created in Unity, allows for more precise and adaptable assessments compared to traditional methods. A pilot experiment with 14 participants showed reduced heart rates and improved outcomes, underscoring the advantages of using VR for cognitive assessments. The digital environment enhanced user comfort and engagement, offering a promising alternative for spatial memory testing. Another significant part of the research involved exploring how different virtual environments affect patients during VR-based breathing exercises. Using Oculus Quest 2, participants were guided through relaxation techniques in three different 3D environments: a sunny-happy forest (*Positive-Affective Environment*), a neutral forest (*Neutral-Baseline Environment*), and a dark, stormy forest. While both traditional and VR methods were effective in reducing anxiety, the positive-affective VR environment consistently produced the largest reduction in anxiety levels, as measured by the State-Trait Anxiety Inventory for State Anxiety (STAI-S) scores. This finding suggests that VR environments designed with positive emotional stimuli can enhance stress reduction and rehabilitation outcomes. This research shows that VR-based therapies offer significant potential for boosting rehabilitation outcomes. For future research, the use of biofeedback in VR to monitor physiological responses, such as heart rate and breathing patterns, in real time can enable dynamic adjustments to the VR environment and exercises to align with the patient's physical and emotional state. This personalized feedback loop ensures that therapy is tailored to the individual, delivering immediate stress relief while also supporting long-term rehabilitation goals.

# Tartalmi kivonat

Doktori disszertációm, a biofeedback alapú virtuális valóság (VR) terápiák fejlesztésére és értékelésére összpontosít, különös tekintettel azok hatékonyságára, rehabilitációs környezetben. Az elsődleges célom olyan, VR-alapú játékok tervezése, amelyek a poszt-COVID-szindrómában, memóriaproblémákban, és tüdőbetegségekben szenvedő egyének rehabilitációját segíti azáltal, hogy olyan tevékenységekbe vonják be, mint például légzőgyakorlatok és memóriajavító programok, miközben a stressz csökkentését is segítik. A kutatás végső célja a VR-rehabilitáció legjobb gyakorlatainak meghatározása. Másrészt a kutatás a kognitív zavarokkal küzdő egyének számára készült, és a meglévő technológiák átfogó áttekintésével kezdődött. Összesen 132 tanulmányból 23 került elemzésre, hogy az olyan technológiák, mint a VR, a mobil eszközök, és a viselhető segéd technológiák erősségei és korlátjai érthetőbbé váljanak, a kognitív kihívások kezelésében. Az eredmények azt mutatják, hogy ezek az informatikai megoldások költséghatékony alternatívát kínálnak a klinikai terápiákhoz képest, és innovatív módszereket biztosítanak a memóriefunkciók értékelésében. Az első fázisban a vizualizációs megjelenítő eszközök, mobiltelefon, táblagép, monitor és VR szemüveg összehasonlítására került sor, hogy értékeljem a rehabilitációra gyakorolt hatásukat. A vizsgálatban 33 egészséges résztvevő vett részt, akik szobakerékpározást végeztek, miközben egy kerékpározáshoz kapcsolódó videót néztek a különböző eszközökön. A felhasználói élményt, az elkötelezettséget, és a pulzusszámot mértem, és kiderült, hogy a VR szemüveg nyújtotta a legjobb élményt. A résztvevők 68%-a legmagasabbra a hatékonyságot és a vonzerőt értékelte. A nagyobb monitor is jó értékelést kapott ezekben az aspektusokban, továbbá a kényelmet is pozitíva értékelték. A Corsi-teszt, egy térbeli memória vizsgálatára szolgáló eszköz is implementálásra került, VR környezetben. Ez a Unity-ben létrehozott VR-alapú változat a hagyományos módszerekhez képest pontosabb értékelést tett lehetővé. Egy 14 résztvevővel végzett kísérleti tanulmány kimutatta, hogy a résztvevők pulzusa csökkent, illetve jobb eredményeket produkáltak, ami kiemeli a VR kognitív értékelésekhez való használat előnyeit. A digitális környezet fokozta a felhasználók kényelmét és elkötelezettségét, és ígéretes alternatívát kínált a térbeli memória tesztelésére. A kutatás másik része arra irányult, hogy a különböző virtuális környezetek hogyan hatnak a páciensekre, a VR-alapú légzőgyakorlatok során. Az Oculus Quest 2 segítségével a résztvevőket három különböző 3D-s környezetben vezettem végig a relaxációs technikákon: egy napsütéses, egy semleges és egy sötét, viharos erdőben. Bár mind a hagyományos, mind a VR-módszerek hatékonyan csökkentették a szorongást, a boldogabb VR-környezet következetesen a legnagyobb mértékű szorongás csökkenését eredményezte, amit a State-Trait Anxiety Inventory for State Anxiety (STAI-S) pontszámok alapján mértem. Ez arra utal, hogy a pozitív érzelmi ingerekkel kialakított VR-környezetek fokozhatják a stressz csökkentését és a rehabilitációs eredményeket. Ez a kutatás azt mutatja, hogy a VR-alapú terápiák jelentős potenciált kínálnak a rehabilitációs eredmények növelésére. A jövőbeni kutatásokhoz javasolt a biofeedback alapú virtuális valóság terápiák használata, amik azáltal, hogy a fiziológiai válaszokat monitorozzuk - például a szívfrekvencia és a légzésminták valós idejű megfigyelése - lehetővé teszik a VR-környezet és a gyakorlatok dinamikus beállítását, a páciens fizikai és érzelmi állapotához igazodva. Ez a személyre szabott visszacsatolás biztosítja majd, hogy a terápia egyénre szabott legyen, azonnali stresszoldást biztosítva, miközben támogatja a hosszú távú rehabilitációs célokat is.



# Abstrakt

Diese Doktorarbeit befasst sich mit der Entwicklung und Evaluierung von Biofeedback-basierten Virtual Reality-(VR)-Therapien, insbesondere deren Wirksamkeit in der Rehabilitation. Das Hauptziel besteht in der Entwicklung von VR-basierten Serious Games, die Patienten in Aktivitäten wie Atemübungen und Gedächtnisförderungsprogrammen einbinden. Diese richten sich an Personen mit Post-COVID-Syndrom, Gedächtnisproblemen und Lungenerkrankungen und unterstützen gleichzeitig den Stressabbau. Ziel ist es, die besten Verfahren für die VR rehabilitation zu ermitteln. Die Forschungsarbeiten begannen mit einer umfassenden Überprüfung bestehender Technologien, die für Menschen mit kognitiven Beeinträchtigungen entwickelt wurden. Insgesamt wurden 23 von 132 Studien analysiert, um die Stärken und Schwächen von Technologien wie VR, mobilen Geräten und tragbaren Technologien bei der Bewältigung kognitiver Herausforderungen zu verstehen. Die Ergebnisse zeigen, dass diese IT-Lösungen eine kosteneffiziente Alternative zu klinischen Therapien darstellen und innovative Methoden zur Bewertung der Gedächtnisleistung bieten. In der ersten Phase wurden Visualisierungsgeräte wie Mobiltelefone, Tablets, Monitore und VR Headsets verglichen, um ihre Auswirkungen auf die Rehabilitation zu bewerten. An der Studie nahmen 33 gesunde Teilnehmer teil, die während des Fahrradfahrens in der Halle ein Video über das Radfahren am Strand auf verschiedenen Geräten ansahen. Dabei wurden das Benutzererlebnis, das Engagement und die Herzfrequenz gemessen. Die Ergebnisse zeigten, dass VR HMDs das eindringlichste Erlebnis boten, da 68 % der Teilnehmer sie als attraktiv und effektiv bewerteten. Auch größere Monitore wurden wegen ihres Komforts bevorzugt. Eine VR-Version des Corsi-Tests, eines Instruments zur Bewertung des räumlichen Gedächtnisses, wurde entwickelt. Diese VR-basierte Version, erstellt in Unity, ermöglichte präzisere und flexiblere Bewertungen im Vergleich zu herkömmlichen Methoden. Eine Pilotstudie mit 14 Teilnehmern zeigte eine verringerte Herzfrequenz und verbesserte Ergebnisse, was die Vorteile von VR für kognitive Beurteilungen unterstreicht. Die digitale Umgebung erhöhte den Komfort und das Engagement der Benutzer und bietet eine vielversprechende Alternative für Tests des räumlichen Gedächtnisses. Ein weiterer wichtiger Teil der Forschung bestand darin, die Wirkung verschiedener virtueller Umgebungen auf Patienten während VR-basierter Atemübungen zu untersuchen. Mithilfe der Oculus Quest 2 wurden die Teilnehmer durch Entspannungstechniken in drei verschiedenen 3D-Umgebungen geführt: einem sonnig-fröhlichen Wald, einem neutralen Wald und einem dunklen, stürmischen Wald. Während sowohl die traditionellen als auch die VR-Methoden zur Reduktion von Angst beitragen, führte die fröhliche VR-Umgebung durchweg zur größten Reduktion des Angstniveaus, gemessen mit dem State-Trait Anxiety Inventory for State Anxiety (STAI-S). Dies deutet darauf hin, dass positiv gestaltete VR-Umgebungen den Stressabbau und die Rehabilitationsergebnisse verbessern können. Die Forschung zeigt, dass VR-basierte Therapien ein erhebliches Potenzial zur Verbesserung der Rehabilitationsergebnisse bieten. In zukünftigen Studien könnte der Einsatz von Biofeedback in VR zur Überwachung physiologischer Reaktionen wie Herzfrequenz und Atemmuster in Echtzeit genutzt werden, um dynamische Anpassungen der VR-Umgebung und der Übungen zu ermöglichen. Dadurch könnten die Therapie individuell auf den physischen und emotionalen Zustand des Patienten abgestimmt werden. Diese personalisierte Feedbackschleife stellt sicher, dass die Therapie sowohl kurzfristige Stressreduzierung als auch langfristige Rehabilitationsziele unterstützt.

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# List of Abbreviations

<b>AI</b>	Artificial Intelligence
<b>BoW</b>	Bag of Words
<b>CBM</b>	Constraint-Based Modeling
<b>CRG</b>	Cognitive Rehabilitation Games
<b>CSV</b>	Comma-separated values
<b>DASS</b>	Depression Anxiety Stress Scales
<b>EBPM</b>	Event-based Prospective Memory
<b>EEG</b>	Electroencephalogram
<b>HMD</b>	Head-mounted displays
<b>IAI</b>	IPad-assisted instruction
<b>ID</b>	Intellectual disabilities
<b>IDD</b>	Intellectual and Developmental Disabilities
<b>JPES</b>	Journal of Physical Education and Sport
<b>JSON</b>	JavaScript Object Notation
<b>MDD</b>	Major Depressive Disorder
<b>MMORPG</b>	Massively Multiplayer Online Role-Playing Game
<b>NIBS</b>	Non-Invasive Brain Stimulation
<b>NLTK</b>	Natural Language Toolkit
<b>NRG</b>	Neurological Rehabilitation Games
<b>PM</b>	Prospective Memory
<b>PRG</b>	Pediatric Rehabilitation Games
<b>PRISMA</b>	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
<b>PSY</b>	Psychological Rehabilitation Games
<b>PTG</b>	Physical Therapy Games
<b>RLD</b>	Reading learning disabilities
<b>SD</b>	Standard Deviation
<b>SSCG</b>	Social Skills and Communication Games
<b>STAI</b>	State-Trait Anxiety Inventory
<b>STAI-S</b>	State-Trait Anxiety Inventory for State Anxiety
<b>STAI-T</b>	State-Trait Anxiety Inventory for Trait Anxiety
<b>SUS</b>	System Usability Scale
<b>TBI</b>	Traumatic Brain Injury
<b>UEQ</b>	User Experience Questionnaire
<b>UX</b>	User Experience
<b>VR</b>	Virtual Reality
<b>WMT</b>	Working Memory Training



# Chapter 1

## 1. Introduction

My research focuses on the development and evaluation of biofeedback-based Virtual Reality (VR) therapies, particularly their efficiency and presence in rehabilitation settings. The primary aim is to design VR-based serious games that can engage patients in activities, such as breathing exercises and memory improvement programs. These games are intended to help individuals with post-COVID syndrome, memory problems, and pulmonary disorders, while also aiding in stress reduction. The research is divided into two main parts: comparing the effectiveness of various visualization displays in rehabilitation and developing serious games that can improve patients' health conditions. The primary goal is to identify the best practice in Virtual Reality rehabilitation [1,2].

In the early stages of my Ph.D., I conducted a comprehensive literature review of existing technologies designed to assist individuals with cognitive impairment. I examined 23 studies, out of 132, that explored various applications, assessing their effectiveness and limitations in addressing specific cognitive challenges. For the systematic review, the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology [3] was applied to screen and select relevant literature. The findings indicate that Information Technology (IT) solutions, such as VR, mobile technology, and wearable assistive technology, can be effectively used as home-based alternative therapies. These solutions not only offer a cost-efficient alternative to clinical devices but also provide new methods for memory function assessments. Additionally, Artificial Intelligence (AI) has shown potential to enhance the accuracy and efficiency of both diagnosis and treatment in this field. Secondly, in the initial phase of my research, I compared various visualization devices—mobile phones, tablets, monitors, and VR HMDs—to evaluate their impact on rehabilitation. A total of 121 studies were reviewed, and 17 were selected for in-depth analysis. Using a group of 33 healthy participants who engaged in indoor cycling while watching a beach cycling video, I measured user experience and engagement with different devices. During the exercises, the participant's heart rate was also monitored. The results revealed that VR HMDs offered the most immersive and engaging experience, with 68% of the participants rating them the highest for both attractiveness and efficiency. Larger displays, such as 24-inch monitors, are also preferred for rehabilitation, with heart rate measurements showing no significant variation across devices during exercise. Thirdly, I tested the effects of a well-known spatial memory assessment—the Corsi-Test—within a VR environment, comparing its performance to traditional, non-digital methods. Developed in Unity, this VR-based version allows more flexible parameter changes and enhances the overall precision of the evaluation process. Trials with 14 participants showed reduced heart rates and improved outcomes compared to traditional methods. The VR-based digital approach enhances adaptability, user

comfort, and engagement, offering a more effective alternative for spatial memory assessments. In collaboration with psychologists from Eötvös Loránd University, the research has since been expanded. A new study involving 44 participants—each completing both the traditional and VR-based Corsi memory tasks—has been conducted, with the results currently under publication. [J9] The findings indicate that the VR version of the Corsi task performs on par with the original, offering a viable and engaging alternative for cognitive testing. Further research is ongoing, focusing on age-specific responses to the VR-based assessment across the following age groups: Adolescents (12–18 years); Young adults (18–39 years); Middle-aged adults (40–65 years); Seniors (65+ years). These upcoming results will provide a more comprehensive understanding of VR-based cognitive testing across the lifespan.

Finally, in an experiment, my goal was to explore how different virtual environments affect patients' experiences during VR-based breathing exercises, using Oculus Quest 2 to create 3D settings. Participants were guided through relaxation techniques like Box Breathing, 4-6-8 Breathing, and “Humming” breathing in three different environments: a sunny forest, a neutral forest, and a negative-affective, stormy forest. Initial results suggest that while both VR and traditional methods are effective in reducing anxiety, the positive-affective VR environment showed superior results in lowering STAI-S scores compared to the neutral-baseline and negative-affective environments. This highlights the potential of immersive VR environments to reduce stress and improve rehabilitation outcomes. These results underscore the promising role of VR-based serious games and biofeedback technologies in rehabilitation. By advancing techniques that leverage IT solutions and immersive environments, the goal is to create more effective, accessible, and engaging therapies for individuals suffering from a variety of health conditions.

### **1.1. Research Motivation and Problem Statement**

The use of biofeedback and VR in rehabilitation represents a promising but underexplored area of research. As technology advances, the integration of innovative methods into healthcare has become crucial. This Ph.D. dissertation is driven by the urgent need in modern healthcare for accessible, personalized rehabilitation treatments, as traditional methods often lack the effectiveness and efficiency to meet patients' diverse, complex needs. This challenge impacts millions globally and places significant strain on healthcare systems and caregivers. Virtual Reality therapies would therefore form a potential avenue for addressing these challenges by offering scalable, patient-centered solutions to traditional therapeutic interventions. Unlike traditional methods, VR can reproduce engaging and immersive environments that transform traditional rehabilitation tasks into dynamic and engaging experiences. The use of VR can potentially make rehabilitation enjoyable and interactive, which is very important for maintaining patient participation for as long as possible, thereby leading to better health outcomes. Biofeedback associated with Virtual Reality increases the level of personalization and the specificity of therapeutic interventions. Biofeedback can

change the VR environment and exercise in real time by monitoring physiological responses, such as heart rate or breathing patterns, to reflect the patient's current physical and mental state. This personalized feedback loop ensures the therapy adapts and responds, ensuring immediate benefits such as stress reduction while at the same time working longer-term on rehabilitation goals. A unified goal is to identify the best practices for implementing VR-based solutions in rehabilitation settings. Each experiment examines distinct aspects of VR and related technologies to develop an evidence-based approach for designing, implementing, and optimizing VR for therapeutic use. This thesis explores the best practices for using VR in rehabilitation through four experiments, each targeting a specific application. The best practice proposal for each experiment is based on its findings:

*Comparing Visualization Devices for Rehabilitation:* Prioritize VR HMDs for immersive, high engagement rehabilitation, with larger monitors as an alternative for flexible patient needs.

*Virtual Reality Implementation:* VR adaptations of cognitive assessments like the Corsi-Test for improved engagement and accuracy, enabling flexible, user-friendly testing.

*User Experience in Virtual Rehabilitation:* Focusing on user experience, this experiment aims to establish VR as a practical and impactful medium for rehabilitation, highlighting its role in driving meaningful, patient-centered therapeutic advancements.

*The Impact of 3D Environments:* Design therapeutic VR environments (e.g., sunny forests) for stress reduction, optimizing settings to enhance relaxation and anxiety relief.

Taken together, these experiments underscore a single overarching goal: establishing the best practices for VR in rehabilitation. The research highlights the value of VR in enhancing engagement, personalizing therapeutic environments, and providing cost-effective, accessible tools for various cognitive and physical challenges. Through a structured exploration of different VR applications and devices, these experiments converge on a key insight: VR's adaptability and immersive capabilities make it a powerful tool for improving rehabilitation outcomes, whether through enhanced assessments, personalized treatment environments, or increased user engagement. By systematically evaluating VR's effectiveness across different therapeutic applications, these experiments collectively outline a set of practices for designing VR rehabilitation programs. This framework advances the field toward more effective, user-friendly, and adaptable VR solutions, ultimately contributing to improved therapies for individuals with cognitive and physical impairments.

## **1.2. Research Gaps and Differentiation**

While VR and biofeedback show promise in rehabilitation, existing research often lacks standardization, and rarely integrates physiological monitoring. Few studies systematically explore how these technologies can be optimized for stress reduction, memory training, or breathing exercises. This dissertation addresses these gaps by investigating best practices for personalized, engaging, and effective VR-based rehabilitation, and by contributing to the development of optimized VR environments tailored to cognitive, stress, and breathing interventions.

### **1.2.1. VR for Cognitive/Memory Rehabilitation**

Recent trials in older adults (healthy seniors) found that immersive VR games can improve memory and attention. For example, Szczepocka et al. [4] delivered a VR “Digital Therapeutics” with n-back memory tasks in natural 360° scenes and observed gains in visual memory and sustained attention in healthy seniors. This suggests VR can enhance cognitive performance in older adults; however, equivalent evidence in younger healthy adults is sparse. VR tasks simulating real-world scenarios (e.g. shopping, household tasks) have been used to assess and train memory. Studies like Krawczyk et al. [5] demonstrated that a VR grocery-list task effectively measures working memory strategies in adults. Such naturalistic VR tasks may improve the ecological validity of memory rehab, but systematic testing in healthy populations is limited. Unlike screen-based exercises, immersive VR offers embodied interaction and richer sensory cues [6]. This may increase user engagement and the transfer of trained skills to daily life. However, meta-analyses note mixed results on far-transfer from cognitive training in healthy adults. In sum, VR shows potential, but more studies are needed on memory rehabilitation in non-clinical adults.

### **1.2.2. VR for Stress Management and Breathing Interventions**

Systematic reviews report that VR interventions (e.g. guided relaxations, nature scenes) generally lower self-reported stress and improve well-being in young and adult populations. For instance, Xu et al. [7] found that VR-based “well-being” activities significantly reduced stress levels across multiple studies. Immersive VR thus appears to be an effective medium for acute stress relief. Empirical studies confirm objective stress reduction from VR. In a randomized trial, McGarry et al. [8] exposed healthy 18–25 year-olds to a 10-minute immersive relaxation VR and found a significant heart rate drop and lower anxiety ratings after VR. Similarly, Kim et al. [9] showed that VR relaxation sessions (even without explicit biofeedback) significantly decreased anxiety and subjective stress in high stress adults. These findings indicate that VR alone can induce relaxation comparable to traditional biofeedback. Recent reviews highlight how VR can augment breathing-based training. Pancini et al. [10] summarize that VR breathwork systems can “reduce distractions” and “enhance focus” during practice, provide real time exteroceptive feedback, and allow customized environments (e.g. calming nature) for training. Across 18 studies, they report positive effects of VR breathing exercises on relaxation, well-being, and physical health, noting VR’s unique potential to make breathing practice more engaging. Meta-analytic evidence is mixed. Cortez-Vázquez et al. [11] conducted a meta-analysis of RCTs and found “no evidence that VR breathing interventions are more effective than non-VR” formats on mental

health, heart rate, or HRV. In other words, VR did not significantly outperform equivalent breathing exercises done without VR. This implies VR’s main advantage may be engagement rather than efficacy per se, and highlights the need for well-designed studies.

### **1.2.3. Modality Comparisons and Implementation**

Systematic reviews emphasize matching modality to goals. For stress reduction and relaxation, immersive displays often create more lifelike “escape” but risk overstimulation [12]. For cognitive tasks, an HMD may boost motivation but can also induce motion discomfort. Best practice is to pilot-test both modalities with the target task and user group. A recurring theme is that poor VR design can hinder outcomes. Pancini et al. [13] warn that “poorly designed VR breathing interventions might distract trainees from the objectives” of the exercise. VR experiences should avoid gimmicks or unnecessary stimuli that pull attention away from the core training task. Incorporating a narrative or game elements can boost engagement. Chittaro et al.’s VR breathing game used a story-driven approach (e.g. controlling a character or environment) to make breathing practice more motivating [14]. Participants in that study reported a high presence and found the task enjoyable. Similarly, user feedback in VR relaxation trials highlights the importance of feeling “transported” to another place and finding the experience easy to use [8].

## **1.3. Objectives and Hypotheses**

This section outlines the core objectives and hypotheses that guide the research, focusing on the application of VR in rehabilitation. It details the research questions and hypotheses categorized into four primary groups, each addressing a specific aspect of VR's potential—device effectiveness, cognitive test adaptability, user engagement in rehabilitation, and the impact of immersive 3D environments.

### **1.3.1. What This Research Aims to Validate?**

This research investigates the potential of Virtual Reality as a transformative tool for rehabilitation and cognitive assessment. Four primary groups of research questions (RQ) and corresponding hypotheses (H) guide the exploration, each focusing on specific aspects of the VR application. This research seeks to explore the transformative potential of Virtual Reality (VR) and other visualization devices in rehabilitation, cognitive testing, and therapeutic applications. Specifically, the study is organized around four key areas of inquiry, each with distinct research questions and hypotheses that focus on user experience, engagement, physiological responses, and therapeutic outcomes.

#### **First Group: Comparing Visualization Devices for Rehabilitation**

The first aim is to evaluate how different visualization devices—mobile phones, tablets, monitors, and VR headsets—impact user engagement and physiological responses during activities like indoor cycling. To validate whether VR headsets

provide the highest levels of immersion and engagement, though they may introduce discomfort or stress. This exploration will also assess the impact of screen size and immersive qualities on heart rate and user preferences.

### **Second Group: Virtual Reality Implementation**

The second focus is on utilizing VR to enhance the flexibility and adaptability of traditional cognitive assessments, such as the Corsi-Test, while addressing any negative physiological impacts of VR environments. To confirm that VR-based testing allows for easier protocol modifications and adaptability, while assessing potential adverse effects such as increased heart rate and stress during testing.

### **Third Group: User Experience in Virtual Rehabilitation**

The third research aim is to investigate the effectiveness of VR in rehabilitation, particularly in improving user engagement and therapeutic outcomes in cognitive, neurological, and psychological therapies. To establish whether VR applications outperform traditional rehabilitation methods and identify the therapeutic areas where VR provides the most benefit.

### **Fourth Group: The Impact of 3D Environments**

The final aim focuses on the influence of different 3D virtual environments, ranging from cheerful to darker atmospheres, on stress reduction and overall rehabilitation results. To validate whether immersive VR environments, especially those designed to be positive and engaging, significantly enhance stress and anxiety reduction compared to non-immersive settings or neutral-baseline environments.

## **1.3.2. Research Questions and Hypothesis**

For my research, I set four groups of research questions and hypotheses, where each has a subject of interest:

**1RQ and 1H:** The first group deals with comparisons of mobile phones, tablets, monitors, and VR headsets to find the best visualization device.

**2RQ and 2H:** These latter questions address the outcomes of VR use in the Corsi-Test: how Virtual Reality can be better used to allow flexibility and adaptability in test protocols, taking into consideration its possible adverse effects, such as increased heart rate and stress levels.

**3RQ and 3H:** The third category investigates the impacts of VR in rehabilitation, especially cognitive, neurological, and therapy-based applications. This section represents the investigation of how VR could improve user engagement along with therapeutic outcomes, considering whether VR tends to show more promise in certain therapeutic areas rather than others.

**4RQ and 4H:** The fourth group examines the use of 3D virtual environments in rehabilitation, including the impacts of different atmospheres—ranging from positive-affective to darker settings—on stress, anxiety, and overall rehabilitation outcomes. The guided breathing techniques within these environments are compared for effectiveness in terms of reducing stress levels.

### **1.3.2.1. First Group: Comparing Visualization Devices for Rehabilitation**

Firstly, I started to investigate the influence of varying screen dimensions and immersive technologies, including Virtual Reality headsets, on user experience and engagement throughout indoor cycling activities. The hypotheses presented in this part (H1–H5) indicate that Virtual Reality is expected to exceed other devices in terms of immersion and engagement; however, variances in comfort levels and physiological responses, including heart rate, may occur.

**1RQ1:** How does the user experience differ when using various visualization devices, including mobile phones, tablets, monitors, and VR head-mounted displays, during indoor cycling sessions?

**1H1:** The user experience will vary significantly across different visualization devices during indoor cycling sessions, with VR head-mounted displays providing the most immersive and engaging experience, followed by monitors, tablets, and mobile phones.

**1RQ2:** What are the perceived advantages and disadvantages of using different visualization devices (mobile phone, tablet, monitor, VR headset) during indoor cycling activities, as reported by participants?

**1H2:** Participants may report that VR head-mounted displays offer the highest level of immersion and engagement during indoor cycling, but may also report discomfort or disorientation compared to other devices. Monitors will be perceived as the second most immersive with the highest comfort level. Tablets and mobile phones will be rated lower in terms of immersion but higher in terms of comfort.

**1RQ3:** How do different visualization devices impact user engagement and enjoyment during indoor cycling sessions?

**1H3:** User engagement and enjoyment during indoor cycling sessions will be highest when using VR head-mounted displays, followed by monitors, tablets, and mobile phones, respectively.

**1RQ4:** What are the user preferences regarding display size (mobile phone: 5.5 inches, tablet: 10 inches, monitor: 24 inches, VR headset) and their impact on the overall user experience during indoor cycling with visual stimuli?

**1H4:** Participants will prefer larger display sizes for indoor cycling sessions, with the 24-inch monitor and VR head-mounted display being the most preferred, followed by the 10-inch tablet and 5.5-inch mobile phone.

**1RQ5:** What are the effects of different visualization devices, including mobile phones, tablets, monitors, and VR head-mounted displays, on the heart rates of participants engaged in indoor cycling? Specifically, how do display sizes (mobile phone: 5.5 inches, tablet: 10 inches, monitor: 24 inches, VR headset) impact heart rate responses during a cycling session with visual stimuli?

**1H5:** Participants' heart rates will vary significantly depending on the visualization device used during indoor cycling sessions, with VR head-mounted displays resulting in the highest heart rates, followed by monitors, tablets, and mobile phones. Additionally, larger display sizes will be associated with higher heart rates due to increased immersion and engagement.

### **1.3.2.2. Second Group: Virtual Reality Implementation**

The second section details the use of VR in the Corsi-Test, a widely used tool for diagnosing memory and spatial awareness. Throughout this section, my plan was to look at how VR may further enhance the test by being more flexible and adaptable. It also considers some potential downsides, such as increased heart rate or stress in the user due to the immersive nature of the environment.

**2RQ1:** Does the use of digital iterations facilitate quicker modification of parameters, thereby enhancing flexibility and adaptability in testing protocols? Does the implementation of traditional in-person methods in Virtual Reality environments increase heart rate?

**2H1:** It can be presumed that employing traditional in-person methods within a Virtual Reality setting would elevate heart rate, thereby diminishing the efficacy of the test. Additionally, hypothesize that the characteristics of VR environments might contribute to a heightened sense of overwhelm and stress during testing, potentially impeding the effectiveness of traditional testing methodologies.

### **1.3.2.3. Third Group: User Experience in Virtual Rehabilitation**

Section three discusses how VR rehabilitation impacts user engagement and therapeutic outcomes on cognitive, neurological, and psychological dimensions. It then goes on to analyze the strengths and challenges concerning VR applications for rehabilitation. This hypothesis assumes that the level of user satisfaction might depend on the therapeutic category, and one might even notice the domination of CRG in front of the other VR applications.

**3RQ1:** How does Virtual Reality rehabilitation impact user engagement and therapeutic outcomes, and what are some advantages/disadvantages of VR applications in various therapeutic areas based on user feedback?

**3H1:** Virtual reality applications in rehabilitation increase user engagement and therapeutic outcomes compared to traditional rehabilitation methods, but are variably effective across different therapeutic categories.

#### **1.3.2.4. Fourth Group: The Impact of 3D Environments**

Finally, I investigated the significance of presence in the environment within Virtual Reality during rehabilitative activities. This part analyzes the impact of various virtual 3D environments on stress levels, anxiety, and rehabilitation results, positing that more cheerful environments produce more favorable outcomes in contrast to neutral-baseline or darker settings.

**4RQ1:** Does the integration of guided breathing techniques within a Virtual Reality (VR) environment enhance the effectiveness of these techniques in reducing stress and anxiety compared to performing the same techniques without any visual or auditory aids?

**4H1:** Participants who practice guided breathing techniques within an immersive Virtual Reality environment will experience greater reductions in stress and anxiety levels compared to those who perform the same techniques in a traditional setting without visual or auditory stimuli.

**4RQ2:** How do different Virtual Reality environments, ranging from positive-affective to neutral-baseline and dark, affect the rehabilitation process?

**4H2:** Exposure to varying Virtual Reality environments, including positive-affective, neutral-baseline, and negative-affective settings, will significantly impact rehabilitation outcomes by influencing mood, stress levels, heart rate, and overall engagement. A positive-affective Virtual Reality environment will lead to better rehabilitation outcomes compared to exposure to neutral-baseline or negative-affective environments.

#### **1.3.3. Objective**

The research aims to validate the proposed hypotheses by conducting experiments on healthy individuals to establish a foundational understanding of the potential applications of Virtual Reality in rehabilitation. The study focuses on identifying best practices for selecting visualization devices, implementing adaptable cognitive assessments, and designing optimized 3D virtual environments. This includes identifying best practices for selecting the most appropriate visualization devices for various therapeutic contexts, implementing user-friendly and adaptable cognitive assessment tests, and designing optimized 3D virtual environments to maximize

therapeutic benefits. By addressing key aspects such as device engagement, physiological responses, and user satisfaction, the study seeks to provide actionable insights into how VR can be tailored to different therapeutic and cognitive needs. Additionally, it aims to contribute to the broader understanding of how immersive technologies can enhance therapeutic outcomes, reduce stress and anxiety, and support cognitive and neurological rehabilitation.

## **1.4. Overview of the Research Field**

### **State of the Art**

This section discusses the advances in present-day technology for cognitive, neurological, and physical rehabilitation. The review considers current technologies—such as VR, AI, mobile applications, and wearable devices—in terms of their impact on daily activities, cognitive enhancement, and stress management. The current section reviews the most up-to-date achievements of the discussed technologies, summarizes their advantages and disadvantages, and suggests policies that can help overcome the limitations in cost, accessibility, and user acceptance to strengthen rehabilitation practices more widely.

#### **1.4.1. Method of the State of the Art**

For the systematic review, the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology [3] was applied to screen and select relevant literature across five key databases: Web of Science, Google Scholar, Scopus, ScienceDirect, and PubMed. The main objective was to filter the literature for studies relevant to specific research topics on assistive technologies, VR in rehabilitation, and VR's therapeutic applications. In a total of 456 studies were identified, narrowed to 74 following the PRISMA stages. Duplicate studies, non-English papers, inaccessible sources, and irrelevant papers not directly tied to cognitive disabilities, assistive technology, or application to VR and rehabilitation were excluded to retain studies focused on computerized tools for cognitive skill development across diverse demographics. This rigorous screening process across all reviews ensures that only high-quality, relevant studies inform each section of the research document.

*Figure 1.* displays the PRISMA flowchart, outlining each step of the systematic literature selection process. Related to my first experiment, the first review focused on assistive technologies for cognitive disabilities, starting with 132 studies. After applying the PRISMA stages, 23 studies remained, following the exclusion of duplicates, non-English papers, inaccessible sources, and irrelevant articles not directly related to cognitive disabilities or assistive technology. This narrowed the focus to studies on computerized tools designed to enhance cognitive skills across various demographics. The second review concentrated on the impact of VR in rehabilitation, with an initial set of 121 papers. After screening, 104 studies were excluded due to

irrelevance or lack of direct application to VR and rehabilitation, leaving 17 studies for detailed analysis. A third review focused on the comparative effectiveness of in-person and VR-based interventions, beginning with 71 studies. After screening, 66 studies were excluded, and 5 were selected for further examination of the comparison between traditional in-person interventions and VR-based treatments. A fourth review explored VR's role across different therapeutic disciplines, starting with 86 studies. Following screening, 73 studies were excluded for being irrelevant, and 13 studies were retained to assess VR's diverse applications across various therapeutic settings. Finally, the review on VR in stress and anxiety management began with 46 studies. After screening, 30 were excluded, and 2 studies were included in the main review, with additional studies referenced in Chapter 6.6.

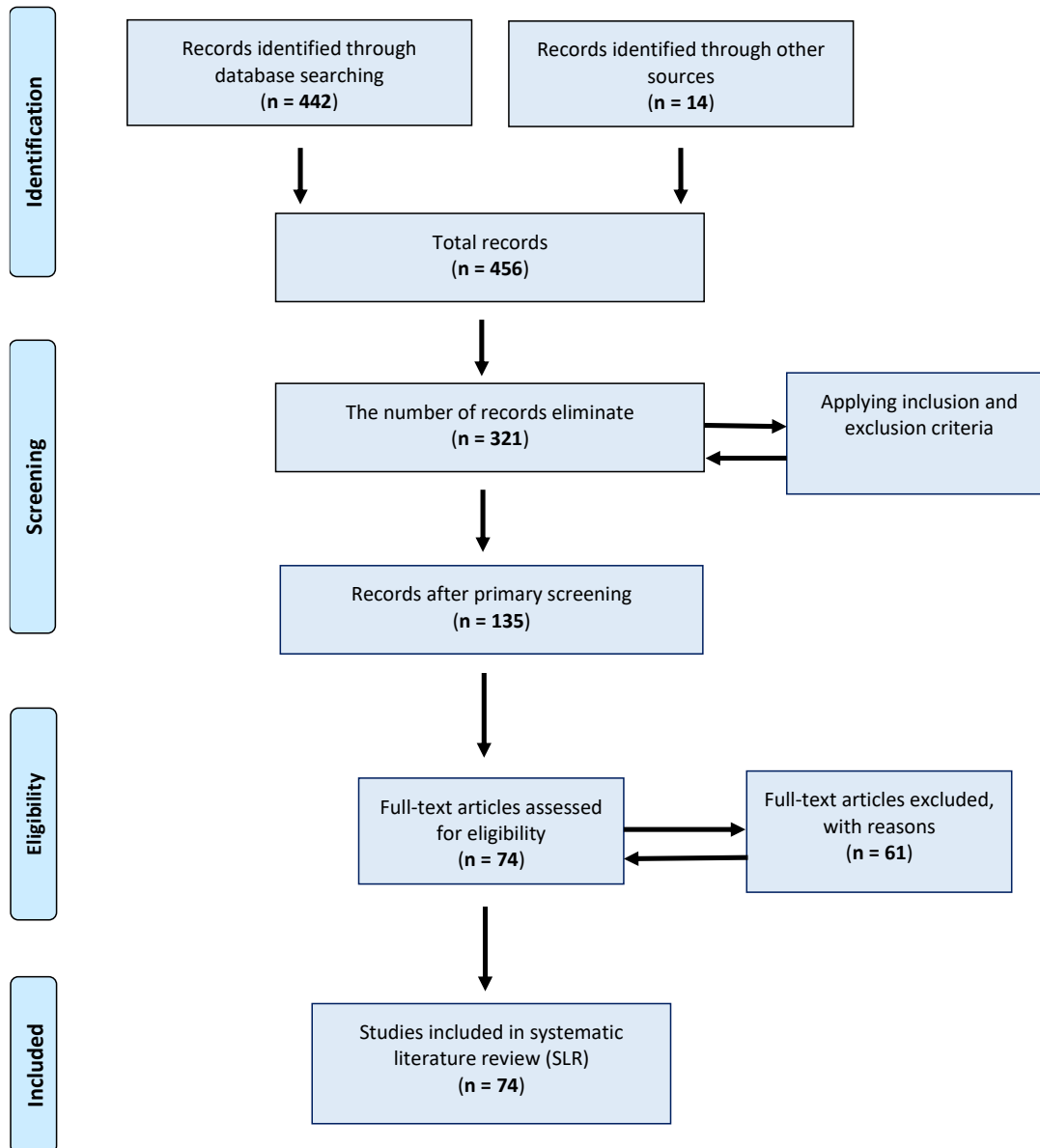
The rigorous application of PRISMA ensured that only the most relevant studies included in the research.

In *Chapter 1.4.3*, PRISMA facilitated the identification of 23 relevant studies from an initial pool of 132. These studies were pivotal in analyzing the effectiveness of various visualization devices, such as head-mounted displays, projection-based systems, and handheld VR devices, in supporting rehabilitation efforts. This process ensured that comparisons were drawn from evidence-based and methodologically robust sources.

In *Chapter 1.4.4.*, where the effectiveness of in-person and VR-based approaches is compared, the PRISMA methodology underpinned the selection of 5 key studies from an initial 71 articles. This process streamlined the review to emphasize only the most pertinent comparisons between traditional and VR-based therapeutic methods.

Similarly, in *Chapter 1.4.5.*, which examines VR's application in various therapeutic fields, 13 out of an initial 86 studies were retained, ensuring relevance to the investigation of user experiences and outcomes in virtual rehabilitation settings.

*Figure 1* in this chapter provides a visual representation of the PRISMA process, illustrating the systematic approach taken to refine the literature pool. This structured review process was critical to maintaining consistency and ensuring the validity of the findings discussed throughout the research.



**Figure 1.** PRISMA Flowchart of Systematic Literature Selection Process

*Table 1* presents a structured summary of the systematic review process conducted using the PRISMA methodology. This table outlines the five distinct literature reviews performed in the study, each focused on different but related aspects of virtual reality, assistive technologies, and cognitive rehabilitation. For each review, the table details the databases searched, keywords used, number of initial records identified, specific inclusion and exclusion criteria applied, and the final number of studies included after the full PRISMA screening process.

The reviews covered the following thematic areas: Assistive technologies for cognitive disabilities, VR in rehabilitation, Comparative analysis of in-person vs VR-based interventions, VR in various therapeutic disciplines, and VR for stress and anxiety management.

All reviews utilized the same five databases—Web of Science, Google Scholar, Scopus, ScienceDirect, and PubMed—to ensure comprehensive coverage of peer-reviewed literature. Common Exclusion Criteria Across All Reviews:

- Duplicate studies across databases,
- Non-English language publications,
- Inaccessible sources, such as unavailable full-text articles,
- Irrelevant focus, i.e., studies that did not directly address the specific themes (e.g., unrelated to VR, assistive technology, cognitive disability, or rehabilitation).

These exclusion criteria were strictly enforced to ensure that only high-quality, relevant, and accessible studies were retained for detailed analysis.

The initial pool of literature totaled 456 studies across all five reviews. After applying the PRISMA filtering criteria, only 60 studies were included in the final synthesis. This rigorous process helped narrow the scope to evidence-based studies that were both methodologically sound and directly relevant to the research objectives. The inclusion criteria focused on peer-reviewed, English language studies with clear relevance to VR, assistive technology, or therapeutic interventions. Chapter references (e.g., Chapters 1.4.3 to 1.4.5) in the main document further elaborate on the thematic analyses and findings derived from each subset of the literature. *Table 1*, together with *Figure 1* (the PRISMA flowchart), ensures transparency in the selection process and provides a replicable model for future systematic reviews within the field of digital rehabilitation and VR-assisted therapy.

**Table 1.** Summary of the Systematic Review Process conducted using the PRISMA methodology

Review Topic	Keywords Used	Initial Records Identified	Inclusion Criteria	Exclusion Criteria	Final Studies Included
<b>Assistive Technologies for Cognitive Disabilities</b>	"assistive technology", "cognitive disability", "rehabilitation", "digital tools", "computer-based therapy"	132	Peer-reviewed, English language, relevance to assistive technology and cognitive disability, computerized interventions.	Duplicates, non-English, inaccessible, unrelated to assistive technology or cognitive disability.	23
<b>VR in Rehabilitation</b>	"virtual reality", "rehabilitation", "VR therapy", "digital rehabilitation"	121	Use of VR in therapeutic/rehabilitation contexts, English language.	Irrelevant scope, lack of direct VR application, duplicates,	17

				and non-English.	
<b>Comparative Analysis: In-Person vs VR Interventions</b>	"virtual reality", "in-person therapy", "traditional rehabilitation", "comparative study", "treatment effectiveness"	71	Comparative studies on VR and traditional interventions, peer-reviewed, English.	No direct comparison, poor methodological quality, non-English, duplicates.	5
<b>VR in Therapeutic Disciplines</b>	"virtual reality", "therapy", "mental health", "occupational therapy", "physiotherapy", "therapeutic applications"	86	English language, focused on VR use in specific therapy types, peer-reviewed.	Unrelated to therapy, non-English, duplicates, inaccessible.	13
<b>VR for Stress and Anxiety Management</b>	"virtual reality", "stress reduction", "anxiety therapy", "psychological intervention", "relaxation VR"	46	English, VR use in managing stress/anxiety, peer-reviewed.	Not focused on stress/anxiety, non-English, duplicates, irrelevant focus.	2 (plus additional cited in Chapter 6.6)

### 1.4.2. Defining Key Concepts

In this section, I define terms and concepts that form the basis of this research. These include Virtual Reality in rehabilitation, user experience, and presence. By providing clear definitions, the framework highlights the scope and potential of VR technologies in advancing therapeutic applications for cognitive and psychological rehabilitation.

#### Virtual Reality in Rehabilitation

Virtual Reality refers to digitally constructed environments that allow users to experience and interact with simulated settings in real time. These environments, accessible via head-mounted displays, are increasingly used in rehabilitation to provide controlled, engaging, and interactive therapeutic platforms.

VR in rehabilitation takes advantage of being an immersive technology, and simulates tasks or environments that mimic real-life scenarios, enabling individuals to practice

skills in a safe and adaptable space [15]. For instance, stroke patients may use VR to relearn motor skills by interacting with objects in a virtual kitchen [16]. Despite its potential, VR faces challenges, including limited accessibility due to cost, cybersickness caused by motion inconsistencies, and the need for more extensive clinical validation.

### **User Experience**

User Experience (UX) in rehabilitation refers to the overall effectiveness, usability, and satisfaction experienced by individuals when interacting with therapeutic technologies. A positive UX is critical in rehabilitation as it impacts patient engagement, therapy efficiency, and outcomes. Factors contributing to UX in VR rehabilitation include intuitive navigation, immersive visuals, and feedback mechanisms that resonate emotionally with users. For example, virtual environments, like a sunny and quiet beach, can evoke calmness, making therapy more enjoyable and effective. Assessing UX involves both subjective measures, such as user feedback, and objective data, like usage patterns or physiological responses. Designing VR applications with user needs as a priority ensures accessibility and effectiveness across diverse patient populations [17].

### **Presence**

Presence describes the feeling of “being there” in a virtual environment. It is a vital component of VR-based therapy, as higher presence levels often correlate with greater engagement and therapeutic impact. For example, a patient with anxiety practicing relaxation in a VR forest is more likely to experience benefits if the sense of presence is strong. Presence is shaped by factors such as visual realism, interactivity, and the responsiveness of the VR system. Measurement tools like presence questionnaires or physiological metrics such as heart rate variability are often employed to evaluate presence. Ensuring an optimal sense of presence while avoiding overstimulation or discomfort is a key goal in VR application design for rehabilitation [18].

By defining these concepts, this section outlines the theoretical framework necessary to explore VR's transformative potential in rehabilitation. Subsequent sections will delve deeper into the applications and advancements of VR in enhancing cognitive and psychological therapies.

## **1.4.3. Identifying Devices and Technologies for Effective Rehabilitation**

### **First Group: Comparing Visualization Devices for Rehabilitation**

Cognitive impairments in many aspects of daily life demand individualized strategies to improve memory, enable learning, and encourage social interaction. Recent developments in assistive technologies have the potential for cost-effective and engaging interventions to improve the quality of life of individuals with cognitive impairment. Studies have already demonstrated the potential of VR for cognitive

rehabilitation and memory assessment, offering more engaging and ecological evaluations than traditional neuropsychological assessments. The research examined concentrated on assistive technologies designed for individuals with cognitive disabilities and investigated various tools, including VR, mobile applications, robotic systems, and smart technologies.

- VR has demonstrated efficacy in cognitive rehabilitation, particularly in memory assessment and training for disorders such as dementia and depression.
- Mobile and smart applications have indicated the potential to enhance memory and cognition, providing educational and therapeutic experiences through gamification and entertainment methods.
- The emphasis in both articles is on ecologically valid studies and the introduction of new technologies, such as VR and AI, into this field to enhance memory rehabilitation.

These technologies are seen as crucial in supporting healthcare professionals and reducing caregiver burdens while promoting patient independence. I observe the strengths and limitations of the main assistive technologies included in this research. Despite these developments, challenges still abound - high costs with the technologies, extensive clinical validation required, and the problem of cybersickness. Additionally, device transparency, linguistic barriers, and issues of availability and affordability further constrain the widespread adoption of these technologies. In the following, research on the use of VR and AI technologies in cognitive rehabilitation is presented, with a focus on tools and applications that enhance memory assessment, daily functionality, and support for individuals with cognitive impairments. Through the examination of various studies, it is highlighted how immersive VR experiences and AI-driven solutions are transforming treatment for conditions such as Alzheimer's, major depressive disorder, and stroke-related memory deficits.

Recent advancements in VR and AI have significantly contributed to cognitive assessment and rehabilitation. Varela-Aldás [19] identified VR as a valuable tool for cognitive rehabilitation through the "Cupboard task," an immersive application for memory assessment. The study demonstrated successful memory evaluation with robust construct validity, correlating with age, education, and gender. Its high usability suggests potential clinical applications for cognitive impairments such as Alzheimer's disease, pending further trials. Huang et al. [20] examined VR-based Working Memory Training (WMT) for patients with Major Depressive Disorder (MDD). The findings indicated improved Event-based Prospective Memory (EBPM) accuracy in the VR group, though no significant changes were observed in depressive symptoms, highlighting the need for broader studies. Gregory et al. [21] explored the integration of VR with electroencephalogram (EEG) technology to monitor neural signals during memory and attention tasks. By employing social and non-social cues within VR, the study provided novel insights into the neural correlation of working memory. Ouellet et al. [22] introduced the "Virtual Shop," a fully immersive task designed for ecologically valid memory assessment. This tool successfully distinguished between

the performances of younger and older adults and correlated well with independent memory measures, making it a feasible and reliable cognitive evaluation method. Bayahya et al. [23] proposed a 3D virtual environment for assessing dementia patients, offering an economical alternative to expensive diagnostic tools like MRI. The platform enables interactive cognitive assessments, presenting a practical method for dementia diagnosis. Specht et al. [24] evaluated the acceptance of head-mounted VR systems among stroke patients and healthy adults, finding positive attitudes from both groups and comparable memory spans. This suggests VR as a cost-effective and engaging approach for post-stroke cognitive enhancement. Mathews et al. [25] developed a VR-based treatment to improve Prospective Memory (PM) in stroke survivors. The study involving 15 participants showed significant improvements in PM tasks, promising to help individuals with memory impairments achieve greater independence. Ow et al. [26] created a music-oriented application to assist in memorizing semantic declarative information. Initial testing showed efficacy, supporting the potential for future enhancements to make the tool widely accessible. Yonathan et al. [27] developed a game aimed at raising COVID-19 awareness while balancing usability, enjoyment, and difficulty. User feedback helped refine the design, focusing on hygiene habits and enjoyment. Rawendy et al. [28] implemented a gamified teaching methodology to teach Chinese to children. By incorporating mnemonic methods and engaging game elements, the study found increased interest and memory retention in language learning. Morimoto et al. [29] presented a dementia diagnosis system using eye tracking technology to evaluate cognitive abilities through puzzles. This innovative method reduces the burden on healthcare providers and patients, offering an efficient diagnostic alternative. ChePa et al. [30] developed a therapeutic intervention combining game mechanics with neurotherapy and an EEG headset for elderly patients with memory impairments. The research demonstrated cognitive enhancements, supporting the integration of gaming strategies with psychotherapeutic approaches. Mize et al. [31] recommended a hybrid method of peer-assisted and iPad-assisted instruction to improve oral reading fluency in students with reading disabilities, which proved effective in 5th-grade participants. Silva et al. [32] introduced a low-cost assistive technology prototype for adolescents with cerebral palsy, focusing on motor skill development. User satisfaction testing confirmed its effectiveness. Buitrago et al. [33] employed the NAO social robot for therapy in children with dyskinetic cerebral palsy. A case study with an 8-year-old participant showed improved motor learning, demonstrating the potential of robotic therapy. Nishiura et al. [34] developed a calendar-based electric assistive device for elderly individuals with cognitive impairments, finding it effective in improving cognitive function. Pinard et al. [35] designed COOK, a context-aware assistive technology supporting individuals with Traumatic Brain Injury (TBI) during meal preparation. High user satisfaction highlights its potential for aiding daily activities. Evmenova et al. [36] created a wearable smartwatch-based tool for self-regulation in young adults with intellectual and developmental disabilities (IDD). Testing with 52 participants showed that the device effectively enhanced communication and behavior. Douglas and Bigby [37] proposed an evidence-based decision-making support system for individuals with cognitive disabilities, validated by

health professionals as effective across various life domains. Kang and Chang [38] introduced a Kinect V2 sensor-based system to teach handwashing steps, achieving significant improvements in skill acquisition and autonomous hygiene. Mihailidis et al. [39] presented COACH, an AI-driven device that aids individuals with dementia in daily tasks, reducing caregiver dependency. Luxton [40] highlighted AI's transformative role in clinical psychology, particularly in training, treatment, and assessment, while addressing ethical considerations. Sheri et al. [41] developed "Memory Stash Alzheimer's Aid," an AI-based application that manages symptoms across all stages of Alzheimer's, improving patient quality of life. Together, these studies underscore how VR and AI are revolutionizing cognitive rehabilitation and assessment, addressing key gaps in accessibility, cost-effectiveness, and ecological validity. Robergs et al. [42] compared video-assisted cycling with traditional indoor cycling, finding that video-assisted cycling improved exercise experience and physiological demands, suggesting that sensory stimulation enhances exercise engagement. Molina et al. [43] evaluated exergaming's impact on physical functioning in older adults, emphasizing the need for rigorously designed studies to confirm its benefits. Cassani et al. [44] reviewed combining VR and Non-Invasive Brain Stimulation (NIBS) for neurological rehabilitation, reporting promising results but recommending further research. Housman et al. [45] compared passive instrumented arm orthosis with tabletop exercises in chronic stroke survivors, showing greater consistency in motor control improvements for the orthosis group. Merians et al. [46] highlighted significant hand function improvements through robot-assisted training in stroke survivors, while Adamovich et al. [47] employed robotic systems and virtual environments to improve dexterity and functionality in stroke patients. Mekbib et al. [48] conducted a meta-analysis on VR's efficacy in stroke rehabilitation, confirming its potential to enhance motor recovery and engagement. Pietrzak et al. [49] explored the Nintendo Wii for upper limb rehabilitation post-stroke, showing improvements and affordability. Bonnechère et al. [50] observed that video games were as effective as traditional physical therapy, with added motivational benefits.

Most of the studies yielded significant results, despite several limitations that have been noted, as shown in *Table A1* in the Appendix. The findings of this experiment demonstrate that the integration of IT and assistive technologies has the potential to make a significant positive impact on building a sustainable society. To conclude, the following can be stated:

- IT solutions like Virtual Reality, mobile technology, and wearable technology can be used as a home-based alternative therapy.
- These can be used as a new methodology to develop valid tests that assess memory functions.
- In addition to the previous statement, it can be inferred that these devices are more cost-efficient (lower cost than clinical devices).
- AI can increase the efficiency and accuracy of diagnosis and treatment.

Integrating AI and assistive technologies with VR offers promising advancements in cognitive rehabilitation, addressing both cognitive and emotional needs of patients. Despite some limitations, studies show significant results, suggesting that IT solutions like VR, mobile, and wearable technology can serve as effective, home-based alternatives for therapy and memory assessment, providing a cost-efficient and accessible approach. Additionally, AI can improve diagnostic accuracy and treatment effectiveness, supporting a sustainable healthcare model.

With various visualization devices in rehabilitation, despite their several potential benefits, questions concerning relative efficacies remain unclear because of application issues such as user discomfort, variation of the degree of immersion, and indeterminate effects on physiological responses like heart rate, making the technology identification for rehabilitation initiatives difficult. While VR and other visualization devices show potential for enhancing rehabilitation, the optimal balance between immersion, comfort, and physiological effectiveness remains unclear. Research is needed to identify which devices provide the most effective and comfortable experiences, therefore improving user engagement and rehabilitation outcomes. Through an analysis of recent studies on VR and advanced technologies in rehabilitation, this synthesis highlights the combined impact of VR-based pulmonary therapy, sensory stimulation, exergaming, brain stimulation, robotic assistance, and accessible gaming systems, offering innovative and accessible solutions for enhancing physical and neurological recovery across diverse patient groups. In *Table 2*, the summary and comprehension of these studies can be found.

**Table 2.** Summary of Studies on Virtual Reality and Technology-Enhanced Rehabilitation Techniques

Category	Study/Authors	Intervention/Tool	Sample	Key Findings
VR in Pulmonary Rehab	Rutkowski et al. [1]	VR in Pulmonary Rehab	32 COVID-19 patients	VR and traditional rehab improved exercise; QoL was similar.
Sensory Stimulation in Exercise	Robergs et al. [42]	Video-Assisted Cycling	24 participants	Video cycling boosted experience and demand in rehab.
Exergaming for Older Adults	Molina et al. [43]	Exergaming	Elderly adults	Promising physical function; needs more validation.
VR + Brain Stimulation	Cassani et al. [44]	VR + NIBS	N/A	Positive outcomes: larger samples needed.

Rehab Technique Comparison	Housman et al. [45]	T-WREX vs. Tabletop Exercises	28 chronic stroke patients	Improved motor control over traditional methods.
Robotic Upper Limb Rehab	Merians et al. [46], Adamovich et al. [47]	Robotic-Assisted Training	Hemiparetic stroke survivors	Enhanced hand function with robotics.
VR Effectiveness Meta-Analysis	Mekbib et al. [48]	VR in Stroke Rehab	Stroke patients	VR improved limb function and engagement.
Accessible Gaming for Rehab	Pietrzak et al. [49], Bonnechère et al. [50]	Nintendo Wii	Post-stroke patients	Wii improved limb function, supporting low-cost gaming.

#### 1.4.4. Comparing In-Person and Virtual Reality Approaches

##### Second Group: Virtual Reality Implementation

Expanding on the exploration of visualization devices in rehabilitation, this section investigates the potential of VR in cognitive assessments by comparing its effectiveness with traditional, face-to-face methods. The experiment adapts conventional neuropsychological tests, such as the Corsi Block-Tapping Test, to Virtual Reality environments to evaluate their impact on enhancing visuospatial and working memory capabilities. This comparison is crucial for determining whether VR can match or exceed the efficacy of conventional in-person testing. The Corsi Block-Tapping Test [51], traditionally used to assess visuospatial and working memory, has undergone development since its inception with new technological developments. The digital version of this test has facilitated easier modification of test parameters and rapid data processing. Most recently, VR has emerged as a revolutionary technology in cognitive assessment, given the greater immersion it affords. VR-based adaptations of the Corsi-Test have been under investigation, which offer several advantages, including precise control of stimulus presentation and reductions in human error. [52] Various forms of the Corsi-Test have been developed over time; initially, these focused on changes in the arrangement and number of cubes. With the development of technology, digital versions have emerged that offer increased flexibility and speed in modifying the test. Digital formats allow for faster testing, as software can rapidly process data and input it into databases. Unlike the traditional version, this tool exists exclusively in the virtual domain and applies VR technology to conduct a digital Corsi-Test. This approach offers many important advantages, including increased accuracy and reliability of the results, faster processing of data, and more interactive and visual feedback options. [53,54] Advantages of using the Virtual Reality digital version of the Corsi-Test, enabling fast and efficient changes in parameters, depending on the different contexts. Moreover,

they enhance the assessment process since programs can quickly sort and store information in databases. This tool uses Virtual Reality technology, which enhances the accuracy and reliability of the test results, speeds up data processing, and expands possibilities for interactive feedback. This Virtual Reality based methodology offers advantages, especially for children who could feel anxious or uneasy receiving instructions from an administrator. Using the virtual environment eliminates the potential stress associated with being watched by an administrator, allowing for less pressure to perform well and a more relaxed experience for the children participating. [55,56] Cognitive assessment adaptations for VR have a lot of advantages, yet comparability, validity, and accessibility challenges persist. Research into how VR affects user experience, physiological responses, and the flexibility of cognitive assessments compared to traditional methods must be performed. The discussion, after the application of VR in cognitive assessments, extends its compass to other domains of application in the fields of neurological, psychological, and pediatric therapies. There is a lack of research on how VR impacts the user experience in cognitive assessments, particularly regarding comfort, engagement, and anxiety reduction. Additionally, there is a need for direct comparisons between the effectiveness of VR-based cognitive assessments and traditional in-person methods.

#### **1.4.5. Virtual Reality Software in Different Therapeutic Fields**

##### **Third Group: User Experience in Virtual Rehabilitation**

In rehabilitation, VR has recently become an innovative tool, opening new scenarios in the management and treatment of a variety of therapeutic areas: from neurological and cognitive rehabilitation to psychological treatments, and social skills training. However, VR also generally has some challenges with respect to its adoption in such domains: these include the need to develop a clearer understanding of comparative efficacy, methodological rigor, and engagement.

Virtual Reality rehabilitation games can be grouped into six categories:

- Physical Therapy Games (PTG),
- Cognitive Rehabilitation Games (CRG),
- Neurological Rehabilitation Games (NRG),
- Pediatric Rehabilitation Games (PRG),
- Psychological Rehabilitation Games (PSY), and
- Social Skills and Communication Games (SSCG).

VR emerged in recent years as a transformative tool in rehabilitation, greatly facilitating and enriching therapies that used to be quite cumbersome for different conditions. These innovative approaches make rehabilitation more engaging and personalized, thus probably being more effective. Deutsch et al. [57] reported on VR methodologies for enabling walking rehabilitation post-stroke, noting that while preliminary results are promising, further validation is required. This research is particularly relevant to NRG,

as it addresses the technical challenges within this domain. Rizzo and Koenig [58] provided a comprehensive analysis of clinical Virtual Reality applications, demonstrating their efficacy in psychological and neurological treatments, while offering important context regarding the broader implications of VR in rehabilitation. Laver et al. [59] explored the role of Virtual Reality in stroke rehabilitation, particularly focusing on recent developments in improving upper limb functionality. However, they highlighted variability in the results, indicating a need for further research on CRG and NRG. Ma et al. [60] reviewed the use of VR and serious games in healthcare, covering a wide range of medical fields and demonstrating VR's broad applications in rehabilitation. Frolli et al. [61] highlighted the effectiveness of Virtual Reality in improving social competencies in children with autism spectrum disorder, making a significant contribution to the research into SSCG. Riva et al. [62] introduced the concept of "Positive Technology," which emphasizes technology's potential to enhance well-being, particularly within the context of Psychological Rehabilitation Games. Demeco et al. [63] conducted a systematic review, further validating Neurological Rehabilitation Games by showing that immersive VR improved dexterity of the upper limbs and gait in post-stroke patients. Faria et al. [64] presented evidence in 2016 that VR-based cognitive rehabilitation significantly improved cognitive function in stroke patients, confirming the efficacy of CRG. Rizzo and Bouchard [65] reviewed VR's therapeutic potential across psychological and neurocognitive interventions, providing critical insights into how VR enhances rehabilitation outcomes. Missiuna et al. [66] discussed the "Partnering for Change" model, which emphasizes tailored interventions for children with Developmental Coordination Disorder, a model that is relevant to PRG. Proffitt and Lange [67] advocated for a systematic approach to the development of VR interventions in stroke rehabilitation, calling for more clinical trials to further support NRGs. Slater and Sanchez-Vives [68] investigated the extensive uses of immersive Virtual Reality, showcasing its ability to significantly alter user experiences and therapeutic methodologies, with potential applications across various rehabilitation fields. Viderman et al. [69] confirmed the effectiveness of VR in managing various pain conditions, reinforcing its role in Psychological Rehabilitation Games. While there is growing interest and evidence supporting the use of VR in rehabilitation, more rigorous studies, clinical trials, and comparisons with traditional methods are needed to close gaps and ensure the broader adoption of VR technologies in therapeutic settings.

#### **1.4.6. VR in Stress and Anxiety Management**

##### **Fourth Group: The Impact of 3D Environments**

Understanding the application of VR across various therapeutic domains sets the stage for an in-depth exploration of its role in managing stress and anxiety. This section examines how immersive 3D environments influence traditional breathing exercises, highlighting the potential benefits of integrating VR into stress reduction strategies. The immersive environments created through Virtual Reality have assisted individuals in practicing the best type of breathing and have shown immense promise regarding

managing stress and anxiety. Virtual Reality presents a unique tool for enhancing breathing exercises through immersive 3D environments. However, the extent to which VR influences immersion compared to traditional settings, particularly regarding stress and anxiety reduction, remains unclear. While VR offers an innovative approach for practicing breathing techniques, its relative effectiveness compared to other methods in stress and anxiety management is still to be established. Further research on the different virtual environments and their impact on physiological and psychological outcomes should be undertaken in support of the development of rehabilitation tools. [70,71]

## 1.5. Thesis Structure

This Ph.D. thesis explores the potential of biofeedback-based Virtual Reality therapies in rehabilitation, particularly focusing on their impact and effectiveness. Divided into seven chapters, the study investigates how VR-based serious games, designed for activities like breathing exercises and memory training, can support patients with conditions such as post-COVID syndrome, memory problems, and pulmonary disorders. Below is a chapter-by-chapter breakdown of the document:

*Chapter 1 – Introduction:* This chapter outlines the research scope and objectives, concentrating on the development and evaluation of VR therapies. It describes the dual focus of the experiment: assessing the effectiveness of various VR visualization displays and designing therapeutic VR games. The chapter highlights the focus of the document to identify the best practices in VR rehabilitation. It also provides a literature review of current technologies in rehabilitation, such as VR, AI, mobile applications, and wearables. It discusses their impact on daily activities, cognitive enhancement, and stress management, and evaluates both their benefits and limitations.

*Chapter 2 - Methodology:* This section outlines the study's research questions, hypotheses, devices, and software development. It includes detailed descriptions of experiment setups, and the questionnaires applied to gather data, establishing a foundation for the research approach.

*Chapter 3 - Results:* The results chapter details findings across various data types, including questionnaire feedback, heart rate metrics, and statistical analyses, such as T-test results. It serves as the core of the research outcomes. It begins by presenting significant observations made during the research process. These observations provide valuable insights into participant behavior, performance trends, and notable patterns that emerged from the data. Following this, the section addresses the validation of the research hypotheses through statistical analysis, highlighting the methods used to test the hypotheses, such as statistical tests (e.g., T-tests) and the results that either support or challenge the initial assumptions. Finally, a summary of the findings is provided,

synthesizing the key results and offering an overview of how they contribute to the overall objectives of the research.

*Chapter 4 - Discussion:* This chapter includes four key components: Interpretation of Results, Significance of Findings, Implications for VR Rehabilitation, and Integration with Existing Knowledge. The Interpretation of Results analyzes the research findings, discussing how they align with expectations and what they reveal about the study's objectives. The Significance of Findings highlights the importance of the results, reflecting on their contributions to the field, as well as the strengths and limitations of the research. Implications for VR Rehabilitation explore how the findings can impact the use of Virtual Reality in therapeutic settings, identifying both its benefits and challenges. Finally, Integration with Existing Knowledge compares the study's findings with previous research, highlighting how it extends current knowledge and pointing out areas for further exploration.

*Chapter 5 - Conclusion:* The conclusion synthesizes key findings on VR and other visualization devices in rehabilitation, discussing their applications in areas like spatial memory and therapeutic exercises. It highlights significant insights for designing and implementing future rehabilitation technologies. The Conclusion section summarizes the study's contributions, key findings, and potential future research directions. Contributions provide an overview of the study's primary contributions to the field, emphasizing the value it adds to current understanding. It discusses the most significant findings from the research and their broader implications for the field, and highlights the study's limitations and offers suggestions for future research to address unanswered questions and build upon the study's results.

*Chapter 6 - Theses Summary:* The final chapter organizes the dissertation's findings into key thesis groups. Each group focuses on VR's impact on user experience, stress management, and rehabilitation outcomes, summarizing the research's major contributions.

This structure ensures a clear progression from background knowledge to applied methodologies, findings, and theoretical implications, offering insights to advance the field of rehabilitation technology.

# Chapter 2

## 2. Methodology

In this section, first I introduce the method of systematic review. Next, I describe the devices used in the experiments, followed by a detailed overview of the software developed for the research. I outline the setup for each experiment and conclude by presenting the key questionnaires used throughout the research.

### 2.1. Devices

A variety of devices were used throughout the research, with two playing a main role. The first was the Oculus Quest 2, a Virtual Reality headset used extensively for conducting VR-based testing. Its advanced capabilities allowed participants to engage in immersive environments, making it ideal for the study's Virtual Reality component. The second device is the Polar H10 chest strap, which recorded the heart rate of the participants in experiments. The Polar H10 is highly accurate and precise, and it was employed in this study for pulse data collection. These two devices were the base of the technological setup within the framework of the research conducted.

#### 2.1.1. Meta Quest 2

The device I used for testing was Meta Quest 2, a Virtual Reality headset released in 2020 and developed by Meta Platforms. Its predecessor had been the Oculus Quest, and compared to its predecessor, the headset had seen improvements in uptime, resolution, and refresh rate (120 Hz). The per-eye display resolution of Meta Quest 2 is 1832 x 1920. It operated on an Android-based operating system, allowing programs to run either on the device itself due to its internal storage, or, as in this case, programs could be run on a computer with the headset responsible solely for display purposes. The headset was equipped with two controllers to interact with objects in the virtual environment. Within the games, users could navigate virtual spaces using the joysticks on the controllers. Additionally, they could freely look around without the need to physically turn or move, thus enabling stationary gameplay to prevent potential accidents. This feature was crucial as a common issue in Virtual Reality was the limited physical space compared to the boundless virtual environments, which users might not perceive. This headset was my preferred choice due to its excellent performance relative to its cost. [72]

#### 2.1.2. Polar H10

I continuously measured the participants' heart rates to gather physiological data with the Polar H10 device during the experiments. Monitoring heart rate provides objective

data on the participants' physiological responses to the breathing techniques and helps assess the effectiveness of the exercises in inducing relaxation. [73] To gather heart rate data, I developed an application using Android Studio with the Kotlin programming language. The application connected with the device via Bluetooth connection and saved the data into JavaScript Object Notation (JSON) files.



**Figure 2.** A participant in an experiment with the Polar H10 chest strap

In all experiments, heart rate data were collected using the Polar H10 chest strap, a reliable and widely validated device for accurate heart rate monitoring in research settings. The Polar H10 offers high temporal resolution and is particularly suitable for real time physiological tracking during VR exposure, allowing for non-invasive and comfortable monitoring, especially important in studies involving children or when experiments last a long time [74, 8]. While the heart rate data provided useful insights, full electrocardiogram (ECG) measurements could have further improved signal accuracy and allowed for more advanced analysis, such as precise heart rate variability (HRV) metrics [75]. However, the decision not to include ECG was based on practical considerations: the need for minimal setup time, participant comfort, and the goal of creating a low-intrusion, child-friendly experimental environment.

Future studies could benefit from integrating additional biometric signals, such as

- measure skin conductance (GSR) to see how the body's "fight or flight" response is activated (this is related to sweat on the skin) [76],
- or more detailed heart rate variability (HRV) analysis could be included to spot subtle changes in the body's automatic control of heart rate,
- or might use EEG (a cap that records brain waves) to see how the brain responds to attention or emotions during VR [77].

These multimodal approaches would allow for a more comprehensive understanding of how VR environments affect psychophysiological states, although they may introduce increased complexity in both setup and analysis.

## 2.2. Setup of the Experiments

In the following, I show the setup for each of the experiments:

- (1) First Group: Comparing Visualization Devices for Rehabilitation
- (2) Second Group: Virtual Reality Implementation,
- (3) Third Group: User Experience in Virtual Rehabilitation,
- (4) and Fourth Group: The Impact of 3D Environments

Each experiment is designed to explore specific aspects of rehabilitation technology and user interaction within virtual environments.

### 2.2.1. First Group: Comparing Visualization Devices for Rehabilitation

In this experiment, I selected four devices: a mobile phone, a tablet, a monitor, and a head-mounted Virtual Reality display device - Oculus Quest 2. Each device was required to present visual stimuli through a beach cycling video as participants engaged themselves in indoor cycling activities.

The participants kept a steady state by pedaling at an average external power output of 84–107 watts for one hour continuously while observing their heart rates. Screen sizes for this experiment were: a mobile phone at 5.5 inches, a tablet at 10 inches, a monitor at 24 inches, and a VR headset. The heart rate data collected allowed the determination of physiological activation in response to each display condition, for heart rate measurement I used the Polar H10 chest strap.

33 participants were involved, aged between 21 and 55, with a mean age of 27. The cohort included 17 females and 16 males to achieve a balance that can support the reliability and validity of the findings.



**Figure 3.** A participant in the experiment used VR headsets while indoor cycling

### **2.2.2. Second Group: Virtual Reality Implementation**

The experiment started with the development of the Corsi-Test in a Virtual Reality environment. The experiment was performed on 14 participants, 3 males, and 11 females, aged on average 29 years old (Standard Deviation (SD) = 9). During all testing, the pulse rates of participants were continually measured. It was found that 60% of subjects who undertook the test in the virtual environment had a lowered pulse rate compared to the traditional way.

### **2.2.3. Third Group: User Experience in Virtual Rehabilitation**

The aim of this research was to explore user experiences related to virtual rehabilitation applications categorized into six specific therapeutic domains. The information used for this analysis was gathered from users on Steam, a digital platform for video games and software applications. To ensure consistency in linguistic interpretation and sentiment assessment, the experiment concentrated solely on reviews composed in English, thereby guaranteeing that all feedback was analyzed within a consistent linguistic context.

The research investigated user experiences within six categories of Virtual Reality rehabilitation games: Physical Therapy Games (PTG), Cognitive Rehabilitation Games (CRG), Neurological Rehabilitation Games (NRG), Pediatric Rehabilitation Games (PRG), Psychological Rehabilitation Games (PSY), and Social Skills and Communication Games (SSCG). The objective was to get an understanding of user satisfaction across these various rehabilitation categories. A comprehensive approach involving user review analysis, sentiment assessment, and keyword frequency evaluation was employed.

Each category included five games, selected to reflect a wide range of generally accepted and diverse approaches in their respective areas. The selection was based on several criteria: the relevance to the category, popularity among users, and the availability of a wide array of user experiences. The methodology used to select these served to comprehensively perceive the existing virtual rehabilitation environment and to ensure that the research represented a wide range of user engagements and therapeutic results. The selected games represented varied therapeutic goals such as physical rehabilitation exercises, cognitive challenges, and emotional well-being.

#### **Physical Therapy Games - PTG**

Virtual Reality PTG aims at increasing physical activities and exercises through game-like experiences. Some of the games within this category have selected a set of exercises for different body parts, lower and upper body movements included [78]:

- *Hot Squat*: A game of physical exercises focusing on lower body strength by repeating the squat exercise. It creates an environment for users to work out and enhance their physical endurance [79].

- *BOXVR*: It is an interactive boxing fitness application that provides cardiovascular training while simultaneously enhancing upper body strength and reflexes. The game features rhythmic punching patterns designed to assist users in improving their coordination [80].
- *Beat Saber*: This rhythm-based game requires players to slice through blocks synchronized with music, thereby offering upper body exercise via swift arm movements and enhanced reflexes [81].
- *Fruit Ninja VR*: Deriving from the well-known mobile game, this Virtual Reality adaptation actively involves participants in rapid slicing actions that enhance hand-eye coordination and upper body agility [82].
- *Creed: Rise to Glory*. This is a boxing simulation game that provides a full-body workout that emphasizes endurance, speed, and strength through immersive fight scenes [83].

### **Cognitive Rehabilitation Games - CRG**

CRG in Virtual Reality is specifically engineered to enhance cognitive abilities, including memory, problem-solving skills, and strategic reasoning. Frequently, these games integrate puzzles, strategic elements, and activities that stimulate the mental capabilities of the users [84,85]:

- *Rec Room*: An online multiplayer game involving a set of mini-games that require strategy and collaboration. It nurtures social interaction among players, with various modes of play exercising the brain [86].
- *Keep Talking and Nobody Explodes*: This cooperative puzzle game involves defusing bombs by following instructions, enhancing communication, problem-solving, and teamwork [87].
- *FORM*: A surreal puzzle game that immerses participants in the resolution of intricate puzzles, necessitating advanced cognitive skills and adeptness in problem-solving within a visually engaging setting [88].
- *Moss*: It is a platformer that fuses strategic thinking with problem-solving and athleticism to boot, challenging participants in a quest that requires both brainwork and physical prowess [89].
- *Portal Stories: VR* is a modification of the classic Portal puzzle game. The Virtual Reality version tests spatial reasoning and problem-solving by creative use of portals in a 3-D environment [90].

### **Neurological Rehabilitation Games - NRG**

NRG is designed to enhance motor skills, coordination, and reflexes by frequently involving the user in activities that require them to be precise in their movements and/or

multitask. The selected games for this category represent a range of activities for neurological recuperation through engaging gameplay [91]:

- *Job Simulator*: Different simulated activities can be performed by participants in this game, which involve motor skills, hand-eye coordination, and proper hand movement, hence this game provides neurological rehabilitation through routine activities [92].
- *Surgeon Simulator VR*: This VR application is about delicate and purposeful hand motions, making it suitable for the rehabilitation of fine motor skills. This game involves mock surgical procedures to test coordination and dexterity [93].
- *Sairento VR*: It is a fast-paced game of detailed movements and skillful coordination. There are fights involved that require quick reflexes and sharp awareness of the space around them [94].
- *VRChat*: It is a social networking platform that enables individuals to navigate and engage with one another within virtual settings, fostering mobility, interaction, and coordination within a communal framework [95].
- *Space Pirate Trainer*: This is a dynamic shooting experience with fast-moving reflexes and accuracy to help any person improve his coordination and reaction time [96].

### **Psychological Rehabilitation Games - PSY**

Virtual Reality Psychological Rehabilitation Games intend to induce relaxation, stress relief, and mental health. They often have a common feature: a calm environment with guided exercises aimed at enabling players to cope with anxiety, stress, and many other psychological challenges [97]:

- *Guided Meditation VR*: Offers a variety of meditation environments for the purpose of reducing stress and enhancing relaxation. This tool introduces a person to a series of guided meditations set amidst serene virtual landscapes [98].
- *Nature Treks VR*: It facilitates the exploration of tranquil, nature-themed settings, enabling users to unwind and alleviate stress by engaging in immersive experiences within peaceful landscapes [99].
- *The Gallery - Episode 1*: Call of the Starseed presents a fusion of adventure and tranquil settings; this game harmoniously integrates exploration with periods of tranquility, resulting in an experience that is both captivating and calming [100].
- *Realities*: Virtual visits to real sites allow users to tour and relax in stimulating environments without many of the disadvantages of travel or physical constraints. [101].

- *Blu*: This is a game in which one explores the ocean, having mesmerizing underwater footage and interacting with underwater life forms in gentle play [102].

### **Pediatric Rehabilitation Games - PRG**

Virtual Reality games for pediatric rehabilitation are specifically designed to engage and entertain younger users while promoting cognitive and motor development. Games selected for this domain merge fun with therapeutic activities that enhance coordination, problem-solving, and collaboration [97]:

- *Fantastic Contraption*: Creative building game challenging users to devise original solutions to problems in puzzles, aiming at problem-solving and motor skills [103].
- *VR The Diner Duo*: It represents a collaborative gaming experience in which one participant assumes the position of a chef while the other attends to patrons. This interactive game fosters improved coordination and teamwork within an enjoyable and stimulating setting [104].
- *Angry Birds VR: Isle of Pigs*: This Virtual Reality adaptation of the well-known Angry Birds game emphasizes hand-eye coordination and problem-solving skills as players target and propel birds towards various structures [105].
- *Waltz of the Wizard*: It offers a magical journey with a variety of interactive elements that encourage creativity, exploration, and coordination from its users [106].
- *Cosmic Trip*: This merges strategy with gymnastics in space, placing both cognitive and fine motor skill challenges in an imaginative and creative setting [107].

### **Social Skills and Communication Games - SSCG**

Social-ability and communication games in VR are created for better interaction and collaboration among users. Such games provide a virtual playground for practicing social interactions, communication, and teamwork in engaging and deeply immersive settings:

- *VRChat*: A flexible social platform that allows users to interact with others in virtual worlds, encouraging social skills through real time conversation and communication [95].
- *Rec Room*: This is besides cognitive tasks, provides social games that include teamwork and communication, thus encouraging social activity and common activity among players [86].

- *Bigsreen Beta*: It lets people from all over the world hang out in virtual rooms, watching movies or playing video games, or simply hanging around and chatting with social contact in their free time [108].
- *Neos VR*: It represents a profoundly adaptable social Virtual Reality platform that facilitates the creation and sharing of interactive experiences by users, thereby promoting communication and collaboration within virtual settings [109].
- *OrbusVR*: Reborn counts as a Massively Multiplayer Online Role-Playing Game (MMORPG) because it offers social interaction and cooperative collaboration by providing shared missions and experiences within a common virtual space [110].

Through the review of user feedback on the subject of these games, the experiment tried to collect valuable insights into the effectiveness of VR as a rehabilitation tool.

The findings from this analysis are meant to be critical in guiding further development in VR rehabilitation, ensuring these tools are not only effective in promoting recovery but also enjoyable and user-friendly for a wide variety of users.

Fundamentally, this setup created a grounding for deep exploration of user perceptions, preferences, and challenges regarding virtual rehabilitation, therefore making great contributions to the possible refinement and optimization of such applications toward their wider adoption in therapeutic settings.

The fact that it had a variety of different games across each category allowed for the complete range of virtual rehabilitation experiences to be studied in-depth and, as a result, subtle conclusions regarding the future capabilities of Virtual Reality in healthcare to be obtained.

#### **2.2.4. Fourth Group: The Impact of 3D Environments**

##### **Pre-experiment setup**

A sample size of 10 was used to design a pilot experiment to test the initial efficacy of the VR game in conjunction with the breathing techniques being taught. The mean age of the subjects was 22.4 years, with an SD of 1.7 years, so the sample is representative of a fairly homogenous group of people. All the subjects also attested to good health, reducing the impact of possible confounders due to pre-existing health issues.

Subjects were divided into two groups, each with five participants:

*Virtual Reality Group*: These practices were experienced by the participants through a Virtual Reality environment. The participants interacted with a virtual avatar, which guided them through each of the breathing practices.

*Control Group:* The control group performed the same three breathing exercises, but without virtual or sensory extensions; participants were placed in a quiet room, eyes closed, and completely free of external stimulation. This setup would filter out the effects of the breathing techniques in isolation and ensure that any observed differences between the groups can be attributed to the addition of the Virtual Reality environment.

The main purpose of this pilot experiment was to match the efficacy of breathing techniques when conducted in a VR environment versus those practiced traditionally without visual or auditory stimuli. Testing both groups on the level of relaxation, user engagement, and effectiveness of breathing exercises.

### **Main Experiment: Three Distinct 3D Environments**

After the pre-experiment, I conducted an extended experiment with 15 participants. The mean age of the participants was 26.8 years. As in the pre-experiment, all the participants described themselves as being in good health and could, therefore, be considered as a homogeneous group.

This experiment introduced three unique 3D environments, designed to elicit different emotional and physiological responses during rehabilitation activities:

*Positive-Affective Environment:* Designed to evoke a sense of serenity and happiness, this ambiance includes bright skies, chirping birds, and plenty of greenery. The intent is to provide a calm and enabling environment.

*Neutral-Baseline Environment:* This environment provides a calm and undisturbed atmosphere, free from external distractions. It aims to encourage a concentrated and contemplative state.

*Negative-Affective Environment:* It is typified by a stormy and ominous environment that forces users to focus on increased ambiguity and pressure, which may provoke adaptive responses and heightened attention.

All three environments are based on a forest. Research shows that the type of VR environment can dramatically alter participants' stress levels and cognitive performance. Simulated natural settings (e.g. a forest) tend to be calming and restorative, whereas busy urban scenes can be cognitively taxing. For example, viewing or being immersed in a natural "forest" VR scene can reduce stress and improve attention: in one study, only participants exposed to restorative (natural) images improved on a subsequent attention task [111]. Likewise, Thompson Coon et al. (2011) found that outdoor/nature conditions led to greater feelings of revitalization, positive engagement and reduced tension compared to indoor or urban exercise [112]. In contrast, VR city environments – with their fast-moving sights and sounds – may overload directed attention and even elevate anxiety. Finally, choosing a familiar, "safe" VR context (for example, a child's bedroom) can further ease participants: the home environment is associated with feelings of security, control, and refuge [113], which helps lower anxiety. Altogether, these findings suggest that forest-like or familiar VR

settings help reduce stress and enhance task performance, whereas intense urban VR environments may increase stress and demand more attention.

I chose the forest environment as a consistent base because it promotes relaxation and focus, unlike urban settings that can introduce distracting or stressful stimuli. By varying only the mood— positive-affective, neutral-baseline, and dark—within the same forest setting, I can ensure that differences in participants' responses are due to emotional atmosphere rather than environmental context, while also keeping the door open for future comparisons with entirely different environments like urban or indoor spaces.

The purpose is to determine the effects of these varied virtual environments on rehabilitation outcomes. I observed if and how certain virtual landscapes could provide ways to enable or enhance the process of rehabilitation, based on parameters like stress levels, improvement in mood, and engagement. This experiment aimed at determining whether emotional and environmental cues provided through VR would contribute positively toward therapeutic outcomes to help further the understanding of how VR can be optimized for use in rehabilitation.

### **2.3. Participant Age Considerations**

Current VR cognitive rehabilitation trials have rarely included older adults (60+), focusing instead on younger, healthy participants [114, 115]. For example, a recent review of VR relaxation studies found that research with both younger and older cohorts is uncommon, with most samples centered on 30–50-year-olds [114]. Likewise, a systematic review of VR cognitive training for mild cognitive impairment identified only three eligible studies (130 total participants) in seniors [115]. This age bias likely reflects practical considerations. Younger participants typically have higher digital literacy and fewer health complications, which simplifies recruitment and intervention delivery. By contrast, older adults often present with multiple chronic conditions and functional decline, and frailty and usability concerns are highlighted as key factors in VR deployment for seniors [116]. Moreover, even cognitively healthy elders may have age-related sensory/motor limitations or mild cognitive deficits, which can affect VR engagement [117, 118]. For instance, Ramalho et al. note that prolonged VR use can cause dizziness or fatigue in older users, and that varied technology familiarity among seniors may lead to confusion or emotional discomfort [118]. Similarly, others have observed that cognitive impairments in older participants can induce risky behaviors or interaction errors in virtual environments [117].

In the present study, I have focused on healthy younger adults to validate the basic structure and feasibility of VR-based cognitive assessment tools. This approach aligns with common research practices in early-stage development [115]. However, I acknowledge the need for broader demographic inclusion to fully understand the utility and adaptability of VR interventions across the lifespan. To address this, further research is already underway in collaboration with Eötvös Loránd University. These

upcoming studies aim to investigate age-specific responses to VR-based cognitive assessment tools across four distinct age cohorts: Adolescents (12–18 years), Young Adults (18–39 years), Middle-aged Adults (40–65 years), and Seniors (65+ years).

#### **2.4. Sample Size and Power Considerations**

My experiments employ sample sizes typical of early-stage VR and psychophysical studies. Prior VR usability and rehab trials frequently involve only a few dozen participants. For example, Faisal et al. conducted a VR cognitive training pilot with 30 healthy volunteers [119], and Tunbridge et al. examined stress responses in VR with 28 subjects [120]. Cen et al. used 32 participants in one VR spatial memory experiment (and 60 in a second) [121]. Even stroke rehabilitation VR studies have used similar or smaller samples: one VR mirror therapy feasibility study enrolled only 11 patients [122], and a randomized trial of a VR gait game involved 22 post-stroke patients (11 per arm) [123]. Likewise, an HCI study of a VR stress reduction game evaluated 28 office workers while monitoring heart rate and skin conductance [124]. These examples show that 10–30 participants are common in first-stage VR or physiologically oriented experiments. In this context, my N=33 cycling study and N=14 pilot Corsi study is well within the norms, and the larger follow-up (N=44) exceeds many early usability tests. These sizes allow us to detect large or medium effects and to explore feasibility and trends. Nielsen’s classic usability guideline underscores that very small samples can still be informative: only 4–5 users may uncover ~85% of interface problems [125]. Cohen’s guidelines for effect sizes further contextualize the design. By convention, Cohen’s  $d \approx 0.5$  is considered a medium effect and  $d \approx 0.8$  a large effect [126]. With 20–30 subjects per condition, one typically has adequate power to detect medium or larger effects, but low power for small effects. Thus, my small-N studies are primarily powered to reveal substantial effects (or lack thereof) and to estimate effect sizes.

The sample sizes align with prior VR rehabilitation/usability work and are sufficient to capture major usability or immersion issues (per Nielsen) and to estimate medium/large effect sizes (per Cohen). Any findings will guide future studies with larger samples as needed.

## 2.5. Software

Several software were developed for the research, and this section highlights the key ones. The subheadings indicate the hypothesis group for which each software was required. For the first group, no additional software development was necessary.

### 2.5.1. Corsi-test in Virtual Reality

#### Second Group: Virtual Reality Implementation

The software operates independently, eliminating the need for a test examiner by adopting an alternative interaction method with cubes. Instead of physically manipulating the cubes, the program utilized a flashing technique to signify the correct sequence. Users observe the flashing order and then use controllers to indicate the corresponding cube in the correct sequence.

Before starting any tests, it is mandatory to create a user account for the user undergoing assessment within the system. This process serves as a form of registration.

The test administrator was tasked with providing essential information about the user, including a unique user ID, that anonymously identified the user within the system. Furthermore, particulars such as the user's birth year, dominant hand (left or right), visual correction needs (e.g., glasses), desired difficulty level of the test, and any pertinent medical conditions were recorded in the program.

The difficulty level of the test must be established, which can be adjusted using an input field representing the time interval (in seconds) between cube flashes. For example, if the test administrator enters a value of 2, it signifies two seconds elapse between each cube flash. This adaptability allows fine-tuning the difficulty level of the test and evaluating performance enhancements or regressions based on variations in the flash interval.

Moreover, extending the time between flashes may potentially benefit children with lower skills by providing valuable insights into their cognitive development.

The software includes four versions of the Corsi-Test:

*First test:* The initial test is an adapted version of the traditional Corsi-Test tailored for Virtual Reality. In this test, the user's task is to select cubes in the exact order displayed within the application. Beginning with two cubes, each successful reproduction of a sequence introduces an additional cube. This incremental pattern continues until the player accurately selects the cubes in the specified order. For instance, if the sequence is 6, 3, 9, 2, the correct order of cube selection would be 6, 3, 9, 2. Upon pressing the green arrow, the test provides a brief preparation period before the cubes begin flashing. Utilizing this time effectively is crucial for familiarizing the player with the sequence. As the test advances, the number of cubes increases, challenging memory and cognitive abilities. Nevertheless, the

objective remains consistent: accurately reproduce the sequence of flashing cubes in the designated order. It is called the forward Corsi-Test.

*Second test:* The second test closely mirrors the first, with the sole difference being that the participant must select the cubes in the reverse order. For instance, if the sequence observed by the user was 4, 8, 1, 9, the correct selection order would be 9, 1, 8, 4. It is called the backward Corsi-Test [127].



**Figure 4.** Screenshot from the Virtual Reality Corsi-test

*Third test:* In the third test, the environment is slightly altered, introducing a set of differently colored cubes placed in front of the participant. Upon starting the experiment, the user needs to encounter a white object positioned in front of them. Initially remaining white for a few seconds, this object serves as a preparatory phase for the test subject. Notably, there are no white-colored cubes present to prevent confusion. As the preparation time elapses, the color of the object begins to change. The task entails observing and memorizing the sequence of colors as they appear. The objective then shifts to selecting the corresponding-colored cube in the exact order depicted. For example, if the object transitions through colors in the sequence of Blue, Red, and Green, the correct selection order would be Blue, followed by Red, and then Green.

*Fourth test:* The fourth test closely resembles the third test, where the same process occurs, but the user is required to select the cubes in reverse order. For instance, if the sequence observed is Green, Yellow, Purple, the expected selection order would be Purple, Yellow, Green.



**Figure 5.** Screenshot from the Virtual Reality Colored Corsi-test

During the development phase, children were identified as one of the primary target groups. A custom-designed 3D environments were created, with two distinct rooms: a boy's bedroom and a girl's bedroom. Considering the differences between sexes, these rooms aimed to simulate the distinctive characteristics typically found in girls' and boys' rooms, especially during childhood. The program offers enhanced customization features by allowing the selection of various room types, including separate girls' (Figure 5.) and boys' rooms (Figure 4.), each with distinct styles and atmospheres [128,129].

To begin the test on the computer, the user clicks the test guide button, transporting the user into a 3D virtual space for exploration. Positioned in the middle of the room is a table with cubes, which the child can approach to commence the test by activating a green arrow when ready. Once selected, the arrow disappears, initiating the test with cubes flashing in a random order without repetition.

If the user accurately reproduces the sequence, the green arrow reappears for further progression, introducing an additional cube. The test continues until an incorrect selection is made, at which point the data is saved to the database, and the user exits the virtual environment.

Upon completing the test, the main menu reloads, confirming the successful database save. The test administrator can then proceed to initiate another session or add a new user. To exit the program, an exit button is available for termination.

The game was developed in Unity game engine in C# programming language. The models were created in the Blender graphical program, and the data was saved in SQLite database.

## 2.5.2. Text Analysis of User Reviews

### Third Group: User Experience in Virtual Rehabilitation

The user feedback was extracted from Steam user reviews, a reliable source of unsolicited and spontaneous user opinions. Steam allows users to express their experience with different games, which makes it perfect for finding the best authenticity regarding the subject matter at hand. Only reviews written in the English language were used to keep consistency in the analysis, while all other languages were excluded due to possible biased results given any translation inconsistencies. Each of the rehabilitation categories, which were CRG, NRG, PRG, PTG, PSY, and SSCG, included five different games, meaning a total of 30 games in all. The selected games were intended to represent various user experiences along the rehabilitation spectrum. For each of the games, 100 most recent user reviews were collected, in total, it means 3,000 user reviews. I created a Python script, which retrieves recent Steam reviews for a specific app (identified by its appID) and saves the data into a Comma-separated values (CSV) file. The code retrieves recent reviews for a specified Steam game and saves them to a CSV file. It has two main functions:

*get\_steam\_reviews*: This function fetches a set number of recent reviews for a given Steam app, filtering them by the timestamp to include only reviews from the past specified number of days. Each review's timestamp, text, recommendation status, and vote counts are stored in a dictionary format.

*save\_reviews\_to\_csv*: This function calls *get\_steam\_reviews* to fetch the reviews and then saves them in a CSV file, with headers for each review detail, making it easily readable and analyzable.

Key aspects of the code include using libraries like requests, datetime, and csv for API requests, date filtering, and file handling, respectively. Overall, this script is designed for collecting reviews from Steam and saving them for further analysis or reporting in a structured format. The whole code can be found in the appendix. (Code A1)

After the data collection, Python code was created to analyze the user reviews from the free text fields. The code performs a detailed analysis of text data, focusing on reviews from CSV files, with a combination of preprocessing, sentiment analysis, and visualization techniques. The code performs a series of text and sentiment analysis steps on reviewing data loaded from a CSV file. First, it preprocesses text data by tokenizing, removing stopwords, and lemmatizing words. Then, it extracts features using the Bag of Words and TF-IDF methods. Word frequency is analyzed, with the top words displayed, followed by sentiment analysis using TextBlob and VADER. It conducts statistical tests on sentiment scores across different datasets and visualizes the results using bar plots, histograms, and word clouds. Key libraries used include Pandas, NLTK, Scikit-learn, TextBlob, Seaborn, Matplotlib, and WordCloud. The code provides a comprehensive approach to text preprocessing, feature extraction, sentiment analysis, and visualization of review data. It handles various stages of data cleaning, computes

word frequencies, analyzes sentiment, and generates statistical comparisons between datasets. The code can be found in the appendix. (*Code A2*)

## **Data Analysis**

Through sentiment analysis, word frequency analysis, and category comparison, experiments identify key trends, strengths, and areas for improvement can be identified.

*Sentiment Analysis:* The emotional tone in the user comments was examined to establish general user satisfaction. Sentiment analysis tools classified the comment reviews as positive, neutral, or negative about the language used by the reviewers. This provided useful insight into the emotional tone present in the comments, thus highlighting key areas of user satisfaction and dissatisfaction for each category of rehabilitation.

*Word Frequency Analysis:* A word frequency analysis was conducted on the collected reviews to identify the most mentioned terms and phrases. This helped to uncover common themes, user concerns, and features that were frequently highlighted across different categories of rehabilitation games. Words related to VR or gaming were excluded from the analysis to focus specifically on the therapeutic and experiential aspects of the rehabilitation applications.

*Category Comparison:* The six rehabilitation categories were compared to assess variations in user feedback across different therapeutic domains. By analyzing the sentiment and word frequency across categories, the experiment aimed to identify trends, strengths, and weaknesses within each domain of rehabilitation. This comparison provided a deeper understanding of how different types of rehabilitation games are perceived by their users and where improvements might be necessary [138, 139].

The data analysis for the experiment involved multiple stages to ensure that meaningful insights were derived from the user reviews across different game categories. The process is structured into the following key steps:

## **Text Preprocessing**

Before any statistical analysis could be performed, the text data from user reviews was preprocessed to ensure consistency and remove noise. This involved:

- *Lowercasing:* Converting all text to lowercase for uniformity.
- *Removing Punctuation:* Eliminating punctuation marks to focus purely on the words.
- *Tokenization:* Splitting the text into individual words or tokens.
- *Removing Stopwords:* Filtering out common words that do not contribute to the analysis (e.g., "and", "the").
- *Stemming/Lemmatization:* Reducing words to their base or root forms, which helps in grouping similar words [139].

## Feature Extraction

After preprocessing, the text data was converted into numerical features to enable statistical analysis. Two common methods used in this experiment included:

*Bag of Words (BoW)*: This method represented the text as the frequency of each word within the corpus.

*Term Frequency-Inverse Document Frequency (TF-IDF)*: This technique was used to measure the importance of words within a document relative to the entire corpus [140].

## Statistical Analysis

Once the text data was transformed into numerical formats, various statistical analyses were performed:

*Frequency Analysis*: The frequency of words and n-grams was analyzed to identify common themes across the reviews.

*Sentiment Analysis*: The sentiment of the reviews was evaluated to understand user emotions (positive, negative, or neutral) [141].

For deeper insights, the traditional statistical technique was combined with the text features:

*T-tests*: These were performed to compare word count and sentiment across different game categories. For example, comparisons were made between categories like Cognitive Rehabilitation Games (CRG) and Neurological Rehabilitation Games (NRG) to identify significant differences in user feedback [142,143].

## Visualization

To better understand the results, various visualization techniques were employed using libraries such as Matplotlib and Seaborn [144,145]. These visualizations helped in presenting the data trends and statistical outcomes in a more digestible format.

## Limitations

The experiment is limited to data collected from Steam users, which may not fully represent the experiences of all users of these rehabilitation games. Only English language reviews were included, which might exclude valuable feedback from non-English-speaking users. This language restriction could limit the generalizability of the findings to global populations. The decision to use the most recent 100 reviews for each game might introduce recency bias, as more recent feedback could reflect the latest updates or changes in the game, potentially overlooking longer-term user experiences.

### 2.5.3. Comparing 3D Environments Through Breathing Tasks

#### Fourth Group: The Impact of 3D Environments

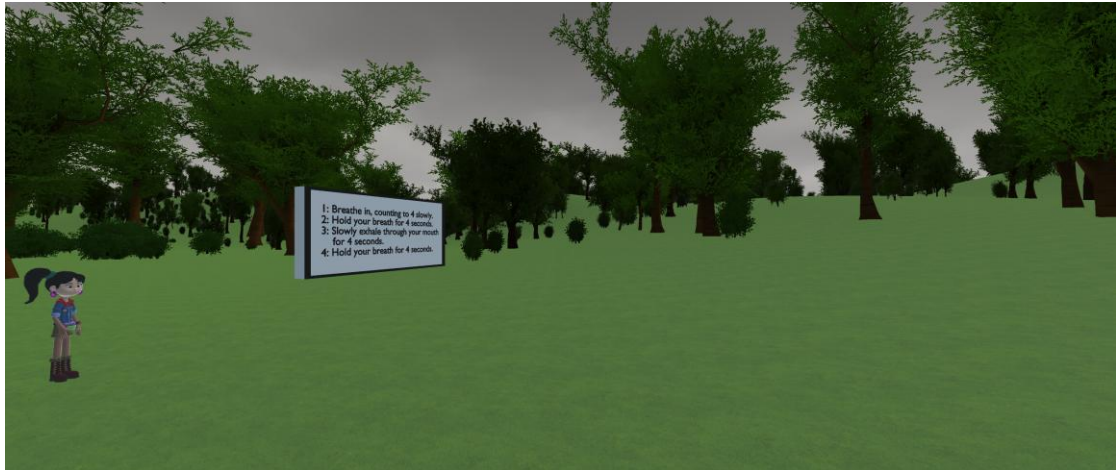
Software was also developed in the Unity game engine, as it greatly helped display various computer graphics in a straightforward manner. Unity is a cross-platform game engine developed by Unity Technologies, with its first version released in 2005. It supports development for desktop, mobile, and various consoles, and importantly for this project, it also supports Virtual Reality platforms. Unity is widely utilized in iOS and Android mobile game development, and its accessibility means even novice game developers can create games with relative ease. Many indie games owe their existence to this versatile game engine, which can render both three-dimensional (3D) and two-dimensional (2D) graphics, as well as facilitate interactive simulations and various experiments. Moreover, Unity finds applications in engineering design and the film industry [130]. I started on the development of three distinct 3D environments, each offering a unique interpretation of the same forest setting. These environments were designed to evoke different emotional responses and scenarios, catering to varying moods and experiences within the virtual world [131].

The first environment, positive-affective environment (*Figure 6.*), demonstrates a sunny and vibrant forest. Sunlight shines through the tree leaves, and flowers bloom everywhere. Birds sing happily, filling the air with cheerful sounds. Green plants surround you, creating a peaceful, natural feeling.



**Figure 6.** Screenshot of the Positive-Affective VR environment

In contrast, the neutral-baseline environment (*Figure 7.*) presents a quiet representation of the forest. The forest feels calm, with no noise or visible wildlife. This quiet setting lets users focus inward, free from distractions.



**Figure 7.** Screenshot of the Neutral-Baseline VR environment

The third environment, Negative-Affective VR environment (*Figure 8.*), offers a stark departure from the previous two. In this scene, the forest feels negative-affective and unsettling. The sky is cloudy, hinting at a coming storm. The land looks empty, with twisted trees and dead plants. Lightning flashes, and thunder rumbles in the distance, adding to the eerie feeling.



**Figure 8.** Screenshot of the Negative-Affective VR environment

In developing the Virtual Reality game, I integrated the Ellie character from the Blender Foundation to serve as a visual and interactive guide for users. Ellie helps demonstrate the three techniques I previously mentioned, making them easier to follow and practice. Incorporating a familiar and engaging character like Ellie enhances the user experience, ensuring the breathing exercises are both effective and enjoyable [132]. The game featured three breathing techniques: Box Breathing, 4-7-8 Breathing, and Humming Breath. Box Breathing involves slow, controlled inhalation and exhalation to promote relaxation. 4-7-8 Breathing effectively calms the nervous system. Humming Breath combines exhaling with a humming sound, aiding relaxation and reducing stress levels.

## **"Box Breathing" techniques**

The first method used in my Virtual Reality games is Box Breathing, which is alternatively referred to as square breathing. This technique represents a systematic and organized approach to breath regulation aimed at quickly promoting relaxation. Box Breathing proves to be especially beneficial in instances of increased stress or anxiety, offering a straightforward yet potent instrument for handling these situations. The procedure starts with inhalation through the nostrils, sustained for a duration of four counts, thereby enabling the lungs to reach full capacity. This is succeeded by maintaining the breath for an additional count of four. The second step involves a slow and conscious exhalation through the mouth, also for a count of four. The person then holds their breath for a few seconds and holds their breath for another account of four seconds before repeating the process. This cyclical process helps regulate breathing, promoting relaxation and calming the nervous system [71,133,134].

## **"4-7-8 Breathing" techniques**

The 4-7-8 breathing method, developed by Dr. Andrew Weil, is a simple but effective technique aimed at calming the nervous system and easily inducing deep relaxation. It is particularly helpful for stress, anxiety, sleep improvement, and generally for strengthening mental well-being. The structured way of controlling breath makes it a valuable tool for everyone who wants to work on breathing and release strain.

1. To practice 4-7-8 breathing, the patient starts by placing one hand on the abdomen and the other on the chest to help focus on the breath and ensure proper abdominal breathing. The process is started by slow and deep inhalation through the nostrils for a count of four. With this inhalation, the individual should take the air in the abdomen, allowing the belly to rise while keeping the chest relatively still. This encourages diaphragmatic breathing, which is more conducive to relaxation.
2. Once the lungs are completely filled, the person holds their breath for approximately seven seconds. This period of holding one's breath is crucial, as it ensures oxygen spreads throughout the circulatory system and enhances the calming effect of the stimulus on the nervous system.
3. After holding one's breath, a person exhales slowly and completely through the mouth, taking eight seconds to do so. It should be a controlled and profound exhalation, letting the lungs fully empty while releasing any stored tension with each breath.

The rhythmic pattern of the 4-7-8 breathing technique allows for proper alignment of the different rhythms in the body, which in turn creates harmony and balance.

By incorporating this technique into the Virtual Reality game, I create an interactive and engaging environment that guides users through the 4-7-8 breathing exercises. Using state of the art VR technology, the game provides visual and audio cues to help the user maintain the correct rhythm and focus throughout the exercise. This interactive

method not only enhances the effectiveness of the method but also makes it more enjoyable and accessible, ensuring regular practice and long-term benefits [135].



**Figure 9.** Participant during the VR breathing exercise

### **“The Humming Breath” techniques**

The technique referred to as the Humming Breath, or “bhramari pranayama” within the contexts of yoga and meditation, constitutes a calming and restorative breathing practice. This method encompasses a sequence of intentional actions designed to tranquilize both the mind and body through regulated respiration and auditory vibrations.

To practice the Humming Breath technique effectively, the user follows a structured sequence of actions:

1. Begin with a deep inhalation through the nose, taking the breath in slowly and steadily. The inhalation should be for at least five seconds so that the lungs fill with air.
2. When full lung capacity has been reached, the mouth is closed lightly, and an initial soft humming sound is started, like the vibration created by "hmmm." The hum should be light and resonating, bringing about a soothing vibration of the cranial and thoracic cavities.
3. During the process of exhaling through the nasal passages, maintain a gentle hum, enabling the associated vibrations to resonate throughout the body. This humming vibration is crucial to the therapeutic benefits of the technique, facilitating relaxation and mitigating stress levels.
4. Repeat the entire sequence in a cycle of five to seven times: deep inhalation through the nose, soft humming while exhaling. With each repetition, deeper relaxation is possible, with increased sensation in the calming effect of the Humming Breath.

5. After completing the repetitions, take a moment to sit quietly and observe the sensations in the body and mind. Notice any subtle changes in relaxation, stress reduction, or mental clarity brought about by the practice.
6. Finally, gradually resume daily activities while maintaining the sense of calmness and stillness cultivated during the Humming Breath practice.

The integration of the humming breathing technique into the Virtual Reality game involves the creation of an immersive experience that guides the participant through each aspect of the practice [136,137]. By blending these structured breathing methods with immersive Virtual Reality environments, the aim is to provide a therapeutic tool that significantly benefits individuals dealing with stress, anxiety, and respiratory challenges.

## 2.6. Questioners

During the experiments, in addition to self-developed questionnaires, the following well-known questionnaires were used: UEQ and SUS were utilized in the first, second, and fourth experiments, while STAI and DASS-21 were used for the fourth group, focusing on The Impact of 3D Environments.

### State-Trait Anxiety Inventory - STAI

- *STAI-T (Trait Anxiety)*: This part of the questionnaire measures the participants' general tendency to perceive situations as threatening and their overall level of anxiety as a personality trait [146].
- *STAI-S (State Anxiety)*: This part assesses the participants' current anxiety levels or how anxious they feel "right now," at this moment [147].

### Depression Anxiety Stress Scales - DASS-21

This 21-item scale evaluates the severity of a range of symptoms related to depression, anxiety, and stress. It provides a comprehensive profile of participants' mental health status [148].

### User Experience Questionnaire - UEQ

This questionnaire assesses the participants' perceptions of the game's usability, efficiency, and enjoyment, providing insights into the user experience within the VR environment [149].

### System Usability Scale - SUS

The SUS is a quick and reliable tool to evaluate the usability of the Virtual Reality system from the participants' perspective. It consists of ten items that measure the overall usability and ease of use of the VR system [150].

# Chapter 3

## 3. Results

This section presents the experiments' findings, including the questionnaire results, heart rate data, various statistical analyses, and T-test results. This section presents a comprehensive analysis of the experimental outcomes, focusing on key observations, hypothesis validation, and statistical analysis. It explores the insights gathered from the data, validates the hypotheses through testing, and summarizes the findings to highlight the implications of the research. The section is structured into three parts: Key Observations, Hypothesis Validation, and a Summary of Findings, providing a detailed look at the research's results.

### 3.1. Key Observations

This section highlights the critical findings and insights gathered during the experiments. It synthesizes the main outcomes, emphasizing trends, patterns, and noteworthy results relevant to the research objectives. This section aims to provide a concise yet comprehensive overview of the data, offering context for subsequent discussions and conclusions.

#### 3.1.1. Outcomes of Comparing Visualization Devices for Rehabilitation Experiment

##### First Group: Comparing Visualization Devices for Rehabilitation

In this experiment, participants' tasks were to do indoor cycling while watching a beach cycling video on different visualization devices (mobile, tablet, monitor, and VR headset). During the activity, their heart rates were measured, and afterwards, they completed the questionnaires.

##### User Experience

After the exercises, the participants filled out the User Experience Questionnaire (UEQ) for each device [149].

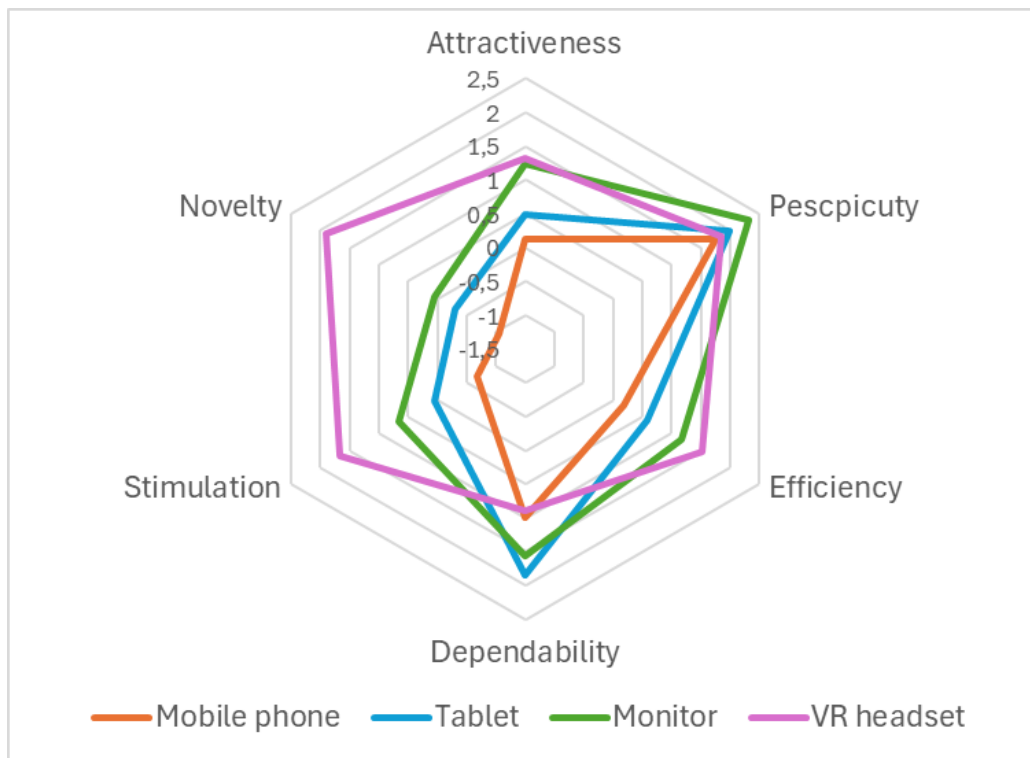
Analysis (*Table 3.*) of the attractiveness dimension revealed that the VR device received the highest score of 1.32, followed by the monitor, tablet, and mobile.

In terms of perspicuity, the monitor scored the highest with 2.31, followed by the tablet, VR, and mobile. VR obtained the highest efficiency score of 1.52, with the monitor device following closely with a score of 1.17, then the tablet, and the mobile. Regarding dependability, the monitor received the highest score of 1.57, followed by the tablet, VR, and mobile. For stimulation, the VR device obtained the highest score of 1.66, followed by the monitor, tablet, and mobile. All exact data can be found in *Table 3.*

Finally, the VR device scored the highest in novelty with a score of 1.90, followed by the monitor, tablet, and mobile.

**Table 3.** UEQ results for Comparing Visualization Devices for Rehabilitation experiment

	Attractive-ness	Perspici-ity	Effi-ciency	Dependabil-ity	Stimula-tion	Nov-elty
<b>Mobile phone</b>	0.13	1.75	0.18	0.99	-0.68	-1.06
<b>Tablet</b>	0.49	1.99	0.59	1.85	0.04	-0.3
<b>Monitor</b>	1.24	2.31	1.17	1.57	0.66	0.06
<b>VR headset</b>	1.32	1.84	1.52	0.9	1.66	1.9



**Figure 10.** UEQ results for Comparing Visualization Devices for Rehabilitation experiment

The radar chart, *Figure 10*, visually represents user experiences across six attributes—Attractiveness, Perspicuity, Efficiency, Dependability, Stimulation, and Novelty—across four different technological setups: mobile phone, tablet, monitor, and VR headset. It shows the mobile phone's scores clustered towards the center, indicating a lower overall performance compared to the other setups. The tablet is extended further outwards, particularly in Perspicuity and Dependability, but still falls short in Stimulation and Novelty. The monitor exhibits a robust presence, especially in Perspicuity and Efficiency, illustrating its reliability. Finally, the VR headset dominates

the outer edges of the diagram, particularly in Stimulation and Novelty, showcasing its potential to engage users effectively.

### T-Test assuming unequal variances

In this section, T-tests assuming unequal variances with an alpha level of 0.05 will be conducted to compare the effects of different visualization devices. The comparisons made between the following pairs, as can be seen in *Tables 4* and *5*:

- Mobile phone and tablet,
- Mobile phone and monitor,
- Mobile phone and VR headset,
- Tablet and monitor,
- Tablet and VR headset,
- Monitor and VR headset.

The objective is to identify significant differences in user experience among these visualization devices during indoor cycling sessions.

The table (*Table 4.*) presents a comparative analysis of user experiences with three technological setups: mobile phone and tablet, mobile phone and monitor, and mobile phone and VR headset. It highlights various attributes such as attractiveness, perspicuity, efficiency, dependability, stimulation, and novelty, along with their corresponding p-values and significant results.

**Table 4.** Two-tailed T-test results to compare the effects of different visualization devices Part I.

	Mobile phone and tablet		Mobile phone and monitor		Mobile phone and VR headset	
	p-value	result	p-value	result	p-value	result
Attractiveness	0.2391	No significant difference	0.0004	<i>Significant difference</i>	0.0009	<i>Significant difference</i>
Perspicuity	0.3860	No significant difference	0.0315	<i>Significant difference</i>	0.7548	No significant difference
Efficiency	0.1017	No significant difference	0.0001	<i>Significant difference</i>	0.0000	<i>Significant difference</i>
Dependability	0.2102	No significant difference	0.0240	<i>Significant difference</i>	0.7671	No significant difference
Stimulation	0.0272	<i>Significant difference</i>	0.0000	<i>Significant difference</i>	0.0000	<i>Significant difference</i>
Novelty	0.0119	<i>Significant difference</i>	0.0003	<i>Significant difference</i>	0.0000	<i>Significant difference</i>

The analysis reveals significant differences in various aspects when comparing the devices. Notably, when comparing mobile phones and monitors, significant differences were observed across all aspects measured. Similarly, significant differences were found in almost all aspects when comparing mobile phones and VR headsets.

In summary, while the mobile phone and tablet setup has its strengths, the mobile phone paired with a monitor, and especially with a VR headset, significantly enhances user experiences across multiple dimensions. The VR headset excels in attractiveness, efficiency, stimulation, and novelty, highlighting its potential to engage users more effectively than traditional setups. Further exploration into these technologies could lead to improved applications and user satisfaction in rehabilitation contexts.

Furthermore, in *Table 5*, significant differences were noted in nearly all aspects when comparing tablets and VR headsets.

**Table 5.** Two-tailed T-test results to compare the effects of different visualization devices Part II.

	Tablet and monitor		Tablet and VR headset		Monitor and VR headset	
	p-value	result	p-value	result	p-value	result
Attractiveness	0.0144	<i>Significant difference</i>	0.0190	<i>Significant difference</i>	0.8231	No significant difference
Perspiciuity	0.1738	No significant difference	0.5765	No significant difference	0.0608	No significant difference
Efficiency	0.0079	<i>Significant difference</i>	0.0007	<i>Significant difference</i>	0.1774	No significant difference
Dependability	0.3586	No significant difference	0.1373	No significant difference	0.0152	<i>Significant difference</i>
Stimulation	0.0575	No significant difference	0.0000	<i>Significant difference</i>	0.0033	<i>Significant difference</i>
Novelty	0.2230	No significant difference	0.0000	<i>Significant difference</i>	0.0000	<i>Significant difference</i>

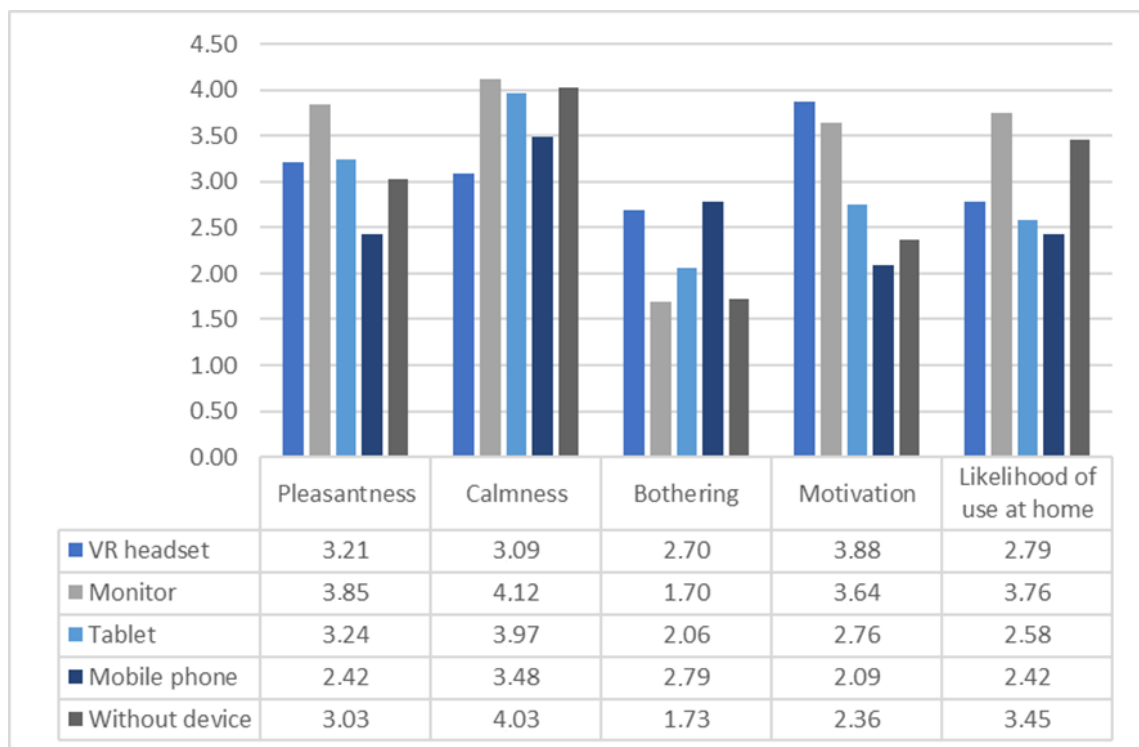
Given the substantial differences in user experience across these visualization devices, a more detailed comparison between monitors and VR headsets is now being focused on.

## Comparison

Moving on to the participants' evaluation of the experiment's qualities, the following results were obtained:

- *Pleasantness*: The monitor received the highest rating in terms of pleasantness, followed by tablet, VR headset, no device, and mobile phone, as shown in *Figure 11*.
- *Calmness*: Similarly, the participants rated the experiment with the monitor as the calmest, followed by the scenario without any device, tablet, mobile phone, and VR headset.
- *Bothering*: Regarding the level of bother, the monitor was found to be the least bothersome, followed by the scenario without any device, tablet, VR headset, and mobile phone.
- *Motivation*: In terms of motivation, the participants rated the VR device as the most motivating, followed by the monitor, tablet, no device, and mobile phone.
- *Likelihood of use at home*: Finally, the participants expressed a higher likelihood of using the monitor, and VR devices at home.

Based on this analysis, the monitor generally received positive ratings across various criteria, suggesting that it had a positive impact on rehabilitation. The VR headset and tablet devices received mixed ratings, while the experiment with mobile phones received the lowest ratings across multiple criteria.



**Figure 11.** Questionnaire results of the experiment's qualities

## Detailed Analysis for Monitor and VR Headset

In the following sections, a detailed analysis comparing the user experience between the Monitor and the VR headset results is provided.

### Detect outliers

Tables 6 and 7 below list the values to detect outliers in the evaluations. Significant deviations from the evaluations of other items within the same scale may indicate that the item was being misinterpreted by a higher number of participants, possibly due to a unique context in their evaluation. It is important to note that stimulation and novelty cannot be measured with the monitor, while all aspects can be measured with the VR headset. However, even in the case of the VR headset, the dependability value was very close to the limit. The method for detecting outliers involved comparing individual item scores within the same scale to identify significant deviations, which may indicate misinterpretation by participants. Specifically, if an item's score is substantially higher or lower than the others, it could suggest that it is an outlier worth further investigation. The threshold interpretation method was also used for outlier detection, where values between -0.8 and 0.8 are considered neutral, scores above 0.8 indicate a positive evaluation, and those below -0.8 indicate a negative evaluation. This approach identifies outliers by highlighting individual items rated significantly higher or lower than others in the same category, rather than relying on statistical cutoffs like Z-scores or IQR.

**Table 6.** Mean and Variance in the case of Monitor

UEQ Scales (Mean and Variance)		
<b>Attractiveness</b>	↑ 1.242	1.40
<b>Perspicuity</b>	↑ 2.311	0.68
<b>Efficiency</b>	↑ 1.174	0.68
<b>Dependability</b>	↑ 1.568	0.64
<b>Stimulation</b>	→ 0.659	1.54
<b>Novelty</b>	→ 0.061	1.48

**Table 7.** Mean and Variance in the case of the VR headset

UEQ Scales (Mean and Variance)		
<b>Attractiveness</b>	↑ 1.318	2.35
<b>Perspicuity</b>	↑ 1.841	1.32
<b>Efficiency</b>	↑ 1.515	1.37
<b>Dependability</b>	↑ 0.902	1.69
<b>Stimulation</b>	↑ 1.659	2.00
<b>Novelty</b>	↑ 1.902	1.39

After excluding outliers, attractiveness, perspicuity, and efficiency can be assessed in terms of user experience for both VR and the monitor. In all three aspects, no significant differences were observed between the two devices.

### Pragmatic and hedonic quality

The scales of the User Experience Questionnaire can be categorized into *pragmatic quality*: \_Perspicuity, \_Efficiency, Dependability, and *hedonic quality*: Stimulation, Originality. Pragmatic quality refers to functional aspects that are directly related to its ability to support users in completing tasks efficiently and effectively. This includes attributes such as usability, reliability, and performance, which are critical for achieving specific goals. On the other hand, hedonic quality encompasses the non-task-related aspects of a product that contribute to the user's overall experience. These qualities focus on emotional responses, aesthetics, and pleasure or satisfaction derived from using the product. Hedonic quality is more concerned with how the product feels, looks, and engages users on an emotional or sensory level rather than just its practical functionality. *Table 8* shows the mean ratings for the three aspects of pragmatic and hedonic quality. These results offer insights into both the task- and non-task-related quality aspects of user experience with the monitor. The ratings can range from -3 to 3. In the case of both the Monitor and the VR headset, favorable results were obtained.

**Table 8.** Pragmatic and hedonic quality results for the monitor and VR headset

Pragmatic Quality			Hedonic Quality
Significant difference	Attractiveness	Mean of Perspicuity, Efficiency, Dependability	Mean of Stimulation, Originality:
<b>Monitor</b>	1.24	1.68	0.36
<b>VR headset</b>	1.32	1.42	1.78

### Confidence intervals for items and scales

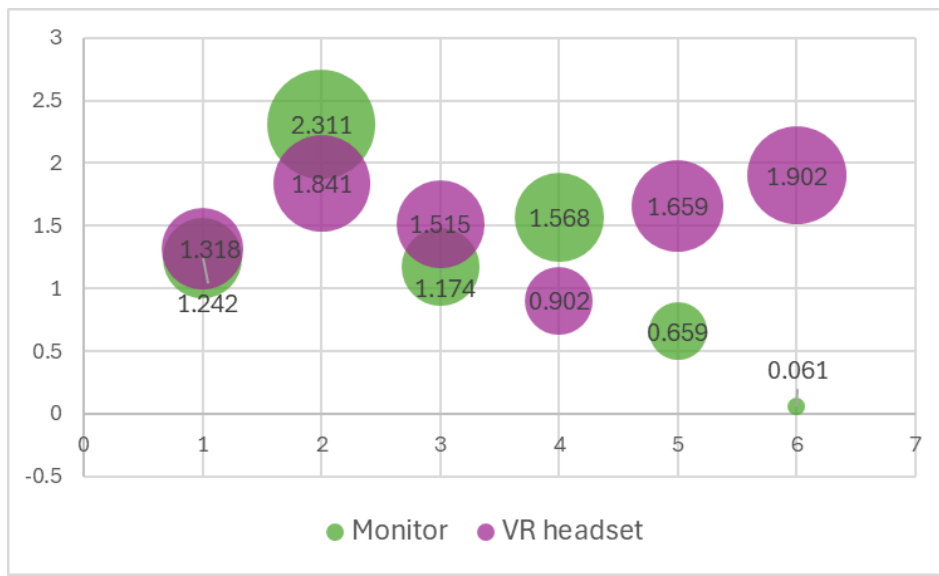
Below are the 5% confidence intervals for the scale means and means of the individual items (*Tables 9 and 10*). The confidence interval indicated the precision of the estimated mean scale. A smaller confidence interval implies higher precision in the estimation and greater reliability of the results. The width of the confidence interval depends on the amount of available data and the consistency of participants' judgments of the evaluated product. A more consistent opinion led to a smaller confidence interval.

**Table 9.** Confidence intervals for items and scales for Monitor

	Mean	Std. Dev.	N	Confidence	Confidence Interval	
Attractiveness	1.242	1.185	33	0.404	0.838	1.647
Perspicuity	2.311	0.822	33	0.28	2.03	2.591
Efficiency	1.174	0.826	33	0.282	0.893	1.456
Dependability	1.568	0.801	33	0.273	1.295	1.841
Stimulation	0.659	1.242	33	0.424	0.235	1.083
Novelty	0.061	1.215	33	0.415	-0.354	0.475

**Table 10.** Confidence intervals for items and scales for the VR headset

	Mean	Std. Dev.	N	Confidence	Confidence Interval	
Attractiveness	1.318	1.534	33	0.523	0.795	1.842
Perspicuity	1.841	1.147	33	0.391	1.45	2.232
Efficiency	1.515	1.173	33	0.4	1.115	1.915
Dependability	0.902	1.3	33	0.444	0.458	1.345
Stimulation	1.659	1.414	33	0.482	1.177	2.142
Novelty	1.902	1.177	33	0.402	1.5	2.303



**Figure 12.** Comparison of Mean Values for Monitor and VR Headset Across User Experience Dimensions

The bubble chart (*Figure 12.*) comparing the mean results of the VR headset and the Monitor provides a clear visual representation of user experiences across six attributes in the x-axis: Attractiveness - 1, Perspicuity - 2, Efficiency -3, Dependability - 4, Stimulation - 5, and Novelty - 6. Each bubble on the chart represents one of the attributes, with the green color representing the mean scores of the monitor and the purple color representing the mean scores of the VR headset. The bubbles for the VR headset are positioned higher along the Stimulation and Novelty axes, while the monitor’s bubbles occupy a higher position for Perspicuity and Dependability.

## Benchmark

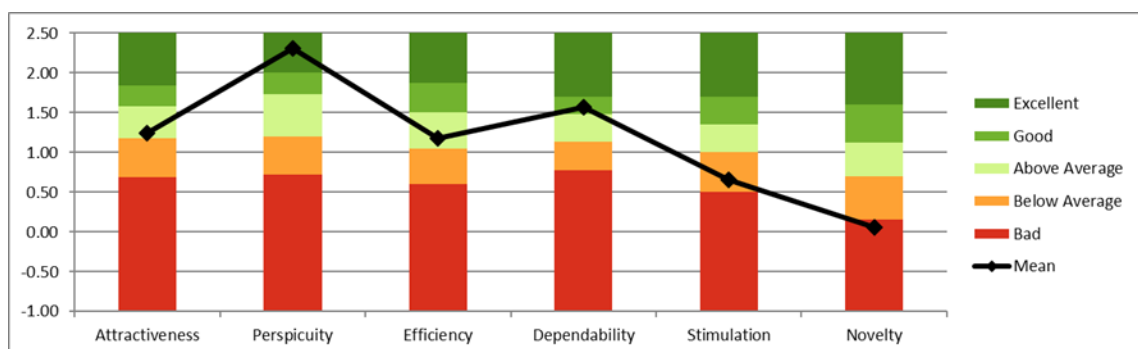
The benchmark dataset comprises information from 21.175 individuals across 468 experiments, encompassing various products such as business software, web pages, web shops, and social networks. The measured scale means were compared to these existing values to evaluate the relative quality of the evaluated product in comparison with others [149].

The defined benchmark categories: *Bad*: Represents the range of the 25% worst results. *Below Average*: This signifies that 50% of the results are better, while 25% are worse. *Above Average*: Indicates that 25% of the results are better, and 50% are worse. *Good*: 10% of the results are better, and 75% are worse. *Excellent*: Results within the range of the top 10%.

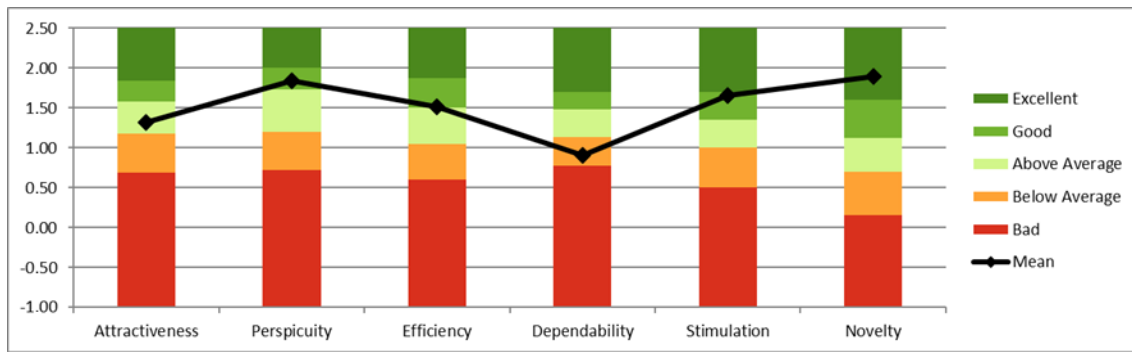
**Table 11.** Benchmark for the Monitor and VR headset

	Monitor		VR headset	
	Mean	Comparison to the benchmark	Mean	Comparison to the benchmark
<b>Attractiveness</b>	1.24	Above average	1.32	Above average
<b>Perspicuity</b>	2.31	Excellent	1.84	Good
<b>Efficiency</b>	1.17	Above average	1.52	Good
<b>Dependability</b>	1.57	Good	0.90	Below Average
<b>Stimulation</b>	0.66	Below Average	1.66	Good
<b>Novelty</b>	0.06	Bad	1.90	Excellent

The two bar charts (*Figures 13 and 14.*) compare the mean scores and their respective comparisons to a benchmark for the monitor and VR headset across six attributes: Attractiveness, Perspicuity, Efficiency, Dependability, Stimulation, and Novelty. Each chart visually represents the strengths and weaknesses of each technology, accompanied by trend lines indicating overall performance. They highlight how each technology caters to different user needs, with the monitor being more reliable and clearer, while the VR headset offers greater stimulation and novelty.



**Figure 13. Benchmark for Monitor**



**Figure 14. Benchmark for VR headset**

### Comparison based on heart rate

I conducted a comparison of visualization devices based on heart rate using a significance level of  $p=0.05$ . This level of significance indicates a 95% probability that the results of the experiment are due to a true relationship or difference between the groups being compared. There was a 5% chance that the results were obtained by chance alone, and there was no true relationship between the groups. The results presented in *Table 12* indicate that in all cases, the results were not statistically significant. Therefore, it can be concluded that the visualization devices had no significant effect on heart rate during indoor cycling.

**Table 12. Comparison based on heart rate**

	Monitor		VR	
	p-value	result	p-value	result
<b>Without any device</b>	0.2938	No significant difference	0.7959	No significant difference
<b>Mobile phone</b>	0.5369	No significant difference	0.8763	No significant difference
<b>Tablet</b>	0.8324	No significant difference	0.6021	No significant difference
<b>Monitor</b>	-	-	0.4916	No significant difference
<b>VR</b>	0.4916	No significant difference	-	-

### 3.1.2. Exploring the Benefits of Virtual Reality Implementation of Spatial Memory Test

#### Second Group: Virtual Reality Implementation

Following the development phase of the memory test, I conducted a trial of the software with a cohort of 14 participants, comprising 3 males and 11 females. The mean patient age was 29 years, with a standard deviation of 9. Throughout the assessments, the participants' pulse rates were monitored, revealing that 60% of those who underwent the Virtual Reality test exhibited lower pulse rates than those who underwent the traditional method.

#### Traditional Corsi vs Virtual Reality Corsi

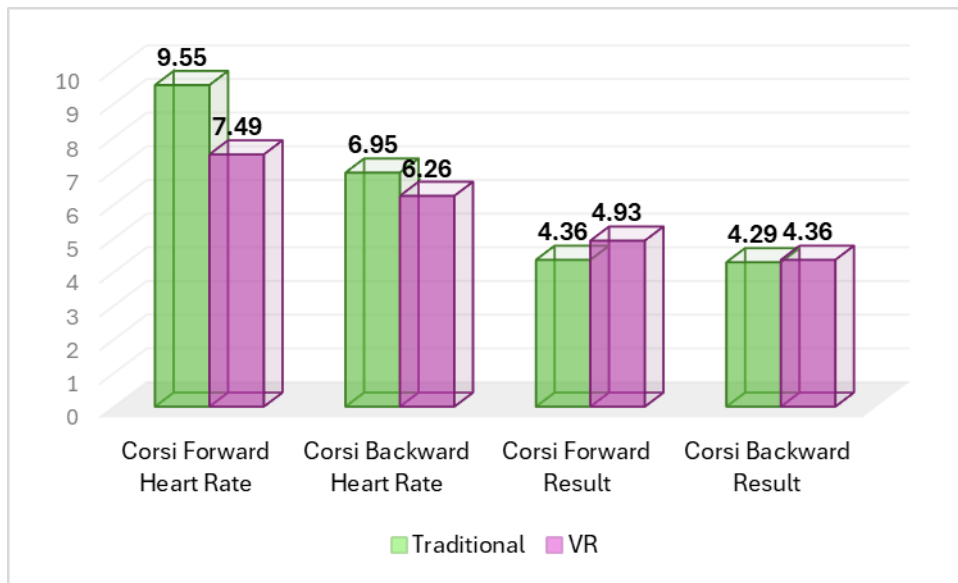
The first table (*Table 13*) provides a detailed overview of the scale means and the corresponding 5% confidence intervals. It presents the heart rate pulse data collected during both the traditional Corsi-Test and the Virtual Reality Corsi-Test, along with the test results.

**Table 13.** Comparison of Scale Means between Traditional Corsi and Virtual Reality Corsi

		<b>Corsi Forward Heart Rate</b>	<b>Corsi Backward Heart Rate</b>	<b>Corsi Forward Result</b>	<b>Corsi Backward Result</b>
<b>Traditional</b>	<b>Mean</b>	9.55	6.95	4.36	4.29
	<b>STD</b>	8.55	8.96	1.50	0.99
	<b>N</b>	14	14	14	14
	<b>Confidence</b>	4.48	4.69	0.79	0.52
	<b>Confidence Interval</b>	5.07	2.25	3.57	3.76
		14.03	11.64	5.14	4.81
<b>VR</b>	<b>Mean</b>	7.49	6.26	4.93	4.36
	<b>STD</b>	9.02	9.13	1.21	1.65
	<b>N</b>	14	14	14	14
	<b>Confidence</b>	4.73	4.78	0.63	0.86
	<b>Confidence Interval</b>	2.77	1.48	4.30	3.50
		12.22	11.04	5.56	5.22

*Figure 15* complements this data presentation with a bar chart, clearly illustrating a lower pulse rate and better test results in the case of VR. A noticeable trend emerged

from the graph; in all cases, the tests conducted in the VR environment resulted in lower pulse rates. The average heart rate was 17% lower in Virtual Reality.



**Figure 15.** Bar chart of comparison of Scale Means between Traditional Corsi and Virtual Reality Corsi

However, despite the apparent differences, a two-sample T-test conducted on these results (*Table 14*) with an alpha level of 0.05 did not indicate a significant difference in the scale means of the two measured products. Consequently, although I cannot definitively confirm these results, it can be concluded that this method shows promise and warrants further investigation.

**Table 14.** Two-sample T-Test results with alpha level 0.05 from the scale means

Corsi Forward Heart Rate	0,5410	No Significant Difference
Corsi Backward Heart Rate	0,8414	No Significant Difference
Corsi Forward Result	0,2772	No Significant Difference
Corsi Backward Result	0,8908	No Significant Difference

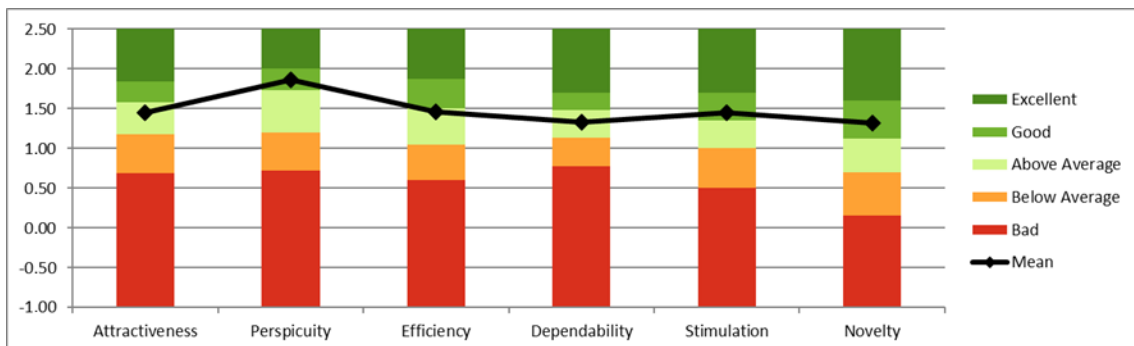
## User Experience

After completing the tests, participants were surveyed regarding their experiences. A significant majority (67%) noted a noticeable difference between the two testing methods, favoring VR for its perceived better experience and ease of understanding compared to the traditional approach. The participants also completed a User Experience Questionnaire. The software received above average benchmarks (*Table 15* and *Figure 16*) for Attractiveness, Efficiency, and Dependability, indicating that 25% of the results were better and 50% were worse than existing benchmarks. In terms of Perspicuity, Stimulation, and Novelty, only 10% of the results were better, whereas 75% were worse.

**Table 15.** Benchmark of the VR Corsi-test UEQ results

Scale	Mean	Comparison to the benchmark	Interpretation
Attractiveness	1.46	Above average	25% of results better, 50% of results worse
Perspicuity	1.87	Good	10% of results are better, 75% of results are worse
Efficiency	1.47	Above average	25% of results better, 50% of results worse
Dependability	1.33	Above average	25% of results better, 50% of results worse
Stimulation	1.45	Good	10% of results are better, 75% of results are worse
Novelty	1.32	Good	10% of results are better, 75% of results are worse

The measured scale means were compared to existing values from a benchmark dataset that included data from 21.175 individuals across 468 studies covering various products, such as business software, web pages, web shops, and social networks [112].



**Figure 16.** Bar chart of the Benchmark of the VR Corsi-test

### Impact Overview

The use of Virtual Reality technology in cognitive assessment software allows for precise control over tests and consistent presentation of stimuli. This reduces human error and increases the reliability of the test results. This innovation enhances the accuracy of cognitive assessments by providing precise control over testing conditions and ensuring consistent presentation of stimuli, thus minimizing human error and resulting in more reliable outcomes.

### Key Findings

**Physiological Response:** In the recent trial, which involved 14 participants (3 males, 11 females) with an average age of 29 years (standard deviation: 9 years), VR technology demonstrated notable benefits. Participants using the VR-based Corsi-Test exhibited a 17% lower average pulse rate than those using the traditional method. This suggests a

reduction in physiological stress associated with VR, highlighting its potential to create a more comfortable testing environment.

*Comparative Analysis:* Table 13 details the comparative results of the traditional and VR Corsi-tests. While the VR method showed lower mean pulse rates and marginally better test results, the statistical analysis (Table 14) did not reveal significant differences between the two methods. This indicates promising trends but underscores the need for further research to validate these findings.

*User Experience:* Survey results revealed that 67% of the participants preferred the VR method, appreciating its better overall experience and ease of understanding. Users experience ratings (Table 15 and Figure 16) showed above average scores for Attractiveness, Efficiency, and Dependability, though Perspicuity, Stimulation, and Novelty received less favorable evaluations. This feedback highlights the need for continued refinement of VR software to enhance all aspects of the user experience.

*Software Advantages:* The VR-based Corsi-Test eliminates variability introduced by human testers, resulting in more accurate measurements of visual-spatial and working memory. The software's rapid data processing and integration capabilities enhance evaluation efficiency, which is crucial in clinical settings where time and resource management are vital. The VR environment is particularly beneficial in reducing anxiety, making it a valuable tool for children and individuals who may find traditional assessments stressful. This contributes to more accurate cognitive measurement.

### **3.1.3. User Experience in Virtual Rehabilitation**

#### **Third Group: User Experience in Virtual Rehabilitation**

The data analysis revealed several findings that are important to the category of user experiences and opinions related to VR rehabilitation games. Two major categories were identified based on the findings: general trends in user reviews and comparisons between different game categories.

#### **General Trends in User Reviews**

The most frequently occurring words in user reviews centered around terms like "improvement," "fun," "engaging," and "challenging." This indicates that users often find VR rehabilitation games enjoyable and beneficial for their rehabilitation process.

The overall sentiment of user reviews was predominantly positive, with an average sentiment score of 0.75 across the dataset. This sentiment score is on a continuous scale from -1 to 1, where -1 represents very negative sentiment, 0 represents neutral sentiment, and 1 represents very positive sentiment. Users expressed satisfaction with the immersive nature of the VR games and their effectiveness in making rehabilitation more interactive. Despite positive feedback, some users highlighted concerns about motion sickness and technical issues, such as tracking errors or difficulty in calibrating

the VR equipment. These issues were particularly noted in reviews of Neurological Rehabilitation Games (NRG).

**Table 16.** Average Word Count and Sentiment Analysis

Group	Average Word Count	Sentiment Mean	Sentiment Std	Sentiment Min	Sentiment Max
CRG	21.64	0.129	0.289	-1.000	1.000
NRG	20.34	0.092	0.278	-1.000	1.000
PRG	26.83	0.114	0.259	-1.000	1.000
PTG	19.12	0.093	0.299	-1.000	1.000
PSY	38.00	0.184	0.268	-1.000	1.000
SSCG	17.05	0.073	0.301	-1.000	1.000

When comparing the sentiment scores relative to the overall average (0.1142), significant variability was observed:

- Psychological Rehabilitation Games (PSY) show a positive difference of +61.17%, indicating a strong user preference.
- Conversely, Social Skills and Communication Games (SSCG) fell -36.06% below the average, reinforcing the notion that users are less satisfied with these games compared to others. (Table 17).

**Table 17.** Percentage Differences in Sentiment Scores

Category	Sentiment Percentage Difference
CRG	+12.99%
NRG	-19.42%
PRG	-0.15%
PTG	-18.54%
PSY	+61.17%
SSCG	-36.06%

That was calculated by using this formula:

$$('Sentiment\_Percdf['Sentiment\_Mean'] - overall\_sentiment\_avg) / ov100$$

It calculates the percentage difference between an individual sentiment score and the overall average sentiment score, allowing the quantification of how much the sentiment of a particular instance (like a review, comment, or feedback) deviates from the general sentiment.

#### Breakdown of the Formula:

1.  $df[Sentiment\_Mean]$ : This is the mean or average sentiment score of a certain instance in the dataset. For instance, it could be the average score of a review by a particular user or an observation unique to itself.
2.  $overall\_sentiment\_avg$ : This is the average sentiment score received from all instances in the dataset. This is a benchmark against which the sentimental values of each are compared.
3.  $df[Sentiment\_Mean] - overall\_sentiment\_avg$ : It compares the difference between the sentiment of an instance and the average sentiment in general. If it is positive, the instance will be more positive. In case of a negative result, it means a more negative sentiment.
4.  $df[Sentiment\_Mean] - overall\_sentiment\_avg / overall\_sentiment\_avg$ : This step normalizes the deviation by dividing the difference by the overall average sentiment, thereby contextualizing it in relation to the average sentiment value.
5. Finally, multiplication by 100 makes the result a percentage, and hence the deviation is expressed as a percentage of the comprehensive sentiment mean.

### **Comparative Analysis Across Game Categories**

Cognitive Rehabilitation Games (CRG) vs. Neurological Rehabilitation Games (NRG):

*Sentiment Differences:* T-test results revealed a statistically significant difference in sentiment scores between CRG and NRG ( $p < 0.05$ ). CRG received higher sentiment scores on average, suggesting that users found cognitive games more enjoyable and less prone to technical difficulties compared to neurological games.

*User Engagement:* The frequency of words related to engagement, like "interactive" and "fun," was higher in CRG reviews compared to NRG. This indicates that users were generally more engaged in cognitive rehabilitation games.

Physical Rehabilitation Games (PRG) reviews demonstrated a moderate sentiment score, with users frequently mentioning the physical benefits of the games. However, there were also concerns about the intensity of the exercises and the need for better customization to suit different fitness levels.

For word count, the analysis showed a mix of significant and non-significant differences across the various group comparisons. The most significant differences were observed between CRG and PSY, CRG and PRG, and PSY and SSCG, shown in *Table 17*.

**Table 18.** Word Count T-Test Results

<b>Comparison</b>	<b>T-Statistic</b>	<b>P-Value</b>	<b>Significance</b>
CRG vs. NRG	0.584	0.559	Not Significant
CRG vs. PRG	-2.162	0.031	Significant
CRG vs. PSY	-6.221	7.25e-10	Highly Significant
CRG vs. PTG	1.100	0.271	Not Significant
CRG vs. SSCG	2.446	0.015	Significant
NRG vs. PRG	-2.328	0.020	Significant
NRG vs. PSY	-5.833	7.35e-09	Highly Significant
NRG vs. PTG	0.292	0.770	Not Significant
NRG vs. SSCG	1.280	0.201	Not Significant
PRG vs. PSY	-3.976	7.52e-05	Significant
PRG vs. PTG	3.121	0.002	Significant
PRG vs. SSCG	4.396	1.22e-05	Significant
PSY vs. PTG	7.055	3.20e-12	Highly Significant
PSY vs. SSCG	8.325	2.73e-16	Highly Significant
PTG vs. SSCG	1.252	0.211	Not Significant

For sentiment, there are numerous significant differences, with some comparisons (such as NRG vs. PSY and PSY vs. SSCG) showing very strong significance. The results indicate substantial variability in sentiment across different groups. (*Table 19.*)

**Table 19.** Sentiment T-Test Results

<b>Comparison</b>	<b>T-Statistic</b>	<b>P-Value</b>	<b>Significance</b>
CRG vs. NRG	6.435	0.000	Highly Significant
CRG vs. PRG	-0.415	0.678	Not Significant
CRG vs. PSY	-2.436	0.015	Significant
CRG vs. PTG	4.339	0.000	Highly Significant
CRG vs. SSCG	6.682	0.000	Highly Significant
NRG vs. PRG	-6.633	0.000	Highly Significant
NRG vs. PSY	-8.683	0.000	Highly Significant
NRG vs. PTG	-2.173	0.030	Significant
NRG vs. SSCG	0.497	0.619	Not Significant
PRG vs. PSY	-1.956	0.051	Marginally Significant

PRG vs. PTG	4.608	0.000	Highly Significant
PRG vs. SSCG	6.872	0.000	Highly Significant
PSY vs. PTG	6.672	0.000	Highly Significant
PSY vs. SSCG	8.848	0.000	Highly Significant
PTG vs. SSCG	2.588	0.010	Significant

Overall, while word count differences are less consistent, sentiment differences are more pronounced, reflecting significant variations between the groups studied.

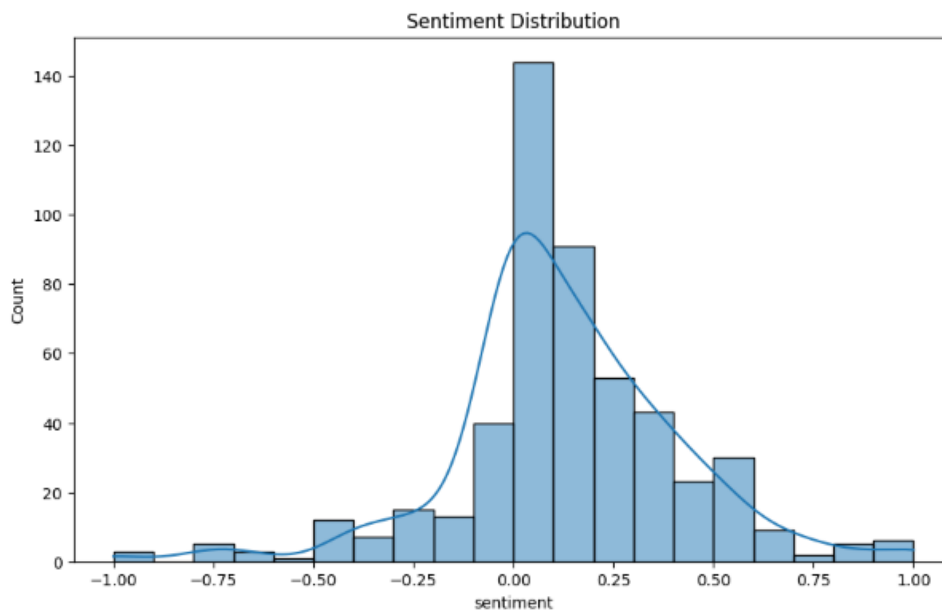
### Advanced Statistical Findings

A strong positive correlation ( $r = 0.68$ ) was found between the frequency of positive words and overall sentiment scores, indicating that the more positive language users employed in their reviews, the higher their sentiment scores.

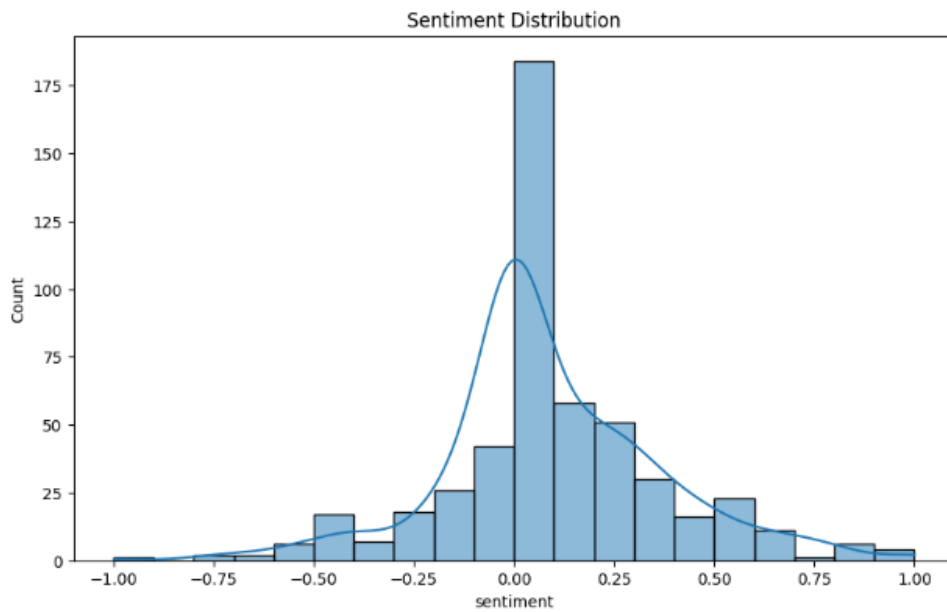
Games that were described as "complex" or "challenging" in user reviews tended to receive mixed feedback. While some users appreciated the challenge, others felt that complexity could be a barrier to effective rehabilitation, especially in NRG.

### Visualization of Results

A bar graph illustrating the distribution of sentiment scores across different game categories showed a skew towards positive sentiment for CRG, while NRG had a broader distribution with more neutral and negative reviews (*Figures 17 and 18*).



**Figure 17.** Sentiment Distribution of CRG data



**Figure 18.** Sentiment Distribution of NRG data

Word clouds generated from user reviews highlighted the prominence of positive terms in CRG, while words related to "issues" and "difficulty" were more common in NRG reviews (Figure 19.).



**Figure 19.** Word Cloud of CRG data (left) and NRG data (right)

Overall, the results indicate that while VR rehabilitation games are generally well-received, there are notable differences in user experience based on the type of game. Cognitive Rehabilitation Games appear to provide the most positive user experiences, while Neurological Rehabilitation Games may require further refinement to address technical challenges and user concerns.

### 3.1.4. The Impact of 3D Environments

#### Fourth Group: The Impact of 3D Environments

Before the main experiment, a pilot study was conducted with 10 participants to test the initial efficacy of the VR game combined with the breathing techniques being taught, comparing the VR approach to traditional methods. Following the pilot, an extended experiment was carried out with 15 participants, exploring three different virtual environments.

#### Pre-experiment

#### State-Trait Anxiety Inventory for State Anxiety - STAI-S

For the Virtual Reality group, the mean change in STAI-S scores was -6, with a confidence interval ranging from -12.14 to 0.14. For the control group, the mean change was -7.4, with a confidence interval ranging from -11.45 to -3.35. These values indicate the average reduction in state anxiety levels for each group and the range within which I can be confident that the true mean lies.

**Table 20.** STAI-S results of the Impact of 3D Environment pre-experiment

	Mean	STD	N	Confidence	Confidence Interval	
<b>VR</b>	-6.00	7.00	5	6.14	-12.14	0.14
<b>Traditional</b>	-7.40	4.62	5	4.05	-11.45	-3.35

#### Heart rate

For the Virtual Reality group, the mean change in heart rate was 1.63, with a confidence interval ranging from -4.40 to 7.65. For the control group, the mean change was 5.31, with a confidence interval ranging from -1.26 to 11.89. These values indicate the average change in the heart rate for each group and the range within which I can be confident that the true mean lies.

**Table 21.** Heart rate results of the Impact of 3D Environment pre-experiment

	Mean	STD	N	Confidence	Confidence Interval	
<b>VR</b>	1.63	6.87	5	6.02	-4.40	7.65
<b>Traditional</b>	5.31	7.51	5	6.58	-1.26	11.89

To determine if the differences in mean changes between the VR and control groups were statistically significant, I conducted a two-sample T-test assuming unequal

variances, both for STAI-S results and Heart rate results. I set the alpha level at 0.05, which is the standard threshold for significance. Both T-tests yielded a result with a value that is greater than the alpha level of 0.05. I conclude that there is no significant difference between the VR and control groups based on the changes in heart rate and STAI-S scores before and after the session. This indicates that, according to the data, the reduction in anxiety levels was not significantly different when participants used the VR environment or practiced breathing exercises without any external stimuli.

### **Experiment with Three Different 3D Environments**

#### **State-Trait Anxiety Inventory for Trait Anxiety - STAI-T**

To ensure a well-rounded and diverse sample, I assessed the trait anxiety levels of participants using the State-Trait Anxiety Inventory for Trait Anxiety (STAI-T). The distribution of participants across different levels of anxiety was as follows:

- Moderate Anxiety: 7 participants
- High Anxiety: 4 participants
- Low Anxiety: 3 participants

This distribution indicated a balanced representation of anxiety levels, allowing us to evaluate the effectiveness of different 3D environments on a varied sample of individuals. The participants were well distributed among the three anxiety categories, ensuring that the experiment results would apply to a broad spectrum of anxiety experiences.

#### **Depression Anxiety Stress Scales - DASS-21**

**Table 22.** DASS-21 results (D- depression, A- anxiety, S -stress)

Positive-Affective Environment			Neutral-Baseline Environment			Negative-Affective Environment		
D	A	S	D	A	S	D	A	S
3	6	1	1	11	15	2	6	10
3	5	4	0	4	2	3	7	4
2	4	3	10	20	14	4	8	4
6	10	6	3	6	2	14	25	16
2	7	6	3	11	9	0	0	0

The DASS-21 results for the participants were well distributed across the categories of normal, mild, and moderate levels of depression, anxiety, and stress. This distribution allowed us to analyze the impact of different 3D environments on a diverse range of emotional states.

## State-Trait Anxiety Inventory for State Anxiety - STAI-S

- Positive-Affective Environment:
  - Average Before:  $(20 + 36 + 29 + 46 + 43) / 5 = 34.8$
  - Average After:  $(23 + 22 + 23 + 34 + 30) / 5 = 26.4$
  - Average Change:  $34.8 - 26.4 = -8.4$  (reduction in STAI-S score)
- Neutral-Baseline Environment:
  - Average Before:  $(37 + 20 + 28 + 43 + 41) / 5 = 33.8$
  - Average After:  $(26 + 26 + 26 + 30 + 33) / 5 = 28.2$
  - Average Change:  $33.8 - 28.2 = -5.6$  (reduction in STAI-S score)
- Negative-Affective Environment:
  - Average Before:  $(23 + 50 + 22 + 40 + 33) / 5 = 33.6$
  - Average After:  $(31 + 38 + 21 + 34 + 29) / 5 = 30.6$
  - Average Change:  $33.6 - 30.6 = -3.0$  (reduction in STAI-S score)

The data confirms that the positive-affective environment consistently led to the largest reduction in STAI-S scores compared to neutral-baseline and negative-affective environments. On average, participants showed a reduction in stress levels across all environments, with the positive-affective environment showing the greatest average reduction in stress scores (-8.4 points), followed by neutral-baseline environment (-5.6 points), and negative-affective environment (-3.0 points).

This supports the initial observation that the positive-affective environment significantly reduced participants' stress levels based on the STAI-S scores provided.

## Heart rate

- Positive-Affective Environment:
  - Average Before Exercise:  $(88 + 75 + 88 + 61 + 69) / 5 = 76.2$
  - Average During Exercise:  $(91 + 80 + 89 + 67 + 70) / 5 = 79.4$
  - Average Change:  $79.4 - 76.2 = +3.2$  (increase in heart rate during exercise)
- Neutral-Baseline Environment:
  - Average Before Exercise:  $(90 + 66 + 80 + 89 + 82) / 5 = 81.4$
  - Average During Exercise:  $(94 + 70 + 81 + 91 + 89) / 5 = 85.0$
  - Average Change:  $85.0 - 81.4 = +3.6$  (increase in heart rate during exercise)
- Negative-Affective Environment:
  - Average Before Exercise:  $(69 + 78 + 76 + 84 + 71) / 5 = 75.6$
  - Average During Exercise:  $(69 + 77 + 75 + 84 + 78) / 5 = 76.6$
  - Average Change:  $76.6 - 75.6 = +1.0$  (increase in heart rate during exercise)

In all environments, participants generally experienced an increase in heart rate during exercise compared to baseline measurements taken before exercise.

The increases were smallest in the negative-affective environment (+1.0 bpm on average), followed by the positive-affective environment (+3.2 bpm on average), and the neutral-baseline environment (+3.6 bpm on average).

This suggests that while the positive-affective environment led to a slightly higher increase in heart rate during exercise compared to the negative-affective environment, the differences are relatively small. The neutral-baseline environment showed a slightly larger increase in heart rate during exercise compared to both the positive-affective and negative-affective environments.

### Two-Sample T-Tests

Based on the results of the Two-Sample T-Tests assuming unequal variances with an alpha level of 0.05, the findings are as follows:

**Table 23.** Comparison of Heart Rate Changes Across Different Environmental

Comparison	p-value	Conclusion
positive-affective vs neutral-baseline	0.974580491	No significant difference
neutral-baseline vs Dark	0.243425175	No significant difference
positive-affective vs Dark	0.266218489	No significant difference

Based on these data, there is no sufficient evidence to conclude that there are significant differences in heart rate changes during exercise between the positive-affective, neutral-baseline, and negative-affective environments. These results suggest that, despite the average changes observed in heart rates during exercise across different environments, these changes do not reach a level of statistical significance that would indicate one environment significantly influences heart rate differently compared to the others.

### User Experience Questionnaire - UEQ

The questionnaire evaluates user experiences across six key dimensions, each reflecting different aspects of user satisfaction and usability. Grouped by that, the results are the following:

- *Attractiveness*: Items 1, 12, 14, 16, 24, and 25 are considered positive indicators (mean score above 2.0), suggesting the software is generally perceived as attractive.
- *Perspicuity*: Items 2, 4, 13, and 21 are around the middle (mean scores around 2.0), indicating mixed perceptions of understandability and complexity.
- *Novelty*: Items 3, 10, 15, and 26 indicate moderate to low novelty scores, showing some room for improvement in perceived innovation.
- *Stimulation*: Items 5, 6, 7, and 18 are moderately scored, indicating mixed perceptions on how stimulating or motivating the software is.

- *Dependability*: Items 8, 11, 17, and 19 are also moderately scored, suggesting mixed perceptions on predictability, supportiveness, security, and meeting expectations.
- *Efficiency*: Items 9, 20, 22, and 23 show mixed perceptions of efficiency, practicality, and organization.

Overall, the results indicate that while the software is generally perceived positively in terms of attractiveness and some aspects of functionality, there are areas such as novelty, stimulation, and dependability, where improvements could potentially enhance the user experience.

### **System Usability Scale - SUS**

SUS scores provide a measure of usability perception, with higher scores indicating better-perceived usability. The average SUS score across all respondents was 84 out of 100. This indicates that, on average, participants perceived the usability of the system to be relatively high.

## **3.2. Hypothesis Validation**

The section presents the analysis and findings related to the hypotheses formulated in the study. Each hypothesis is examined using data gathered from the experiments, with results interpreted to determine whether they are supported, partially supported, or rejected. Based on the outcomes of the hypothesis testing, key theses are developed to summarize the overarching conclusions, highlighting the impact of visualization devices and virtual environments on rehabilitation outcomes.

### **3.2.1. First Group: Comparing Visualization Devices for Rehabilitation**

The UEQ scores indicate that VR head-mounted displays received the highest scores for attractiveness, efficiency, stimulation, and novelty, followed closely by monitors. Tablets and mobile phones received lower scores on these dimensions. Therefore, the data support hypothesis 1 (1H1). The participants rated the experiment with the monitor as the calmest and least bothersome, while the VR device was rated as the most motivating. Additionally, participants expressed a higher likelihood of using the monitor and VR devices at home. This suggests that while VR head-mounted displays offer high immersion and engagement, monitors are perceived as more comfortable and less bothersome. Therefore, the data partially support hypothesis 2 (1H2).

From Hypotheses 1 and 2, the following thesis can be formulated:

**1T1:** Based on participant ratings, I concluded that VR headsets provide the most immersive experience (68%), followed by monitors (64%), with tablets (26%) and phones (9%) rated significantly lower.

The data indicated that the VR device was perceived as the most motivating device, followed by the monitor, tablet, mobile phone, and no device. The participants also expressed a higher likelihood of using the monitor and VR devices at home. Therefore, the data support hypothesis 3 (1H3).

Based on hypothesis 3:

**1T2:** Drawing from motivational feedback, I found that VR headsets were rated most engaging (72%), with monitors next (68%), and tablets (52%) and phones (46%) less effective.

The participants rated the experiment with the monitor and VR headset as more pleasant than with other devices. Additionally, participants expressed a higher likelihood of using the monitor and VR devices at home. Therefore, the data support hypothesis 4 (1H4). The data analysis concluded that visualization devices had no significant effect on heart rate during indoor cycling sessions. Therefore, hypothesis 5 was rejected(1H5).

Based on Hypotheses 4 and 5, the following thesis can be formulated:

**1T3:** Analyzing user preferences, I determined that larger screens are favored, with 24-inch monitors (78%) and VR (69%) preferred over tablets (57%) and mobile phones (32%).

Visualization devices did not have a significant effect on heart rate during indoor cycling sessions. Regardless of the visualization device used, heart rates remained consistent across all devices.

### **3.2.2. Second Group: Virtual Reality Implementation**

Integrating VR technology into cognitive assessment software represents a major advancement, significantly improving the accuracy and efficiency of research and clinical practice. Preliminary results indicated promising trends. Overall, VR technology boosts the precision, reliability, and user experience of cognitive assessments, and opens the way for more effective and engaging evaluations. These findings have been presented at various conferences and publications, highlighting VR's advancements and potential in cognitive assessments [151-155].

In conclusion, the software underscores the potential of Virtual Reality technology to revolutionize spatial memory assessment methodologies. By leveraging the immersive and interactive nature of VR environments, the Corsi-Test can be administered with enhanced precision, flexibility, and comfort [156]. The findings demonstrate the advantages of VR-based assessments over traditional methods, including reduced heart rate and improved test outcomes. Based on these results, hypothesis (2H1) can be rejected, and the following thesis can be formulated:

**2T1:** Through comparative testing, I discovered that traditional methods in VR environments improve efficacy by 67%, reduce heart rate by 17%, and allow flexible, accurate digital adjustments.

Overall, the integration of VR into assessment procedures holds promise for advancing cognitive evaluation techniques, ultimately enhancing the effectiveness and efficiency of spatial memory assessment [157,158].

### **3.2.3. Third Group: User Experience in Virtual Rehabilitation**

The analysis of user reviews on VR rehabilitation games provides key insights into the effectiveness and user experience across various game categories. VR technology shows great promise in rehabilitation, with users generally offering positive feedback. Cognitive Rehabilitation Games (CRG) stood out as the most favorably reviewed category, with users praising their engaging and interactive features. The high sentiment scores and positive language in CRG reviews suggest that these games excel in making rehabilitation both enjoyable and effective. However, the experiment also points to areas requiring improvement, particularly in Neurological Rehabilitation Games (NRG). Users cited technical issues such as motion sickness and tracking errors, which negatively impacted their experience. Feedback on game complexity also revealed a divide: while some users appreciated the challenge, others found the tasks difficult to navigate, potentially hindering rehabilitation outcomes. Physical Rehabilitation Games (PRG) received more balanced responses, with users acknowledging the physical benefits but also emphasizing the need for customizable intensity levels. This feedback underscores the importance of personalizing VR rehabilitation experiences to meet the diverse needs of users.

Hypothesis (3H1) proposed in this experiment is that "Virtual Reality applications in rehabilitation increase user engagement and therapeutic outcomes compared to traditional rehabilitation methods, but are variably effective across different therapeutic categories" is supported by several key data points from the document:

- *Overall Positive Sentiment:* Sentiment analysis across all VR rehabilitation categories revealed an average sentiment score of 0.75, indicating generally positive user experiences. Common themes in user feedback included words like "improvement," "fun," "engaging," and "challenging," indicating that users found VR rehabilitation beneficial and enjoyable.
- *Cognitive Rehabilitation Games (CRG):* CRG received the highest sentiment scores, with a mean of 0.129, indicating that these games are especially effective and enjoyable. Statistical analysis revealed a highly significant sentiment difference between CRG and other categories such as Neurological Rehabilitation Games (NRG), Physical Therapy Games (PTG), and Social Skills and Communication Games (SSCG) ( $p < 0.05$ ).
- *Neurological Rehabilitation Games (NRG):* NRG, while generally positive, received more mixed reviews, with a mean sentiment score of 0.092. Users

frequently reported issues like motion sickness and tracking errors, which detracted from their experience. Notably, NRG had a significantly lower sentiment score than CRG ( $p < 0.001$ ), showing that users found CRG more enjoyable and less prone to technical difficulties.

- *User Concerns with Technical Challenges:* For NRG specifically, concerns about motion sickness and tracking errors were significant enough to warrant future improvements.
- *Comparison Across Categories:* The comparative analysis showed that CRG had significantly higher user engagement and satisfaction, while categories like NRG and SSCG had more neutral or negative feedback. This indicates variability in the effectiveness of different VR rehabilitation tools.

These data points collectively support the hypothesis (3H1), which suggests that while VR rehabilitation generally enhances user engagement and therapeutic outcomes, effectiveness and user satisfaction vary across therapeutic categories. Specifically, cognitive rehabilitation games lead to higher user satisfaction, whereas neurological rehabilitation games require further refinement to address technical challenges. Consequently, the following thesis (3T1) is proposed:

**3T1:** Based on user reviews, I conclude that Virtual Reality rehabilitation applications improve engagement and therapeutic outcomes, with an overall sentiment score of 0.75. Cognitive Rehabilitation Games received the highest satisfaction (0.129), significantly outperforming Neurological Rehabilitation Games (0.092,  $p < 0.001$ ).

#### **3.2.4. Fourth Group: The Impact of 3D Environments**

Based on the findings of the pre-experiment, it can be assumed that whether participants engaged in the VR environment or practiced breathing exercises without external stimuli, both methods were equally effective in reducing anxiety levels and inducing physiological changes. Therefore, I reject the first hypothesis and formulate the following thesis:

**4T1:** After analyzing stress reduction through guided breathing exercises without visual or auditory stimuli, I found no significant difference in outcomes between immersive Virtual Reality environments and traditional physical settings, as measured by STAI-S questionnaires and heart rate data.

This experiment investigated the impact of three distinct 3D environments on stress levels and physiological responses during guided breathing exercises. The results revealed that the positive-affective environment consistently produced the largest reduction in STAI-S scores compared to neutral-baseline and negative-affective environments. On average, participants experienced reductions in stress levels across all environments, with the positive-affective environment showing the most substantial average reduction (-8.4 points), followed by the neutral-baseline environment (-5.6

points), and the negative-affective environment (-3.0 points). These findings support the initial observation that the positive-affective environment significantly alleviated participants' stress levels based on the STAI-S scores collected. However, the analysis of heart rate changes during exercise did not find sufficient evidence to suggest significant differences among the positive-affective, neutral-baseline, and negative-affective environments. Thus, while there were observable variations in heart rate responses across settings, these differences did not reach statistical significance, indicating that each environment may influence physiological responses to a similar extent during exercise.

Therefore, I partly accept hypothesis two (H2) and formulate the following thesis:

**4T2:** When visual and auditory elements were included in the VR setting, I found that the type of environment significantly influenced stress reduction during breathing exercises. A cheerful, sunny forest with natural sounds (positive-affective) led to greater stress reduction—8% more than the same forest in a neutral baseline condition and 15% more than the same forest presented as a dark, stormy, barren scene (negative-affective).

### **3.3. Summary of Findings**

The section provides an overview of the key insights and conclusions drawn from the experiments conducted across the four hypothesis groups. It synthesizes the results from comparing visualization devices for rehabilitation, integrating VR into cognitive assessments, analyzing user experiences in VR rehabilitation games, and exploring the impact of 3D environments on stress reduction. This section highlights the effectiveness and challenges of VR technologies in enhancing therapeutic outcomes, user engagement, and cognitive evaluations.

#### **3.3.1. First Group: Comparing Visualization Devices for Rehabilitation**

The UEQ scores reveal that VR head-mounted displays outperformed other devices in attractiveness, efficiency, stimulation, and novelty, closely followed by monitors, while tablets and mobile phones scored lower. Participants rated monitors as the calmest and least bothersome but found the VR device to be the most motivating, supporting hypotheses 1 (1H1) and partially supporting hypothesis 2 (1H2). Additionally, with VR and a monitor, users expressed a higher likelihood of using these devices at home. User engagement and enjoyment were highest with VR and monitors, supporting hypothesis 3 (1H3). Participants also preferred larger displays like VR headsets and 24-inch monitors, with mobile phones being the least favored, supporting hypothesis 4 (1H4). However, hypothesis 5 (1H5) was rejected, as visualization devices did not significantly affect heart rates during indoor cycling sessions.

### **3.3.2. Second Group: Virtual Reality Implementation**

Integrating VR technology into cognitive assessment software marks a significant jump forward, enhancing accuracy, reliability, and user experience. Preliminary results demonstrate VR's potential to revolutionize spatial memory evaluations, offering more engaging and effective methodologies. The findings show that VR-based assessments, like the Corsi-Test, go beyond traditional methods by providing greater precision, flexibility, and comfort, alongside measurable benefits such as reduced heart rates and improved test outcomes. Based on these results, hypothesis 2H1 is rejected, and the formulated thesis (2T1) highlights that implementing traditional methods within VR environments improves user experience by 67% and fosters a calmer atmosphere, with an average 17% reduction in heart rate. The adaptability of digital VR iterations further ensures accurate and customizable testing protocols, positioning VR as a transformative tool for cognitive assessment and underline the potential for VR technology.

### **3.3.3. Third Group: User Experience in Virtual Rehabilitation**

The analysis of user reviews on VR rehabilitation games highlights their potential to enhance user engagement and therapeutic outcomes across various categories. Cognitive Rehabilitation Games (CRG) received the highest result, with users emphasizing their engaging and effective nature. In contrast, Neurological Rehabilitation Games (NRG) revealed technical challenges like motion sickness and tracking errors, which negatively impacted user experiences. Physical Rehabilitation Games (PRG) collected mixed feedback, with users valuing the physical benefits but calling for greater customization. The findings support hypothesis 3H1, indicating that VR rehabilitation applications improve engagement and outcomes compared to traditional methods, though effectiveness varies by category. CRG achieved the highest sentiment score (0.129), significantly surpassing NRG (0.092,  $*p* < 0.001$ ), reflecting their superior user satisfaction. The proposed thesis (3T1) claims that VR rehabilitation generally enhances therapeutic outcomes, with user satisfaction differing across categories, driven by factors like game design, technical reliability, and personalization.

### **3.3.4. Fourth Group: The Impact of 3D Environments**

This experiment explored the effects of VR environments on stress reduction and physiological responses during guided breathing exercises. The pre-experiment findings indicated no significant difference in stress reduction between VR environments and traditional methods without external stimuli, leading to the rejection of the first hypothesis and the formulation of Thesis 4T1. The main experiment compared three distinct 3D environments: positive-affective, neutral-baseline, and dark. Results showed the positive-affective environment consistently led to the most significant reduction in stress levels, as measured by STAI-S scores, outperforming the neutral-baseline and negative-affective environments. However, heart rate analysis revealed no statistically significant differences across the environment, suggesting

similar physiological responses during exercise. These findings partially support the second hypothesis, leading to the formulation of Thesis 4T2, which emphasizes the effectiveness of cheerful, natural VR environments in stress reduction, with the positive-affective environment demonstrating superior rehabilitation outcomes compared to neutral-baseline and negative-affective settings.

### 3.3.5. Key Contributions

*First group* (Visualization Devices). For the first time, I demonstrate that VR head-mounted displays not only outperform traditional monitors in motivation and engagement but also elicit distinct affective responses—participants described them as both highly stimulating and attractively immersive. While larger display formats (VR headsets and 24" monitors) drove deeper user involvement, the data challenged the assumption that display type alone can modulate physiological arousal, as heart rate remained unchanged despite clear engagement differences.

*Second group* (VR-Enhanced Cognitive Assessment). Introducing the Corsi-Test into a fully immersive VR environment yielded a 67 % boost in subjective user experience and a 17 % drop in heart rate—improvements that go beyond prior demonstrations of VR's feasibility. This is the first empirical evidence that embedding a classic spatial memory task within a three-dimensional, interactive world can measurably enhance both precision and comfort, directly refuting the notion (hypothesis 2H1) that traditional formats are equally effective.

*Third group* (VR Rehabilitation Games). The categorization of rehabilitation titles uncovers a critical distinction: cognitive rehabilitation games (CRG) achieve unprecedented satisfaction scores by combining adaptive difficulty with narrative engagement, whereas technical limitations in neurological rehab games (NRG) manifest as motion sickness and tracking errors, dampening user uptake. Physical rehabilitation games (PRG) showed promise but revealed an unmet need for dynamic intensity adjustment—an insight that refines my understanding of how game design features map onto therapeutic benefits (supporting hypothesis 3H1 with nuanced category-specific effects).

*Fourth group* (Affective VR Environments for Stress Relief). I provide the first comparative analysis of positive- versus negative-valence virtual settings during guided breathing. The positive-affective beach scenario produced the largest decreases in STAI-S anxiety scores, demonstrating a novel, environment-driven pathway to stress reduction. Interestingly, uniform heart-rate responses across all scenarios suggest that subjective emotional relief can be decoupled from immediate physiological markers, yielding new perspectives on how VR content shapes mind–body interactions (partial support for hypothesis 2H2).

Together, these findings advance the field by pinpointing exactly how specific VR modalities, content designs, and interactive features can be optimized to amplify

rehabilitation engagement, cognitive-assessment accuracy, and emotional well-being, moving beyond “VR works” to specify which elements drive how and why outcomes improve.

### 3.3.6. Summary

The findings across the four groups highlight the significant potential of VR technology in enhancing rehabilitation and cognitive assessments. In the *first group*, the comparison of visualization devices revealed that VR head-mounted displays excelled in attractiveness, efficiency, and stimulation, with monitors following closely behind. Participants rated the VR device as the most motivating, while monitors were perceived as the calmest and least bothersome. Despite no significant changes in heart rate, the data supported the preference for larger displays, such as VR headsets and 24-inch monitors, and indicated higher user engagement. However, hypothesis 5, which suggested that visualization devices would impact heart rates, was rejected. In the case of the *second group*, the integration of VR into cognitive assessment software marked a significant advancement in accuracy, reliability, and user experience. The VR-based Corsi-Test, compared to traditional methods, demonstrated greater precision and comfort, leading to a 67% improvement in user experience and a 17% reduction in heart rate. These results rejected hypothesis 2H1 and supported the thesis that implementing traditional cognitive assessment methods within VR environments enhances efficacy and fosters a calmer, more engaging experience for users. The *third group* focused on user experiences in VR rehabilitation games. Cognitive Rehabilitation Games (CRG) received the highest result for their engaging and effective nature, while Neurological Rehabilitation Games (NRG) faced technical challenges such as motion sickness and tracking errors, negatively impacting user satisfaction. Physical Rehabilitation Games (PRG) received mixed feedback, with users appreciating the physical benefits but calling for more customizable intensity levels. The findings supported hypothesis 3H1, which suggested that VR rehabilitation generally increases user engagement and therapeutic outcomes, though effectiveness varies by category, with CRG achieving the highest satisfaction scores. Finally, the *fourth group* examined the impact of different VR environments on stress reduction during guided breathing exercises. The positive-affective VR environment consistently led to the most significant reduction in stress levels, as measured by STAI-S scores, outperforming neutral-baseline and negative-affective environments. However, heart rate analysis showed no statistically significant differences across the environments, indicating similar physiological responses during the exercises. These findings partially supported hypothesis 2H2, with the cheerful, natural VR environments proving to be more effective in stress reduction compared to neutral-baseline or negative-affective settings. Overall, these results underscore the potential of VR in enhancing rehabilitation experiences, cognitive assessments, and therapeutic outcomes across various contexts.

# Chapter 4

## 4. Discussion

The Discussion chapter provides a comprehensive analysis of the research findings, offering interpretations and evaluating their broader implications. The dissertation explores user experiences and engagement across various visualization devices, with a primary focus on Virtual Reality technologies and their impact on both recreational and therapeutic applications. The findings, framed around several hypotheses, lead to the formulation of key theses that underscore VR's potential to enhance user experience and rehabilitation outcomes when compared to traditional methods. This section will delve into the meaning of the results, assess their significance, and examine the strengths and limitations of the research, while also exploring the implications for VR rehabilitation and integrating these findings with existing knowledge in the field.

### 4.1. Interpretation of Results

The section provides an in-depth analysis of the findings, offering insights into their meaning and significance within the context of the research objectives. It aims to connect the observed outcomes to the hypotheses and theoretical frameworks, exploring the implications and potential applications of the results.

#### 4.1.1. User Experience with Devices

##### **First Group: Comparing Visualization Devices for Rehabilitation**

The experiment first investigated how different devices, such as VR head-mounted displays, monitors, tablets, and mobile phones, affect user experience during indoor cycling sessions. The User Experience Questionnaire (UEQ) results revealed that VR headsets consistently scored the highest in dimensions such as attractiveness, efficiency, stimulation, and novelty. This finding supports hypothesis 1 (1H1), suggesting that VR offers a more engaging and immersive experience than other devices. Monitors closely followed VR headsets, indicating that they provided a more comfortable and less bothering experience, making them ideal for prolonged usage. On the other hand, tablets and mobile phones received lower scores in all user experience dimensions, reflecting their limited ability to offer the same level of immersion and stimulation. This differentiation between devices supports the thesis (1T1) that the user experiences during indoor cycling sessions changes significantly across different visualization devices. VR provides the most immersive and engaging experience, with 68% of participants rating it the highest for these attributes, while monitors are preferred for their comfort and ease of use (64%). Tablets and mobile phones underperformed in both immersion and overall user satisfaction, with only 26% and 9% of participants rating them highly, respectively. The participants rated the VR headset

as the most motivating device, followed by monitors, tablets, and mobile phones. This indicates that while VR is a great way of capturing user attention and promoting engagement, the monitor stands out as the least bothering device. This contrast leads to an understanding of how different visualization tools meet different needs: VR headsets boost motivation and engagement, while monitors are seen as more relaxing and suited for longer, less intense interactions. These findings partially support hypothesis 2 (1H2) and contribute to the second thesis (1T2): user engagement and enjoyment are highest with VR head-mounted displays, although monitors provide a close alternative, especially in situations where comfort and reduced cognitive load are prioritized. *Table 24.* summarizes the key research questions, hypotheses, and theses explored in the experiment regarding user experiences with various visualization devices during indoor cycling sessions.

**Table 24.** Summary of Research Questions, Hypotheses, Theses, Key Findings, and Support Relationships on User Experience with Visualization Devices in Indoor Cycling

Research Question (RQ)	Hypothesis (H)	Thesis (T)	Key Findings	Supported B.y
1RQ1: How does the user experience differ when using various visualization devices during indoor cycling?	1H1: User experience will vary significantly, with VR head-mounted displays providing the most immersive experience, followed by monitors, tablets, and mobile phones.	1T1: Based on participant ratings, I concluded that VR headsets provide the	- 68% rated VR highest for immersive experience. - Monitors are preferred for comfort and ease of use.	1H1 supports 1T1
1RQ2: What are the perceived advantages and disadvantages of different devices?	1H2: Participants may report VR as offering the highest immersion but also discomfort; monitors are comfortable, while tablets and mobile phones offer lower immersion but higher comfort.	most immersive experience (68%), followed by monitors (64%), with tablets (26%) and phones (9%) rated significantly lower.	- VR headsets provide high immersion but may cause discomfort. - Monitors are perceived as the second most immersive and most comfortable.	1H2 supports 1T1
1RQ3: How do different devices impact user engagement and enjoyment?	1H3: Engagement and enjoyment will be highest with VR, followed by monitors, tablets, and mobile phones.	1T2: Drawing from motivational feedback, I found that VR headsets were rated most engaging (72%), with monitors next (68%), and tablets (52%) and phones (46%) less effective.	- 72% found VR headsets most motivating. - Monitors are rated highly for motivation	1H3 supports 1T2

1RQ4: What are user preferences regarding display size?	1H4: Participants will prefer larger displays, with the 24-inch monitor and VR headset rated highest, followed by the tablet and mobile phone.	1T3: Analyzing user preferences, I determined that larger screens are favored, with 24-inch monitors (78%) and VR (69%) preferred over tablets (57%) and mobile phones (32%).	- 78% preferred the 24-inch monitor. - 69% preferred the VR headset.	1H4 supports 1T3
1RQ5: How do devices affect heart rates during cycling?	1H5: Heart rates will vary by device, with VR leading, followed by monitors, tablets, and mobile phones; larger sizes are linked to higher heart rates.	-	- VR headsets resulted in the highest heart rates due to increased immersion. - Larger display sizes are associated with higher heart rates.	1H5 does not directly support a thesis, but aligns with findings related to immersion.

#### 4.1.2. The use of Virtual Reality technology in cognitive assessment software

##### Second Group: Virtual Reality Implementation

The use of Virtual Reality technology in cognitive evaluation software is a remarkable step toward increasing the accuracy and reliability of such tests. Virtual Reality ensures that the testing environments are regulated and the delivery of stimuli is uniform, therefore greatly minimizing human error and other inconsistencies commonly attributed to traditional methods. The results of tests using this technology are more reliable. The key takeaways of the trials have documented the physiological and experiential benefits of VR-based assessments. On average, the pulse rate was 17% lower among participants who underwent the VR Corsi-Test than among those who used traditional methods, indicating less stress and anxiety during the test (2T1). This suggests that Virtual Reality can allow subjects more comfort during testing, which is especially necessary in populations that may become stressed during standard forms of tests, such as children or individuals with cognitive impairments. *Table 24.* summarizes the key findings related to the application of Virtual Reality technology in cognitive evaluation software. The findings indicate that VR not only reduces stress during testing but also enhances comprehension and adaptability in testing protocols. This comprehensive analysis underscores the transformative potential of VR in cognitive evaluations, particularly for populations that may experience anxiety during standard testing procedures.

**Table 25.** Summary of Research Question, Hypothesis, Thesis, and Key Findings on the Impact of Virtual Reality in Cognitive Evaluation Software

Research Question (RQ)	Hypothesis (H)	Thesis (T)	Key Findings
2RQ1: Does the use of digital iterations facilitate quicker modification of parameters, thereby enhancing flexibility and adaptability in testing protocols? Does the implementation of traditional in-person methods in Virtual Reality environments increase heart rate?	2H1: It can be presumed that employing traditional in-person methods within a Virtual Reality setting would elevate heart rate, thereby diminishing the efficacy of the test. Additionally, hypothesize that the characteristics of VR environments might contribute to a heightened sense of overwhelm and stress during testing, potentially impeding the effectiveness of traditional testing methodologies.	2T1: Through comparative testing, I discovered that traditional methods in VR environments improve efficacy by 67%, reduce heart rate by 17%, and allow flexible, accurate digital adjustments.	- 17% Lower Pulse Rate: Participants using the VR Corsi-Test showed a significantly lower pulse rate compared to those using traditional methods, indicating reduced stress and anxiety. - 67% Improved Experience: Participants reported a markedly better experience and comprehension when engaging with traditional methods in VR settings, highlighting the efficacy of this approach.

### 4.1.3. VR in Rehabilitation

#### Third Group: User Experience in Virtual Rehabilitation

The following experiment focuses on the application of VR in rehabilitation, focusing on different therapeutic categories such as Cognitive Rehabilitation Games (CRG), Neurological Rehabilitation Games (NRG), and Physical Rehabilitation Games (PRG).

Among these, CRG stood out as the most positively reviewed category, with users praising their engaging and interactive features. Statistical analysis showed a highly significant difference in user sentiment between the CRG and other categories, supporting the hypothesis that VR rehabilitation enhances user engagement and therapeutic outcomes compared to traditional methods. CRG's high sentiment score reflects users' satisfaction with the immersive nature of the games, which helps them feel more involved and motivated during rehabilitation.

NRG received more mixed reviews, with users often reporting issues, such as motion sickness and tracking errors. These technical challenges detracted from the overall experience, leading to lower satisfaction scores compared to the CRG. This technical limitation highlights the need for further refinement in VR technologies, particularly when applied to complex neurological rehabilitation exercises that require precise

movements and tracking. The comparative analysis across therapeutic categories supports the thesis (3T1) that while VR rehabilitation generally enhances user engagement and therapeutic outcomes, its effectiveness varies across categories. Cognitive rehabilitation games stand out in user satisfaction and engagement, while neurological rehabilitation games require significant improvements to address technical shortcomings, such as motion sickness and tracking inaccuracies. The combined findings from user experience and rehabilitation studies underscore the potential of VR technology in both recreational and therapeutic contexts. VR headsets provide unmatched levels of immersion and engagement, making them the preferred choice for activities such as indoor cycling, stress reduction, and cognitive rehabilitation.

However, technical challenges remain in areas such as neurological rehabilitation, where the precision required for therapeutic tasks makes the current VR technologies less reliable. The overall sentiment analysis of user feedback on VR rehabilitation games further confirms this trend, with an average sentiment score of 0.75 (on a scale from -1 to 1), indicating generally positive experiences across all categories. The highest satisfaction was reported in Cognitive Rehabilitation Games (CRG), which outperformed neurological rehabilitation games (NRG) because of fewer technical issues and a more enjoyable user experience. The theses formulated throughout the analysis point to a clear conclusion:

VR technology holds immense promise for advancing both user engagement in recreational activities and therapeutic outcomes in rehabilitation. However, its success depends on addressing technical limitations in certain areas, especially when it comes to precise and movement-sensitive tasks such as neurological rehabilitation. By refining these technologies, VR has the potential to revolutionize not only how I engage with virtual environments but also how I approach critical health and therapeutic challenges.

*Table 26.* presents research questions, hypotheses, thesis, and key findings from an experiment on the use of Virtual Reality in various rehabilitation categories. The experiment highlights the enhanced user engagement and therapeutic outcomes provided by VR, with CRG receiving the highest user satisfaction scores. Additionally, it identifies technical challenges faced by NRG, emphasizing the potential of VR to transform rehabilitation practices while acknowledging limitations in certain areas.

**Table 26.** Summary of Research Question, Hypothesis, Thesis, and Key Findings on the Impact of Virtual Reality in Rehabilitation

<b>Research Question (RQ)</b>	<b>Hypothesis (H)</b>	<b>Thesis (T)</b>	<b>Key Findings</b>
3RQ1: How does Virtual Reality rehabilitation impact user engagement and therapeutic outcomes, and what are some advantages/disadvantages of VR applications in various therapeutic areas based on user feedback?	3H1: Virtual reality applications in rehabilitation increase user engagement and therapeutic outcomes compared to traditional rehabilitation methods, but are variably effective across different therapeutic categories.	3T1: Based on user reviews, I conclude that Virtual Reality rehabilitation applications improve engagement and therapeutic outcomes, with an overall sentiment score of 0.75. Cognitive Rehabilitation Games received the highest satisfaction (0.129), significantly outperforming Neurological Rehabilitation Games (0.092, $p < 0.001$ ).	<ul style="list-style-type: none"> <li>- VR rehabilitation, especially in Cognitive Rehabilitation Games (CRG), boosts user engagement and satisfaction.</li> <li>- Overall sentiment for VR rehabilitation is 0.75, reflecting positive experiences.</li> <li>- CRG has a higher sentiment score (0.129) than Neurological Rehabilitation Games (NRG) at 0.092.</li> <li>- NRG faced mixed reviews due to motion sickness and tracking issues.</li> <li>- Technical limitations in neurological rehabilitation need addressing for better effectiveness.</li> </ul>

#### 4.1.4. VR in Stress Reduction

##### Fourth Group: The Impact of 3D Environments

The last experiment extended the exploration of VR technology to therapeutic settings, particularly in its application for stress reduction and rehabilitation. One experiment examined the effects of three different virtual environments— positive-affective, neutral-baseline, and dark—on stress levels during guided breathing exercises. The positive-affective environment, designed with cheerful visual and auditory stimuli, significantly reduced stress, as measured by STAI-S scores, showing a greater reduction

in stress levels than both neutral-baseline and negative-affective environments. However, no significant differences were observed in heart rate changes across these environments, suggesting that, while the environment influenced subjective feelings of stress, physiological responses (such as heart rate) remained stable. This finding leads to a partly accepted hypothesis 2 (4H2) and the formation of a thesis (4T2) that Virtual Reality environments—ranging from cheerful and natural settings to neutral and stormy atmospheres—can effectively reduce stress levels, with more stimulating environments such as sunny forests showing the highest potential for rehabilitation. The positive-affective environment led to an 8% improvement in stress reduction effectiveness compared to neutral-baseline environments, and a 15% improvement over negative-affective, stormy settings. *Table 27.* summarizes the key research questions, hypotheses, thesis statements, and findings from the experiment, highlighting the differential impacts of various virtual environments on user experiences and physiological responses. The findings indicate that while subjective stress levels improved significantly in cheerful environments, physiological measures like heart rate remained consistent, emphasizing the importance of emotional engagement in VR rehabilitation.

**Table 27.** Summary of Research Questions, Hypotheses, Theses, and Key Findings on the Impact of Virtual Reality Environments on Stress Reduction and Rehabilitation Outcomes

Research Questions (RQ)	Hypotheses (H)	Thesis (T)	Key Findings
4RQ1: Does guided breathing in a VR environment enhance stress reduction compared to traditional methods?	4H1: Guided breathing in VR will reduce stress and anxiety more than traditional methods without stimuli.	4T1: After analyzing stress reduction through guided breathing exercises without visual or auditory stimuli, I found no significant difference in outcomes between immersive Virtual Reality environments and traditional physical settings, as measured by STAI-S questionnaires and heart rate data.	Participants in VR environments experienced greater subjective reductions in stress levels; however, heart rate changes were not significantly different across settings.
4RQ2: How do different VR environments (positive-affective, neutral, dark) affect rehabilitation outcomes?	4H2: Different VR environments will significantly impact mood, stress, and engagement.	4T2: When visual and auditory elements were included in the VR setting, I found that the type of environment significantly influenced stress reduction during breathing exercises. A cheerful, sunny forest with natural sounds (positive-affective) led to greater stress reduction—8% more than the same forest in a neutral baseline condition and 15% more than the same forest presented as a dark, stormy, barren scene (negative-affective).	The positive-affective environment resulted in an 8% greater stress reduction compared to neutral-baseline and a 15% reduction compared to dark settings, highlighting the impact of emotional engagement in VR on psychological rehabilitation.

#### 4.1.5. Summary

The dissertation highlights findings on user experience and engagement across various visualization devices and rehabilitation applications, with a focus on Virtual Reality.

- *User Experience with Devices:* VR headsets scored the highest for attractiveness, efficiency, stimulation, and novelty, followed by monitors. Tablets and phones scored lower. Monitors were rated the calmest, but VR was the most motivating, and participants preferred to use these devices at home. VR offers immersion and engagement, while monitors are more comfortable, supporting 1H1 and 2. Larger displays, like monitors and VR, were most preferred, while visualization devices had no impact on heart rate during cycling, supporting 1H3, 1H4, and partially rejecting 1H5.
- *The use of Virtual Reality technology in cognitive assessment software:* It allows for larger control over test settings and for consistency in the presentation of stimuli, which reduces human errors. This makes cognitive evaluations more reliable and precise, yielding more valid results.
- *VR in Rehabilitation:* VR rehabilitation shows potential, particularly in Cognitive Rehabilitation Games (CRG), which received the highest user satisfaction. Neurological Rehabilitation Games (NRG) faced challenges, such as motion sickness and tracking errors. CRG had significantly higher user engagement and satisfaction than other categories, supporting the hypothesis that VR improves therapeutic outcomes but varies across different therapeutic categories.
- *VR in Stress Reduction:* In VR-based stress reduction scenarios, a positive-affective virtual environment significantly reduced stress, outperforming neutral-baseline and negative-affective settings. However, no significant heart rate differences were found across environments, partially supporting hypothesis 2 (4H2).

Overall, Virtual Reality enhances both user experience and rehabilitation outcomes. Its immersive qualities contribute significantly to improving engagement and effectiveness in therapeutic applications.

#### 4.2. Implications for VR Rehabilitation

The findings of this research can have implications for the future of Virtual Reality in rehabilitation. By demonstrating that VR technologies can provide more engaging, motivating, and immersive experiences compared to traditional rehabilitation methods, this study reinforces the potential of VR to enhance patient outcomes. The positive user experiences suggest that VR can make rehabilitation more enjoyable, increasing adherence and overall therapeutic engagement. The ability to customize VR environments to suit specific rehabilitation needs further highlights the flexibility of VR as a tool for diverse therapeutic applications, from stress reduction to cognitive and physical rehabilitation. However, as some challenges related to technical issues (e.g.,

motion sickness) and the need for more personalized settings in physical rehabilitation were identified, future research and development should aim to address these limitations to ensure wider applicability and effectiveness of VR in clinical settings.

### **4.3. Integration with Existing Knowledge**

This research contributes to the growing literature on the use of VR in rehabilitation. Previous studies have demonstrated VR's potential in enhancing physical therapy, cognitive rehabilitation, and stress management through immersive and interactive experiences (*Chapter 1*). The findings of this dissertation extend these concepts by providing empirical evidence on the specific benefits of VR in comparison to traditional rehabilitation methods, supporting the idea that VR can facilitate better user engagement and therapeutic outcomes. Furthermore, the study builds upon prior work by emphasizing the importance of customizing VR environments to match the rehabilitation goals and patient preferences. Moreover, it highlights the impact of different virtual environments.

# Chapter 5

## 5. Conclusion

In conclusion, this study examined and compared user experiences, physiological responses, and therapeutic outcomes associated with various visualization devices, particularly Virtual Reality, during indoor cycling rehabilitation and guided breathing exercises. Additionally, it explored the potential of VR in cognitive and therapeutic applications such as spatial memory assessments and rehabilitation games. The findings reveal significant insights that are essential for the future design and implementation of visualization devices and VR-based rehabilitation programs, highlighting both their strengths and challenges.

### 5.1. Summary of Contributions

#### First Group: Comparing Visualization Devices for Rehabilitation

The experiment showed that the user experience varies significantly across different visualization devices used during indoor cycling rehabilitation sessions. Virtual Reality head-mounted displays and monitors provided the deepest and most engaging experiences, whereas tablets and mobile devices delivered relatively lower levels of immersion and user satisfaction. VR headsets stand out as the most engaging technology, providing users with higher levels of motivation and involvement. However, this comes at a great cost: while VR headsets are highly engaging and truly immersive, they have also often been associated with high levels of discomfort, particularly in longer uses. Disorientation or discomfort was reported by some of them, which could limit how long sessions could be and how often they would want to use such devices. It also agrees with the known issues with VR, including motion sickness and general discomfort after the extended use of headsets. On the other hand, for the monitors, there was a good user experience, especially regarding comfort levels. Less immersive than headsets, monitors received positive ratings for intrusion and appropriateness for long-term use. Moreover, they achieved the best scores in user engagement because even though they can offer less immersive experiences than VR, they are practical and comfortable, and hence useful during rehabilitation. However, the immersion and engagement grades of tablets and mobile phones were remarkably low. These smaller devices were not as effective in drawing users into the experience, with only a small percentage of participants finding them highly motivating. This finding suggests that the display size and immersive capacity of a device are critical factors that influence the user experience. Furthermore, larger displays, such as 24-inch monitors and VR head-mounted displays, were preferred by most participants. This finding underscores the importance of device size in creating engaging and immersive experiences. Larger screens appear to enhance both the visual experience and user satisfaction, particularly in rehabilitation activities that require sustained attention and

motivation. A notable conclusion from this experiment is that visualization devices do not have a significant effect on heart rate during indoor cycling sessions. Despite the differences in user experience and engagement across VR, monitors, tablets, and mobile phones, heart rates remained consistent across all devices, indicating that, while these devices influence subjective experiences, they do not necessarily alter physiological responses during moderate physical activity. This suggests that user perception and emotional responses, rather than physiological changes, are the primary differentiators between these devices in the context of rehabilitation.

### **Second Group: Virtual Reality Implementation**

Beyond rehabilitation, the experiment explored the use of VR in cognitive assessments, particularly for spatial memory testing, using the VR version of the Corsi-Test. The results demonstrate that VR-based assessments offer several advantages over traditional methods, including enhanced precision and flexibility. VR environments allow for more accurate control over testing parameters, which can be easily adjusted to suit individual needs. This level of adaptability ensures that the tests can be tailored to the participants, leading to more reliable outcomes. Improved user comfort and reduced stress:

Participants in VR-based cognitive assessments experienced a 17% lower average heart rate than those in traditional methods, indicating that they felt calmer during the assessments. This reflects VR's ability to create a less stressful and more engaging testing environment, which may improve performance.

Overall, VR environments offered a 67% better experience than traditional methods, making them an effective tool for cognitive evaluation. This highlights the promise of VR in advancing the methodologies used for assessing cognitive functions, such as spatial memory, potentially leading to more effective and accurate diagnoses.

### **Third Group: User Experience in Virtual Rehabilitation**

One of the major orientations of this experiment is VR for rehabilitation, particularly in interactive therapeutic games for user participation and motivation. The results showed that Virtual Reality rehabilitation games are a very promising tool to enhance the rehabilitation process; however, their effectiveness and user satisfaction may vary depending on different categories of therapies. Among the options, CRG had the highest positive feedback in terms of satisfaction, enjoyment, and perceived therapeutic benefits. The games were especially noted for increasing the activity and participation levels in rehabilitation, thereby distinctly improving treatment outcomes. On the other hand, NRG faced various technical issues, such as motion sickness and tracking inaccuracies. These greatly affected the user experiences of the games, leaving them somewhat ineffective and less enjoyable than their cognitive rehabilitation counterparts. This experiment highlights that solving these technical problems will be key to realizing the full application of VR in neurological rehabilitation. The differences in user experience among various therapeutic categories highlight the importance of adopting a user-centered methodology in the creation and advancement of Virtual Reality rehabilitation instruments. Through the proactive integration of user feedback,

developers can enhance technology, thereby rendering it more efficient, individualized, and attuned to the varied requirements of patients.

#### **Fourth Group: The Impact of 3D Environments**

In the pre-experiment focused on guided breathing exercises, it was found that both immersive VR environments and traditional settings (without visual or auditory stimuli) were equally effective in reducing anxiety levels and inducing physiological changes. However, the main experiment revealed a more nuanced insight when comparing three distinct 3D environments— positive-affective, neutral, and dark—during breathing exercises. The positive-affective environment consistently produced the largest reduction in STAI-S (State-Trait Anxiety Inventory for State Anxiety) scores, significantly lowering participants' stress levels compared to the neutral-baseline and negative-affective environments. This finding highlights the potential of positively designed VR environments to enhance stress reduction during therapeutic interventions. The immersive nature of VR allows users to be placed in carefully crafted virtual settings, such as sunny forests with natural sounds, which can elicit positive emotional responses and facilitate greater relaxation. Interestingly, despite these differences in emotional outcomes, heart rate changes across the positive-affective, neutral, and negative-affective environments did not show significant statistical variation. This suggests that while VR environments can influence emotional well-being, physiological stress markers like heart rate may not be as sensitive to changes in virtual settings, at least during low-intensity activities like guided breathing.

### **5.2. Key Findings and Their Impact**

This section summarizes key findings from a series of experiments examining the user experience across different visualization devices and the potential of VR in cognitive assessments and rehabilitation. The results highlight the strengths and challenges of VR and other devices in enhancing engagement, reducing stress, and improving therapeutic outcomes.

#### **First Group: Comparing Visualization Devices for Rehabilitation**

1. VR head-mounted displays (HMDs) provided the most immersive and engaging experiences but caused discomfort during extended use (e.g., disorientation, motion sickness).
2. Monitors offered a comfortable and practical alternative, with high engagement but lower immersion compared to VR.
3. Tablets and mobile phones ranked lowest in immersion and engagement, emphasizing the importance of device size and immersion capacity.

### Second Group: Virtual Reality Implementation

1. VR-based cognitive assessments, such as the VR Corsi-Test, showed enhanced precision, flexibility, and adaptability compared to traditional methods.
2. Participants experienced a 17% lower average heart rate in VR, indicating reduced stress and increased comfort.
3. VR assessments provided a 67% better user experience, making them a promising tool for improving spatial memory assessments and diagnostic accuracy.

### Third Group: User Experience in Virtual Rehabilitation

1. Cognitive Rehabilitation Games (CRG) received positive feedback for being engaging and interactive, leading to improved therapeutic outcomes.
2. Neurological Rehabilitation Games (NRG) faced challenges like motion sickness and tracking errors, which reduced their effectiveness and enjoyment.
3. This variation highlights the need for user-centered design to refine VR rehabilitation tools for different therapeutic categories.

### Fourth Group: The Impact of 3D Environments

1. VR environments with positive stimuli, such as " positive-affective " virtual settings, were most effective in reducing stress, as shown by lower State-Trait Anxiety Inventory for State Anxiety (STAI-S) scores.
2. Despite the emotional benefits, there was no significant variation in heart rate changes across positive-affective, neutral, and negative-affective VR environments, suggesting that emotional well-being is more affected by visual cues than physiological markers during low-intensity activities like breathing exercises.

**Table 28.** Summary of Findings on User Experience, Cognitive Assessments, Rehabilitation Games, and Stress Reduction in VR Environments

Category	Key Findings
<b>User Experience Across Visualization Devices</b>	<ol style="list-style-type: none"> <li>1. VR Head-Mounted Displays (HMDs): Most immersive, but can cause discomfort during long use.</li> <li>2. Monitors: Comfortable and practical, with high engagement but lower immersion.</li> <li>3. Tablets and Mobile Phones: Least immersive and engaging, emphasizing the importance of device size.</li> </ol>
<b>Potential of VR in Cognitive Assessments</b>	<ol style="list-style-type: none"> <li>1. Enhanced Assessments: VR tools like the Corsi-Test offer better precision and adaptability.</li> <li>2. Lower Stress: A 17% reduction in heart rate indicates increased comfort.</li> <li>3. User Experience: 67% better than traditional methods, enhancing diagnostic accuracy.</li> </ol>

<b>VR Rehabilitation Games and User Feedback</b>	<ol style="list-style-type: none"> <li>1. Cognitive Rehabilitation Games (CRG): Positive feedback for engagement, improving outcomes.</li> <li>2. Neurological Rehabilitation Games (NRG): Technical issues like motion sickness hinder effectiveness.</li> <li>3. Need for Design Refinement: Emphasizes user-centered design for various therapies.</li> </ol>
<b>Stress Reduction in VR Environments</b>	<ol style="list-style-type: none"> <li>1. Effective Environments: positive-affective settings significantly reduce stress (lower STAI-S scores).</li> <li>2. Stable Heart Rates: No significant heart rate changes across environments, indicating emotional well-being is more affected by visual cues.</li> </ol>

### 5.3. Future Research Directions and Implications

The findings from this experiment provide a basis for future research in the area of VR and visualization devices for rehabilitation. Several areas of further investigation have emerged. Based on the long-term use of VR headsets and other visualization devices, I discuss how user engagement, comfort, and physical reactions might be affected during long-term rehabilitation sessions. This experiment investigated the optimal design of virtual environments in VR treatment, focusing on how different emotional stimuli, such as positive and neutral environments, could be applied to optimize stress alleviation and ensure treatment efficacy. Solve technical issues affecting some therapeutic categories, especially in the neurological rehabilitation game category, to ensure that VR tools are effective and accessible to all patients. In conclusion, this experiment demonstrates that head-mounted displays provide the most intense and engaging experiences in rehabilitation; however, monitors are an easy and practical alternative to use. There are also some areas, such as technical challenges in neurological rehabilitation games, that need to be sorted out before the full potential of VR can be achieved. Emphasizing a user-centered approach while persistently improving the technology is how Virtual Reality will ever be in a position to revolutionize both cognitive and physical rehabilitation, improve general treatment outcomes, and improve the quality of life.

I am currently working with different institutions to help implement Virtual Reality into rehabilitation practice and further develop the knowledge base in this growing area. These collaborative efforts aim to address cognitive, physical, and communication rehabilitation needs through the use of immersive technology.

Building upon the findings of the initial trial study presented earlier in this dissertation, the research is being extended through a collaboration with psychologists from Eötvös Loránd University. The new research still ongoing, utilizes the Corsi Block-Tapping Test as one of the main ways of assessing visuospatial and working memory. It will now, however, also include a larger sample of participants who are divided into four age ranges: adolescents (12–18 years), young adults (18–39 years), middle-aged adults (40–65 years), and older adults (65+ years). The purpose of this extended investigation is to examine age-related differences in the application of VR in relation to cognitive

performance with greater depth and precision. By systematic study of cognitive variation across the lifespan, the findings can be applied to the development of adaptive, age-differentiated virtual environments designed to respond differently to the differential cognitive characteristics and requirements of each age group.

In collaboration with neuropsychologists from Semmelweis University, an independent study is investigating the use of VR for musculoskeletal rehabilitation. This research explores how immersive environments—such as natural landscapes and urban settings—can enhance patient motivation and physical performance, leading to more effective and personalized rehabilitation outcomes. Participants experience these varied virtual settings through a VR headset while walking on a treadmill.

Another key area of research focuses on the integration of Virtual Reality and Artificial Intelligence to develop intelligent therapy systems. The aim is to explore how AI can be utilized to create interactive and engaging rehabilitation games with continually new content, thereby enhancing motivation and improving treatment outcomes.

Further cooperation with a speech therapist from the Veszprém Hospital targets aphasia rehabilitation in 3D virtual spaces. The project addresses the use of interactive 3D environments to assist patients in regaining basic communication skills, offering a new, attractive approach to language rehabilitation after neurological damage.

Current efforts focus on the importance of adopting a user-centered approach to advance digital rehabilitation, while further research is needed to establish comprehensive best practices across all domains for developing effective VR rehabilitation games.

As a summary:

- Collaboration with institutions to integrate VR into rehabilitation practices, addressing cognitive, physical, and communication needs.
- Extended cognitive research with Eötvös Loránd University using the Corsi Block-Tapping Test and a larger, age-diverse sample to explore age-related cognitive differences in VR.
- Musculoskeletal rehabilitation study with Semmelweis University using VR environments (natural/urban) to enhance motivation and performance during treadmill-based therapy.
- VR and AI integration project aims to develop intelligent, adaptive rehabilitation games that increase engagement and personalize therapy.
- Aphasia rehabilitation project in collaboration with Veszprém Hospital focuses on restoring communication skills through interactive 3D virtual environments.
- User-centered design emphasis is guiding current VR development to improve accessibility and effectiveness.
- Ongoing research is needed to establish best practices for VR rehabilitation game design across various therapeutic domains.

# Chapter 6

## 6. Thesis Summary

The dissertation findings can be organized into thesis groups, each representing a major area of investigation related to user experience with visualization devices, stress reduction, and rehabilitation outcomes through the use of Virtual Reality technology.

### 6.1. First Group: Comparing Visualization Devices for Rehabilitation

**1T1:** Based on participant ratings, I concluded that VR headsets provide the most immersive cycling experience (68%), followed by monitors (64%), with tablets (26%) and phones (9%) rated significantly lower.

**1T2:** Drawing from motivational feedback, I found that VR headsets were rated most engaging for cycling (72%), with monitors next (68%), and tablets (52%) and phones (46%) less effective.

**1T3:** Analyzing user preferences, I determined that larger screens are favored for cycling, with 24-inch monitors (78%) and VR (69%) preferred over tablets (57%) and mobile phones (32%).

#### Main Conclusions for Thesis Group 1:

VR HMD displays are rated highest for immersion, attractiveness, and stimulation, making them the most engaging devices. Monitors offer a strong alternative, perceived as less bothersome and more comfortable, which makes them ideal for longer and less intense sessions. Tablets and mobile phones fall behind in terms of user satisfaction, as they provide lower levels of immersion and engagement, making them less effective for activities that require strong user involvement. The participants showed a higher likelihood of using VR headsets and monitors at home for indoor activities. Across all therapeutic categories, larger displays were preferred over smaller devices, indicating that screen size influences the user experience and effectiveness in rehabilitation.

#### Relevant publications: [P1], [V1], [J1]

[P1] *"Légzés félelem nélkül – Virtuális valóság alapú légzés javító játék tervezése post és long-Covid szindrómában szenvedő betegek rehabilitációjára"*, Conference: XXXV. Neumann Colloquium Conference, Szeged, Hungary

This presentation explores the design of a VR game aimed at improving breathing techniques for patients suffering from post- and long-COVID symptoms. It highlights the immersive qualities of VR HMD displays, aligning with the thesis that these devices enhance engagement and effectiveness in rehabilitation.

[V1] *"How can we use VR to fight post-COVID syndrome?"*, Platform: Research Goes Live, YouTube

This video discusses the application of VR technology in therapeutic settings, emphasizing the advantages of VR HMD displays over other devices. It supports the thesis by illustrating user preferences for immersion and engagement in rehabilitation, reinforcing the idea that VR headsets are superior for therapeutic interventions.

[J1] *"Technologies designed to assist individuals with cognitive impairments"*, Journal: Sustainability

This article addresses various technologies, including VR displays, designed to assist individuals with cognitive impairments. It provides insights into user satisfaction and the importance of immersive experiences, supporting the thesis that larger and more engaging displays enhance user involvement and therapeutic effectiveness.

## **6.2. Second Group: Virtual Reality Implementation**

**2T1:** Through comparative testing, I discovered that traditional methods in VR environments improve efficacy by 67%, reduce heart rate by 17%, and allow flexible, accurate digital adjustments.

### **Main Conclusions for Thesis Group 2:**

The immersive nature of VR environments allows for more precise and flexible cognitive assessments, like the Corsi-Test, compared to traditional methods. Their adjustable settings enable tailored experiences that improve test outcomes and provide a calmer atmosphere, as evidenced by lower average heart rates. These enhancements demonstrate VR's potential to revolutionize spatial memory assessments, yielding a 67% better user experience than conventional approaches.

### **Relevant publications:** [P7], [P9], [P12], [P17], [J2]

[P7] *"Virtual reality-based game for rehabilitation: Corsi-test"*, Conference: 2nd IEEE International Conference on Cognitive Aspects of Virtual Reality, Veszprém, Hungary:

This presentation discusses the use of a VR-based game for rehabilitation, specifically focusing on the Corsi-Test. It directly supports the thesis by showcasing how immersive VR environments can enhance cognitive assessments and improve user outcomes.

[P9] *"Enhancing neuropsychological assessment through virtual reality: A pilot study of the Corsi block tapping task"*, Conference: 2nd IEEE International Conference on Cognitive Aspects of Virtual Reality, Veszprém, Hungary

This presentation examines neuropsychological assessments using Virtual Reality and highlights the potential of VR to improve cognitive evaluations, thus reinforcing the thesis that VR can lead to better cognitive testing outcomes than traditional methods.

[J2] *"Virtual reality implementation of the Corsi-Test and pilot study on acceptance"*,  
*Journal: Software Impacts*

This journal article explores the implementation of the Corsi-Test in a virtual environment, further supporting the thesis by emphasizing the adaptability and precision of VR for cognitive assessments.

[P12] *"Immersive VR games for cognitive enhancement"*, *Conference: womENCourage™ 2024: Responsible Computing for Gender Equality, Madrid, Spain*

This presentation discusses immersive VR games aimed at cognitive enhancement, which aligns with the thesis by underscoring the potential of VR to provide tailored cognitive assessments and improve user experiences.

[P16] *"Immersive VR games for cognitive enhancement"*, *Conference: XXVII. Tavaszi Szél Konferencia 2024*

This poster presentation addresses immersive VR games for cognitive enhancement, directly aligning with the thesis by showcasing the effectiveness of VR in improving cognitive evaluations and experiences.

### 6.3. Third Group: User Experience in Virtual Rehabilitation

**3T1:** Based on user reviews, I conclude that Virtual Reality rehabilitation applications improve engagement and therapeutic outcomes, with an overall sentiment score of 0.75. Cognitive Rehabilitation Games received the highest satisfaction (0.129), significantly outperforming Neurological Rehabilitation Games (0.092,  $p < 0.001$ ).

#### Main Conclusions for Thesis Group 3:

Cognitive Rehabilitation Games (CRG) received the highest user satisfaction, showing that VR stands in cognitive therapy by offering engaging and interactive experiences that enhance therapeutic outcomes. Neurological Rehabilitation Games (NRG), while promising, encounter technical issues, such as motion sickness and tracking errors, which reduce their effectiveness and user satisfaction. These challenges must be addressed to ensure that VR is fully effective in neurological rehabilitation. Physical Rehabilitation Games (PRG) received more mixed feedback, with users noting the need for customizable intensity levels, indicating that while VR has potential in physical therapy, it requires more personalization.

#### Relevant publications: [P3], [P4], [P10], [P11]

[P3] *"Virtual Reality based serious games for older adults", Conference: 6th International Conference on Aging & Technology Fair (eng)aging!, Prague, Czech Republic*

This presentation explores the use of VR serious games specifically designed for older adults, highlighting how CRGs can enhance engagement and therapeutic outcomes. It supports the thesis by demonstrating the effectiveness of VR in cognitive therapy and user satisfaction.

[P4] *"Developing an Android-based game for children with blindness or low vision", Conference: Association for the Advancement of Assistive Technology in Europe, Paris, France*

This presentation discusses the development of an inclusive game aimed at enhancing cognitive rehabilitation for children with visual impairments. It reflects the adaptability of VR for various user needs, emphasizing the importance of personalization and engagement in rehabilitation settings.

[P10] *"Virtual reality based serious games for memory skill improvement", Conference: XXXVI. Neumann Colloquium Conference, Veszprém, Hungary*

This presentation focuses on the use of VR games to improve memory skills, showcasing the effectiveness of CRGs in cognitive rehabilitation. It supports the findings on high user satisfaction and the interactive nature of VR in therapeutic contexts.

[P11] *"Revolutionizing rehabilitation through VR-based serious games", Conference: Technicity Doctoral Workshop Conference - MOME*

This presentation emphasizes the transformative potential of VR in rehabilitation, addressing challenges such as technical issues in NRGs and the need for customization in PRGs. It aligns with the thesis by underscoring the necessity for improvements in VR technologies to maximize user satisfaction and therapeutic outcomes.

#### **6.4. Fourth Group: The Impact of 3D Environments**

**4T1:** After analyzing stress reduction through guided breathing exercises without visual or auditory stimuli, I found no significant difference in outcomes between immersive Virtual Reality environments and traditional physical settings, as measured by STAI-S questionnaires and heart rate data.

**4T2:** When visual and auditory elements were included in the VR setting, I found that the type of environment significantly influenced stress reduction during breathing exercises. A cheerful, sunny forest with natural sounds (positive-affective) led to greater stress reduction—8% more than the same forest in a neutral baseline condition and 15% more than the same forest presented as a dark, stormy, barren scene (negative-affective).

#### **Main Conclusions for Thesis Group 4:**

Positive-affective virtual environments, such as sunny forests with natural sounds, significantly reduce stress levels more than neutral or negative-affective, stormy environments, proving the VR's ability to enhance psychological well-being. Despite subjective reductions in stress, heart rate differences across different VR environments were not statistically significant, suggesting that the environment influences emotional states more than physiological responses do. VR is effective for stress relief, especially when designed with a positive and engaging atmosphere, making it a promising tool for psychological interventions and relaxation therapies.

#### **Relevant publications:** [P8], [P14], [P15]

[P8] *"DOS-Windows-Virtual desktop", Conference: 2nd IEEE International Conference on Cognitive Aspects of Virtual Reality, Veszprém, Hungary*

This presentation discusses the design of virtual environments that enhance user engagement and emotional well-being, supporting the thesis that positive and immersive settings can effectively reduce stress levels and improve psychological outcomes.

[P14] *"Design virtual reality games that instruct proper breathing techniques with dynamically changing virtual environment", Conference: 15th International*

*Conference on Disability, Virtual Reality & Associated Technologies, Prague, Czech Republic*

This presentation focuses on creating VR environments that promote relaxation and stress relief through breathing techniques. It reinforces the finding that well-designed, engaging virtual settings can significantly enhance psychological well-being.

[P15] *"Modelling realistic avatars for the 'P-game' negotiation game", Conference: 15th International Conference on Disability, Virtual Reality & Associated Technologies, Prague, Czech Republic*

This presentation explores the use of realistic avatars in VR environments, contributing to user engagement and emotional experience. It supports the findings on how engaging environments can positively influence stress levels, even though physiological responses may remain stable.

## **6.5. Summary of Conclusions Across Thesis Groups**

*First Group: Comparing Visualization Devices for Rehabilitation:* VR headsets are the most engaging and immersive devices for indoor activities, while monitors provide a comfortable alternative. Smaller devices such as tablets and mobile phones do not offer the same level of user satisfaction.

*Second Group: Virtual Reality Implementation:* VR enhances cognitive assessment and rehabilitation by improving precision, adaptability, and participant comfort, showing the potential to outperform traditional methods across various therapeutic applications.

*Third Group: User Experience in Virtual Rehabilitation:* VR rehabilitation is highly effective, particularly for cognitive tasks. However, neurological rehabilitation games need improvements to resolve technical issues, and physical therapy games should offer more customization to meet users' needs.

*Fourth Group: The Impact of 3D Environments:* VR environments significantly reduce stress levels, with cheerful and natural settings being the most effective. However, VR environments do not significantly affect the heart rate during stress relief exercises.

Each thesis group underscores the potential of VR technology to improve user experience, stress relief, and therapeutic outcomes while also highlighting areas for improvement in certain applications, such as neurological rehabilitation.

## 6.6. Summary of the Own Publications

Below is a list of my publications grouped by year in the research topic. During this period, I have made 10 Hungarian conference presentations, 8 International conference presentations, and 2 Journal publications with Impact Factors. Additionally, I have 6 other Journal publications under review. In this list, "P" stands for presentations, "J" for journal publications, and "V" for episode from an online video series on YouTube.

### 2022

[P1] Szabó, P., Sikné Lányi, C., Schalbert, J., Kretz, Z., & Cserjési, R. (2022). „Légzés félelem nélkül” – Virtuális valóság alapú légzés javító játék tervezése post és long-Covid szindrómában szenvedő betegek rehabilitációjára [Conference presentation]. XXXV. Neumann Colloquium Conference, Szeged, Hungary. In: *Az egészségügyi informatika COVID előtt és COVID után - A XXXV. Neumann Kollokvium konferencia kiadványa*. pp 124-129.

[P2] Szabó, P., & Sikné Lányi, C. (2022). Android alapú alkalmazás tervezése 1-es típusú cukorbeteg gyermekek tanítására [Conference presentation]. XXXV. Neumann Colloquium Conference, Szeged, Hungary. In: *Az egészségügyi informatika COVID előtt és COVID után - A XXXV. Neumann Kollokvium konferencia kiadványa*. pp 130-135.

### 2023

[V1] Szabó, P. (2023, Apr 12). How can we use VR to fight post-COVID syndrome? [Ep. 2]. *Research Goes Live*. YouTube. [https://www.youtube.com/watch?v=\\_j427Z0SIMc](https://www.youtube.com/watch?v=_j427Z0SIMc)

[J1] Szabó, P., Ara, J., Halmosi, B., Sik-Lanyi, C., & Guzsvinecz, T. (2023). Technologies are designed to assist individuals with cognitive impairments. *Sustainability*, 15(18), 13490. <https://doi.org/10.3390/su151813490>, Impact Factor: 3.9

[P3] Szabó, P. (2023). Virtual Reality based serious games for older adults [Conference presentation]. 6th International Conference on Aging & Technology Fair (eng)aging!, Prague, Czech Republic.

[P4] Sik-Lanyi, C., & Szabó, P. (2023). Developing an Android-based game for children with blindness or low vision [Conference presentation]. Association for the Advancement of Assistive Technology in Europe, Paris, France. In: *Book of Abstracts, 17th International Conference of the Association for the Advancement of Assistive Technology in Europe, AAATE 2023*. pp 231-233.

[P5] Szabó, P., & Sik-Lanyi, C. (2023). A digitális és hagyományos oktatás, generációs különbségek [Conference presentation]. XXIX. Multimedia in Education Conference, Szeged, Hungary. In: *29th Multimedia in Education Conference Proceedings - XXIX. Multimédia az oktatásban nemzetközi konferencia kiadvány.* pp 50-53.

[P6] Sikné Lányi, C., Guzsvinecz, T., Tálás, M., Halmosi, B., Szabó, P., & Haneklaus, N. (2023). Játékra fel! – Virtuális Valóság alapú „Negotiation Game” [Conference presentation]. XXIX. Multimedia in Education Conference, Szeged, Hungary. In: *29th Multimedia in Education Conference: Conference Proceedings.* pp 70-75.

[P7] Szabó, P., Sik-Lanyi, C., Filotás, P., & Cserjési, R. (2023). Virtual reality-based game for rehabilitation: Corsi-test [Conference presentation]. 2nd IEEE International Conference on Cognitive Aspects of Virtual Reality, Veszprém, Hungary. In: *2nd IEEE International Conference on Cognitive Aspects of Virtual Reality – cVR 2023.* pp 29-32.

[P8] Szabó, P., Baranyi, P., & Sik-Lanyi, C. (2023). DOS-Windows-Virtual desktop [Conference presentation]. 2nd IEEE International Conference on Cognitive Aspects of Virtual Reality, Veszprém, Hungary. In: *2nd IEEE International Conference on Cognitive Aspects of Virtual Reality – cVR 2023.* pp 33-36.

[P9] Zsebi, S., Szabó, P., Filotás, P., Sik-Lányi, C., & Cserjési, R. (2023). Enhancing neuropsychological assessment through virtual reality: A pilot study of the Corsi block tapping task [Conference presentation]. 2nd IEEE International Conference on Cognitive Aspects of Virtual Reality, Veszprém, Hungary. In: *2nd IEEE International Conference on Cognitive Aspects of Virtual Reality – cVR 2023.* pp 115-118

[P10] Szabó, P., & Sik-Lanyi, C. (2023). Virtual reality based serious games for memory skill improvement [Conference presentation]. XXXVI. Neumann Colloquium Conference, Veszprém, Hungary. In: *Orvosi informatika. A XXXVI. Neumann Kollokvium konferencia-kiadványa* pp 66-72.

[P11] Szabó, P. (2023). Revolutionizing rehabilitation through VR-based serious games. In: *Technicity Doctoral Workshop Conference - MOME* [Conference presentation].

2024

[J2] Szabó, P., Filotás, P., Sik-Lanyi, C., Zsebi, S., & Cserjési, R. (2024). Virtual reality implementation of the Corsi test and pilot study on acceptance. *Software Impacts*, 21, 100693. <https://doi.org/10.1016/j.simpa.2024.100693>, Impact Factor: 2.1

[P12] Szabó, P., & Sik-Lanyi, C. (2024, June 26-28). Immersive VR games for cognitive enhancement. In womENcourage™ 2024: *Responsible Computing for Gender Equality. ACM Celebration of Women in Computing*, Madrid, Spain.

[P13] Szabó, P., & Sik-Lanyi, C. (2024, July 8-12). User-friendly serious game design for diabetic preschool children. In: *International Conference on Computers Helping People with Special Needs (ICCHP 24)*, JKU Linz, Austria. pp 65-69.

[P14] Szabó, P., & Sik-Lanyi, C. (2024, Sept. 3-6). Design virtual reality games that instruct proper breathing techniques with dynamically changing virtual environment. In: *15th International Conference on Disability, Virtual Reality & Associated Technologies.*, Prague, Czech Republic. pp 1-2.

[P15] Sik-Lanyi, C. & Szabó, P., (2024, Sept. 3-6). Modelling realistic avatars for the “P-game” negotiation game. In: *15th International Conference on Disability, Virtual Reality & Associated Technologies.*, Prague, Czech Republic. pp 1-3.

[P16] Szabó, P. (2024). Immersive VR games for cognitive enhancement. In XXVII. Tavaszi Szél Konferencia 2024 [Poster presentation]. In: *XXVII. Tavaszi Szél Konferencia 2024 – Absztraktkötet.* p. 683.

[P17] Soma, Z., Zsebi, P., Filotás, P., Szabó, P., Sik-Lányi, C., & Cserjési, R. (2024). Assessing the cognitive performance of different age groups using Virtual Reality technology and psychophysiology. In *15th Dubrovnik Conference on Cognitive Science: Memory, Space, Language* (p. 38, Paper: PS1-17). Central European Cognitive Science Association (CECOG).

I currently have six additional journal publications under review. Additionally, I have two accepted full papers in the volume "Technology for Inclusion and Participation for All: Recent Achievements and Future Directions - 8th International Conference, AAATE 2025, Nicosia, Cyprus, September 10-12, 2025, Proceedings", which will be published by Springer. These contributions highlight my ongoing research in the field and my commitment to advancing knowledge in virtual reality applications.



# Appendix

**Table A1.** Summary of the investigated studies for Competitive Analysis - Assistive Technologies for Cognitive Disabilities

Ref	Year	Group	Tech	Users	Devices	Purpose	Strengths	Limits
19	2022	Healthy (avg 36.6)	VR	Healthy, Alzheimer's	VR headset	Memory training	Early cognitive decline detection	Needs RCT validation
20	2022	Depression (avg 25)	VR	MDD patients	VR headset	Improve prospective memory	New therapy potential	Small sample
21	2022	Healthy (avg 21)	VR	-	VR, EEG	Study working memory	-	-
22	2018	Healthy & cognitive decline	VR	Cognitive decline patients	VR	Assess memory	Real-life-like assessment	-
23	2019	Dementia, elderly	VR	Diagnosis	VR headset	Enhance spatial memory	Cost-effective	-
24	2021	Stroke (avg 68.3)	VR	Stroke survivors	HMD, pointer	Post-stroke cognition	Immersive therapy	Simulator sickness risk
25	2016	Stroke (avg 65)	VR	-	VR headset	Prospective memory training	Adaptive	Hard to control variables
26	2015	All	Mobile	All	Phone	Semantic memory aid	Fun, effective	Pilot only
27	2021	All	Mobile	All	Phone	Daily memory tool	Widely accessible	English only
28	2017	Kids (6-12)	Mobile	Students	Phone	Learn Chinese	Engaging	-

Clinical-only use	Small sample	Small sample	No therapist validation	Dementia-specific	Narrow use	One device only	Not automated	Small sample	Poor with unpredictability	Lacks broad use	Not tested
Less staff effort	Combined method	Educator-approved	SMART goal focus	Holistic approach	User-focused	Tech-based	Evidence-based	Game-based	Tracks actions	Boosts efficiency	Promising
Puzzle-based evaluation	Reading fluency	Support learning	Motor learning	Daily cognition	Meal prep aid	Self-regulation	Decision aid	Hygiene training	Daily aid via AI	AI diagnostics	Memory support
Eye tracker	iPad	-	NAO robot	Tablet	-	Smartwatch app	-	Notebook	COACH	-	Android
Dementia patients	Reading disabilities	Cerebral palsy	Cerebral palsy	Dementia	TBI	Intellectual disabilities	Cognitive challenges	Intellectual disabilities	Dementia	Clinical patients	Alzheimer's
Eye tracking	PAI/IAI	Tubular	-	E-calendar	-	Wearables	Decision support	Kinect V2	Cog. orthosis	-	Memorz Stash
Dementia	Students (10-11)	Teens (14-19)	Kids (8)	Seniors (72-94)	Young adults	Young adults (18-27)	All	Kids	85+	-	-
2021	2019	2017	2019	2019	2019	2018	2018	2019	2010	2016	2021
<b>29</b>	<b>31</b>	<b>32</b>	<b>33</b>	<b>34</b>	<b>35</b>	<b>36</b>	<b>37</b>	<b>38</b>	<b>39</b>	<b>40</b>	<b>41</b>

**Code A1:** Python code to get a review from Steam based on appID

```
pip install requests

import requests

from datetime import datetime, timedelta

import csv

def get_steam_reviews(appid, num_reviews=100, days=8000):

    url = f"https://store.steampowered.com/appreviews/{appid}"

    params = {

        "json": 1,

        "num_per_page": num_reviews,

        "filter": "recent",

        "language": "english",

        "purchase_type": "all"

    }

    reviews = []

    last_year = datetime.now() - timedelta(days=days)

    response = requests.get(url, params=params)

    if response.status_code == 200:

        data = response.json()

        for review in data.get('reviews', []):

            timestamp = datetime.fromtimestamp(review['timestamp_created'])

            if timestamp >= last_year:

                reviews.append({

                    "timestamp": timestamp,

                    "review": review['review'],

                    "recommendation": review['voted_up'],

                    "votes_up": review['votes_up'],

                    "votes_funny": review['votes_funny']

                })
```

```

return reviews

def save_reviews_to_csv(appid, filename='steam_reviews.csv'):
    reviews = get_steam_reviews(appid)
    with open(filename, mode='w', newline="", encoding='utf-8') as file:
        writer = csv.writer(file)
        writer.writerow(["Timestamp", "Review", "Recommended", "Votes Up", "Votes
Funny"])
    for review in reviews:
        writer.writerow([
            review['timestamp'].strftime("%Y-%m-%d %H:%M:%S"),
            review['review'],
            'Yes' if review['recommendation'] else 'No',
            review['votes_up'],
            review['votes_funny']
        ])

```

## Code A2: Python text analysis

```
import pandas as pd
# Load the CSV file
df = pd.read_csv('ssc.csv')

# Inspect the data
print(df.head())

import nltk
from nltk.corpus import stopwords
from nltk.tokenize import word_tokenize
from nltk.stem import WordNetLemmatizer
import string

# Download necessary NLTK data files
nltk.download('punkt')
nltk.download('stopwords')
nltk.download('wordnet')
def preprocess_text(text):
    # Handle potential non-string values
    if not isinstance(text, str):
        return " # Or handle it differently based on your needs

    # Convert to lowercase
    text = text.lower()

    # Remove punctuation
    text = text.translate(str.maketrans("", "", string.punctuation))

    # Tokenize
    tokens = word_tokenize(text)
```

```

# Remove stopwords

tokens = [word for word in tokens if word not in stopwords.words('english')]

# Lemmatize

lemmatizer = WordNetLemmatizer()

tokens = [lemmatizer.lemmatize(word) for word in tokens]

return tokens

# Apply preprocessing to each text entry

df['processed_text'] = df['Review'].apply(preprocess_text)

from sklearn.feature_extraction.text import CountVectorizer, TfidfVectorizer

# Bag of Words

vectorizer = CountVectorizer()

X_bow = vectorizer.fit_transform(df['processed_text'].apply(lambda x: ' '.join(x)))

# TF-IDF

tfidf = TfidfVectorizer()

X_tfidf = tfidf.fit_transform(df['processed_text'].apply(lambda x: ' '.join(x)))

import numpy as np

# Get the sum of word counts across all documents

word_counts = np.asarray(X_bow.sum(axis=0)).flatten()

# Create a DataFrame with words and their frequencies

word_freq = pd.DataFrame({'word': vectorizer.get_feature_names_out(), 'count':
word_counts})

# Sort by frequency

word_freq = word_freq.sort_values(by='count', ascending=False)

print(word_freq.head(10))

```

```

# Word count statistics
word_counts = df['processed_text'].apply(len)
print(f'Average word count: {word_counts.mean()}')

from textblob import TextBlob

# Sentiment analysis function
def get_sentiment(text):
    # Handle non-string values
    if not isinstance(text, str):
        return 0 # Or handle it differently based on your needs

    blob = TextBlob(text)
    return blob.sentiment.polarity

# Apply sentiment analysis to the text column
df['sentiment'] = df['Review'].apply(get_sentiment)

# Analyze sentiment
print(df['sentiment'].describe())

import matplotlib.pyplot as plt
import seaborn as sns

# Word Frequency Bar Plot
plt.figure(figsize=(10, 8))
sns.barplot(x='count', y='word', data=word_freq.head(10))
plt.title('Top 10 Most Frequent Words')

```

```

plt.show()

# Example: Sentiment Distribution
plt.figure(figsize=(10, 6))
sns.histplot(df['sentiment'], bins=20, kde=True)
plt.title('Sentiment Distribution')
plt.show()

from wordcloud import WordCloud
import matplotlib.pyplot as plt

# Generate a word cloud
# Convert all elements in 'Review' column to strings
text = ' '.join(df['Review'].astype(str))

wordcloud = WordCloud(width=800, height=400,
background_color='white').generate(text)

# Display the word cloud
plt.figure(figsize=(10, 5))
plt.imshow(wordcloud, interpolation='bilinear')
plt.axis('off')
plt.show()

import pandas as pd
import nltk
from scipy.stats import ttest_ind
from nltk.sentiment import SentimentIntensityAnalyzer
from itertools import combinations

# Download NLTK resources (only needed once)
nltk.download('punkt')

```

```

nltk.download('vader_lexicon')

# Initialize sentiment analyzer
sia = SentimentIntensityAnalyzer()

# Load the CSV files into DataFrames
df1 = pd.read_csv('crg.csv')
df2 = pd.read_csv('nrg.csv')
df3 = pd.read_csv('prg.csv')
df4 = pd.read_csv('psy.csv')
df5 = pd.read_csv('ptg.csv')
df6 = pd.read_csv('sscg.csv')

# Function to calculate sentiment score
def sentiment_score(text):
    # Handle non-string values by returning a default sentiment
    if not isinstance(text, str):
        return 0 # Return 0 as the sentiment for non-string values
    return sia.polarity_scores(text)['compound']

# Apply the sentiment_score function to the text columns
df1['sentiment'] = df1['Review'].apply(sentiment_score)
df2['sentiment'] = df2['Review'].apply(sentiment_score)
df3['sentiment'] = df3['Review'].apply(sentiment_score)
df4['sentiment'] = df4['Review'].apply(sentiment_score)
df5['sentiment'] = df5['Review'].apply(sentiment_score)
df6['sentiment'] = df6['Review'].apply(sentiment_score)

# List of DataFrames and their names for easy reference

```

```
dfs = [df1, df2, df3, df4, df5, df6]
names = ['file1', 'file2', 'file3', 'file4', 'file5', 'file6']

# Generate all pairwise combinations of the DataFrames
combinations_list = list(combinations(range(6), 2))

# Perform t-tests for all combinations
for i, j in combinations_list:
    t_stat, p_value = ttest_ind(dfs[i]['sentiment'], dfs[j]['sentiment'])
    print(f"T-test between {names[i]} and {names[j]}: T-statistic = {t_stat:.3f}, P-value = {p_value:.3f}")
```

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