

Article

Virtual Reality Rehabilitation Platform for Mild Cognitive Impairment: A Metaverse Approach

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Abstract. Mild Cognitive Impairment (MCI) is increasingly prevalent among elderly populations, necessitating new approaches that support cognitive engagement, social interaction, and remote monitoring. This study presents a Virtual Reality Rehabilitation Platform designed within a metaverse-based framework to enhance usability and accessibility for elderly individuals with cognitive impairment. Unlike conventional VR rehabilitation systems, the proposed platform integrates three key innovations: (1) a metaverse-oriented, multi-user environment that enables avatar-based social interaction, co-presence with therapists, and persistent shared game spaces; (2) an MQTT-based real-time monitoring and control channel that allows therapists to observe gameplay events, adjust sessions, and supervise users remotely with low latency; and (3) deployment and preliminary usability validation with elderly individuals with MCI in a real-world clinical context, demonstrating its feasibility for remote, home-based rehabilitation via high-speed wireless networks, including 5G-ready infrastructure. A total of 18 elderly participants engaged with the platform over a five-week period, using Oculus Quest 2 devices to perform memory, spatial awareness, and interaction-based VR tasks. This study intentionally focuses on evaluating usability, acceptance, and user experience rather than clinical cognitive outcomes; as such, no pre-/post-intervention cognitive assessments were conducted. Quantitative satisfaction surveys, game evaluations, and qualitative focus group findings revealed generally positive user engagement, clear task comprehension, and moderate-to-high satisfaction across VR interaction elements, while also identifying areas for improvement such as device comfort and motion smoothness. The results highlight the potential of metaverse-supported VR rehabilitation as an accessible and socially engaging tool for elderly individuals with cognitive impairment, and they establish a foundation for future studies evaluating clinical efficacy and long-term cognitive benefits.

Keywords: Cognitive Impairment, Rehabilitation, Virtual Reality Game, Elderly, Transient Global Amnesia, Dementia, Reminiscence

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1. Introduction

Thailand, like many countries, is undergoing a rapid transformation into an aging society, with a burgeoning population of elderly citizens [1-2]. As this demographic shift unfolds, the imperative to provide comprehensive care for the elderly, encompassing both their physical and mental health, has become increasingly evident. Among the multifaceted challenges associated with aging, the mental health of the elderly has emerged as a matter of paramount importance, with a specific focus on reminiscence therapy. Thailand is currently experiencing a shift towards an aging society, with about 16.7% of its total population, which amounts to approximately 11 million people, aged 60 or older. According to data from the Thai National Health Examination Survey, the prevalence of dementia among elderly individuals in Thailand is 8.1% [3-4]. It is well-established that reminiscence therapy can be remarkably effective during Mild Cognitive Impairment (MCI). From a psychological perspective, elderly individuals, acutely aware of their limited life span, may find themselves losing interest in their future, making the preservation of their mental well-being a critical endeavor [5-6]. Concurrently, physiological changes manifest as a decline in short-term memory, while long-term memory relatively strengthens with age. Thus, intervening during the MCI assumes profound significance. Left un-addressed, cognitive impairments such as MCI can escalate into more debilitating conditions, including Transient Global Amnesia and Dementia, creating not only personal challenges for affected individuals but also reverberating social problems that place a substantial burden on families and society at large, with potential economic ramifications for Thailand [7]. It is within this context of evolving demographics and the paramount importance of addressing cognitive health in the elderly that this research explores an approach: the utilization of Virtual Reality Rehabilitation Platform within a metaverse framework to cater to the cognitive needs of elderly individuals with MCI.

Cognitive impairment presents a multifaceted challenge that confronts many older adults, affecting their cognitive faculties related to memory, thought processes, reasoning, and language comprehension. Among the spectrum of cognitive impairments, Alzheimer's Disease emerges as one of the most severe types, characterized by profound memory loss, challenges in problem-solving, and noticeable behavioral shifts. Its impact reaches beyond individuals, profoundly affecting their families. However, it's equally imperative to address MCI, which serves as a pivotal intermediary stage between the normal age-related cognitive changes and more severe conditions such as Alzheimer's [8-10]. While MCI is less debilitating than full-blown dementia, it holds significance due to its potential to progress into more severe cognitive disorders. Individuals with MCI face an increased risk of developing Alzheimer's Disease or other forms of dementia, underscoring the importance

of emphasizing MCI in our approach. Although complete cures for cognitive impairment remain elusive, effective treatments offer promise in slowing down or even halting the decline. Early identification and personalized treatment strategies for MCI constitute critical measures for preserving cognitive function, enhancing the well-being of older adults, and mitigating the broader societal and economic repercussions associated with severe cognitive impairments.

The treatment of MCI employs a diverse range of methods to address its multifaceted challenges comprehensively [11-13]. Regular Monitoring and Follow-Up, conducted by healthcare professionals, play a pivotal role in tracking progress and ensuring treatment plans remain tailored to individual needs. Lifestyle modifications, encompassing a balanced diet, regular physical exercise, and active social engagement, contribute significantly to MCI management. Psychological support, including counseling or therapy, assists in managing emotional aspects associated with MCI. Caregiver education and support are crucial, offering both emotional and practical assistance to individuals with MCI. Among these methods, Cognitive Training and Rehabilitation is a widely recognized and popular approach. It effectively targets memory enhancement, problem-solving, and overall cognitive function, making it a valuable tool in the treatment of MCI.

Cognitive Training and Rehabilitation, as a treatment for Mild Cognitive Impairment (MCI), has shown promise in various studies. In an approach, researchers utilized an interactive mobile platform to enhance communication skills and positive emotions among the elderly [14]. This involved incorporating digital somatosensory games into reminiscence therapy, resulting in improved daily living activities and intergenerational interactions, creating a positive impact. Reminiscence therapy, as discussed in several studies [15-17], also demonstrated its effectiveness in slowing down the physiological and psychological effects of aging. It actively engaged elderly individuals in positive social interactions, enhancing social behaviors, interpersonal relationships, and preserving cognitive and communication skills. This approach was found to contribute to improved psycho-logical health and life satisfaction through interpersonal interactions and experiential ex-change [16]. Moreover, the focus group method in reminiscence therapy helped elderly participants enhance their social adaptation skills, emotional interactions, and relationships, reducing feelings of loneliness and alienation [17]. In the context of dementia, reminiscence therapy involving nostalgic items, images, videos, and music was explored to enhance cognition and social emotions [18]. Next, reminiscence therapy was found to help elderly individuals integrate life experiences, leading to improved physiological and psychological well-being, ultimately enhancing their overall quality of life [19].

Cognitive training and rehabilitation have shown significant potential in mitigating the progression of Mild Cognitive Impairment (MCI), particularly when delivered through engaging and interactive activities. In this regard, Virtual Reality (VR)-based cognitive games offer immersive 3D experiences that can enhance memory, attention, and spatial awareness more effectively than traditional activities such as board games, card games, or drawing. VR environments also tend to be more motivating for elderly users, providing a stimulating context that supports sustained engagement.

Furthermore, social interaction plays an important role in maintaining emotional wellbeing among older adults. The proposed Virtual Reality Rehabilitation Platform incorporates a social module that enables elders to interact with peers and caregivers through avatars, encouraging social adaptation, emotional expression, and relationship building. The platform also records gameplay data—such as scores, task duration, and usage patterns—which can be reviewed by healthcare professionals to support progress monitoring in a non-intrusive manner.

Although VR-based cognitive training systems for older adults have been reported in the literature, most existing platforms are designed as single-user applications deployed locally in hospitals or laboratories, with limited support for persistent social interaction, therapist co-presence, or remote monitoring over modern communication networks. In particular, there is a lack of rehabilitation platforms that combine a metaverse-inspired multi-user environment, real-time therapist supervision, and in-home usage for elderly individuals with Mild Cognitive Impairment (MCI). To address this gap, this study develops and evaluates a Virtual Reality Rehabilitation Platform based on a metaverse architecture. The main contributions of this work are threefold: (1) we design a metaverse-based VR rehabilitation environment that supports social interaction, avatar-based co-presence, and multiplayer cognitive games tailored for elderly users; (2) we integrate an MQTT-based network communication layer that enables therapists to monitor gameplay, adjust sessions, and supervise patients in real time; and (3) we conduct an initial usability and acceptance study with 18 elderly participants with cognitive impairment in a real clinical setting, demonstrating the feasibility of deploying the platform as an online rehabilitation tool.

2. Materials and Methods

2.1. Objectives and Usage Environment of the Virtual Reality Rehabilitation Platform

This study has been conducted with the oversight and approval of the Institutional Review Board (IRB) at the Faculty of Medicine, Chulalongkorn University in Bangkok, Thailand. The IRB has granted approval for this study, ensuring its adherence to international guidelines for the protection of human research

participants, including the Declaration of Helsinki, The Belmont Report, CIOMS Guidelines, and the International Conference of Harmonization in Good Clinical Practice (ICH-GCP). The Certificate of Expedited Review Approval has been issued with the reference COA No. 0089/2023, IRB No. 0823/65. The title of the study is “Assessment of Acceptance and Initial Efficacy of an Online Rehabilitation Platform for Elderly Individuals with Cognitive Impairment Utilizing Virtual Reality via 5G Wireless Networks.”

2.1.1. Traditional Cognitive Training and Rehabilitation

In the traditional approach to Cognitive Training and Rehabilitation, families often face the logistical challenge of transporting elderly individuals to hospitals or reminiscence therapy centers for these activities as shown in Fig. 1. Many elders may not have the means to drive or attend sessions independently. Moreover, traditional therapies typically require elders to engage in these activities more than twice a week, with each session lasting about 3-4 hours. These traditional activities commonly involve memory-boosting games, such as memorizing images or numbers on cards and subsequently recalling them. Elders also participate in various other activities like board games, singing, and drawing alongside their friends during these sessions. Additionally, mobile games may be integrated into the activities, with therapists closely monitoring the progress at hospitals or reminiscence therapy centers. While traditional techniques have been effective for Cognitive Training and Rehabilitation, the emergence of new technology has created opportunities for implementing innovative approaches within the Virtual Reality Rehabilitation Platform.



Fig. 1. Traditional activity environment used in conventional cognitive rehabilitation. This figure illustrates the typical on-site training setting—such as paper-based tasks, group exercises, and therapist-guided activities—that the proposed metaverse-based VR rehabilitation platform aims to complement and modernize through immersive and remotely accessible digital interaction.

on the broker for multi-user synchronization, the backend services can be migrated to commercial cloud servers or 5G edge-computing infrastructure without modifying the VR application. The Oculus Quest 2 natively supports high-speed Wi-Fi and 5G mobile hotspots, allowing elderly users to access the rehabilitation platform from home using either broadband or 5G networks. This design ensures that the system is not limited to the present university environment and can be expanded to regional or nationwide deployments in future clinical studies.

2.2. Virtual Reality Rehabilitation Platform Setup

2.2.1. Overview

The Virtual Reality Rehabilitation Platform comprises three subsystems: (1) Main Server, (2) Web Client, and (3) VR Devices. Fig. 3 illustrates these platform subsystems.

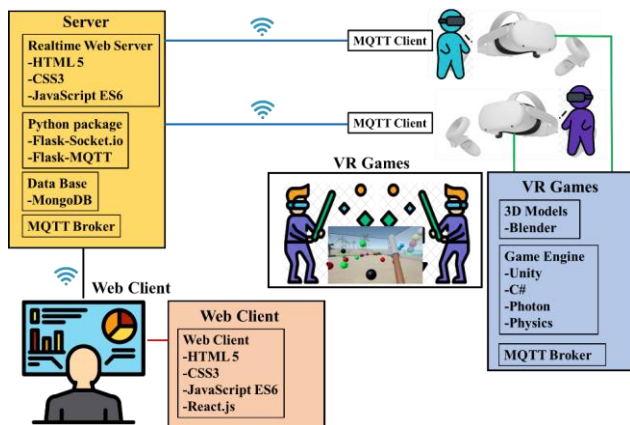


Fig. 3. Overview of the main components of the metaverse-based Virtual Reality Rehabilitation Platform. This figure illustrates how the main server, web client, and VR devices communicate through the MQTT-based architecture to support real-time multi-user interaction, therapist monitoring, and synchronized rehabilitation activities within the shared virtual environment.

2.2.2. Main Server

The primary server runs on a computer featuring an Intel Xeon Silver 4210 processor with 10 cores and 20 threads, operating at 2.2GHz, 768 GB of RAM, 5TB storage, and two NVIDIA Tesla P40 GPUs. It is managed by the university administrator and is utilized for installing the Mosquitto MQTT broker [22–24] as well as the backend and frontend web applications or web client.

MQTT serves as a communication protocol specifically designed for machine-to-machine or device-to-device communication [25]. It is structured around a Client/Server architecture with a hub-and-spoke topology, relying on TCP/IP. This design makes device-

to-device communication more straightforward compared to the HTTP protocol. MQTT also minimizes bandwidth usage through Publisher/Subscriber facilitated by a Broker and supports event-driven execution. Fig. 4 illustrates the MQTT concept. In this project, MQTT is employed to segment communication between the backend web application and the device hardware. MQTT incorporates useful features such as retained messages, last will, clean session management, and keep-alive mechanisms for practical use. In the metaverse-based rehabilitation environment, MQTT topics are organized by virtual room, user ID, and game session, allowing each VR headset to publish avatar states (e.g., head pose, hand interactions, game actions) and to subscribe to updates from other users in the same room. Therapists' web clients subscribe to the same topics to observe user behaviour in real time and publish control messages (e.g., starting or pausing a game, changing game difficulty) that immediately affect the shared virtual environment. This topic structure enables therapist co-presence and synchronized multi-user interaction with low latency.

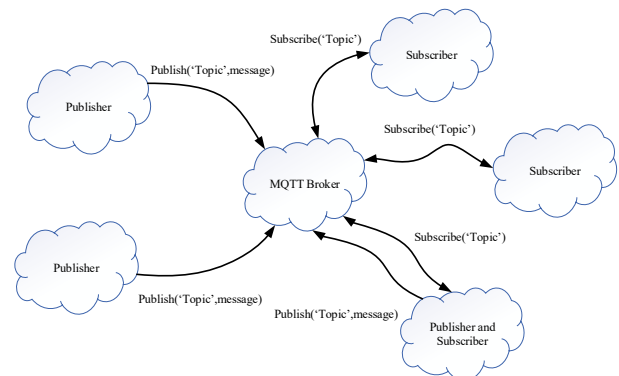


Fig. 4. MQTT publish-broker-subscribe communication model used in the Virtual Reality Rehabilitation Platform. This figure illustrates how VR devices publish avatar-state updates, how the MQTT broker manages message distribution, and how therapists and other users subscribe to the relevant topics to enable synchronized multi-user interaction and real-time monitoring within the metaverse environment.

In the proposed platform, the MQTT communication layer organizes topics by virtual room, user ID, and game session. The main topic hierarchy follows the pattern: `/room/{roomId}/user/{userID}/state` for avatar pose and interaction events, `/room/{roomId}/broadcast` for shared game-state updates, `/therapist/{therapistID}/command` for therapist-issued control messages, and `/system/logs` for system-level monitoring. Each VR headset publishes its state updates at approximately 20–30 messages per second during active gameplay, while therapist command messages occur at a much lower rate (typically less than 1 message per second). To balance reliability and latency, QoS 0 is used for high-frequency avatar and interaction updates,

whereas QoS 1 is employed for therapist commands and session-control messages to ensure that critical instructions are delivered at least once.

To ensure smooth therapist–patient interaction in real time, the platform incorporates several latency-mitigation mechanisms in the MQTT communication pipeline. Message packets related to avatar pose, hand interactions, and therapist control commands are transmitted at 20–30 Hz using lightweight JSON payloads to reduce processing overhead. Local buffering is minimized, and the MQTT broker operates in a low-latency configuration with a keep-alive interval of 10 seconds and immediate forwarding of subscribed messages. Within the campus intranet, average end-to-end latency between the VR device and the server was measured at 18–25 ms, while remote internet users typically experienced 35–55 ms depending on home Wi-Fi and ISP conditions. These values were sufficient to maintain synchronous multi-user interaction, smooth avatar movement, and timely therapist supervision during gameplay.

The backend web application functions as a server linked to MQTT, enabling the retrieval of data and information from the physical hardware. Its communication with MQTT is facilitated through Socket.IO.

To ensure user privacy and secure data transmission, all MQTT communications in the platform are transmitted over TLS-encrypted WebSocket connections. No personally identifiable information (PII) is stored on the VR devices; instead, each user is represented only by anonymized session and device identifiers. Avatar-state data—including head pose, controller inputs, and interaction events—is treated as non-sensitive and is retained only for the duration of the session, after which it is immediately discarded. The server stores gameplay logs and interaction metrics in a secured database with role-based access control, and therapist clients must authenticate before subscribing to user-state topics or issuing control commands. This design ensures that sensitive information such as user identity, cognitive status, and session metadata cannot be accessed by unauthorized parties and complies with standard data-protection practices for non-medical VR applications.

SocketIO is built upon a package, specifically designed for enabling real-time bidirectional communication across various platforms. This technology serves as a rapid communication link connecting the server with the HTML web interface. Essentially, it's a library geared towards WebSocket functionality, employing an event-driven approach, and boasting minimal package size for efficient performance.

In addition to the main server, the backend web application is deployed, which incorporates a database for the application's functionalities. MongoDB is the chosen database system for storing various data related to the application, including game scores, playing time, and non-private user information. MongoDB is a

NoSQL database that offers flexibility in managing and organizing data. Unlike traditional relational databases, MongoDB stores data in a document-oriented format, making it suitable for handling unstructured or semi-structured data like the game-related information in this context. It allows for efficient storage and retrieval of data, making it an ideal choice for collecting and managing the data required for the treatment application.

2.2.3. Web Client

The Web Client serves as a front-end web application for therapists, psychologists, or doctors to monitor the elderly's activities [25]. This interface is hosted on the main server. To create a reliable real-time web interface for the VR devices, it is created with three essential programming languages: HTML, JavaScript, and Python. HTML, or Hypertext Markup Language, defines how content is displayed in web browsers. While Cascading Style Sheets (CSS) are responsible for formatting, they won't be discussed here as they are less relevant to the study. JavaScript is embedded within HTML to enable interactive features on the web. Many web browsers have dedicated JavaScript engines to execute these functions. While frameworks like React.js or Angular.js can create responsive web applications, this web client is developed for a real-time web interface using the Python Flask framework. Embracing an event-driven programming approach is highly recommended, where user actions, such as clicking on a web page, trigger events controlling hardware. This minimizes data transfer in real-time communication.

On the server-side, code is used to manage the EVENT. When the EVENT labeled "Start" is triggered, the server sends the received 'start_val' to the MQTT server, which is installed on the same server. This process involves the utilization of two different programming languages to facilitate data transmission, starting from entering the number on the web interface to delivering it to the MQTT server. The physical equipment connected to the MQTT server responds to incoming messages. MQTT, a message transport protocol designed with an event-driven concept, is employed to efficiently handle messages, especially in this context. When there is any change in the VR game EVENT, the VR device communicates with the MQTT server. On the server-side, Python establishes a connection with MQTT and forwards the message to the client-side through socket IO. Subsequently, JavaScript processes this EVENT and dynamically updates the text and visuals on the web interface. Thus, therapists, psychologists, or doctors can monitor the process of the elderly's activities.

2.2.4. VR Devices

The Oculus Quest 2 VR device serves as the platform for playing 3D games, aligning with the project's objectives. Developers can easily create a range

of 3D games to fulfill these objectives. In the initial phase, three 3D games were developed: “Decor Detective: Furniture Challenge,” “Veggie Quest: Harvest Challenge,” and “Balloon Busting Challenge.” These games are expertly crafted with the elderly in mind, ensuring that they can easily become familiar with the game environment and understand the game rules. Additionally, each game employs different methods to provide memory exercises for the elderly and offers various sub-objectives tailored to their needs.

The process of creating a 3D game using Unity, driven by C# scripting, and integrating 3D models crafted in Blender, forms a collaborative and comprehensive game development workflow. Within Unity, C# scripting plays a pivotal role in defining game mechanics, behaviors, and interactions. Blender serves as the primary tool for generating intricate 3D models, characters, and assets, allowing for rich visual elements in the game. This collaborative effort is further enhanced by additional software tools such as graphic editors like Photoshop or GIMP for creating textures and audio editing software like Audacity for sound assets. Unity, in conjunction with its Asset Store, provides a vast library of pre-made assets and scripts, streamlining the development process and enabling developers to augment their games with existing content. This combination of Unity's versatile game engine, Blender's advanced 3D modeling capabilities, C# programming, and supplementary software creates a robust and holistic environment for the creation of immersive 3D games, accessible across a range of platforms. Then, more details about each game are provided in the following section.

2.2.4.1. Decor Detective: Furniture Challenge

The aim of this game is to improve color and object location memory, spatial awareness, and social skills while fostering emotional interactions and relationships. It's a two-player game designed for the elderly and another participant, who can be a therapist, friend, or family member. To get started, the player must log in to their account, allowing for progress tracking and scorekeeping. Next, they can select a game level that suits their abilities and preferences.

The game generates random furniture colors and places them in random locations within a room. The elderly player explores the room to memorize the furniture colors and their locations, with a specific time limit based on the chosen level (e.g., 30, 45, or 60 seconds). Once the time is up, the game reshuffles the furniture colors and locations.

Now, the challenge begins: the elderly player must rearrange the furniture to match the initial setup. During this task, they can communicate with their partner, whether it's a therapist, friend, or family member, for assistance. The partner can view the original room layout but is not allowed to send images or provide direct answers to maintain the game's integrity. The elderly earn scores based on the number of correctly matched colors

and/or locations. The example game images are shown in Fig. 5.

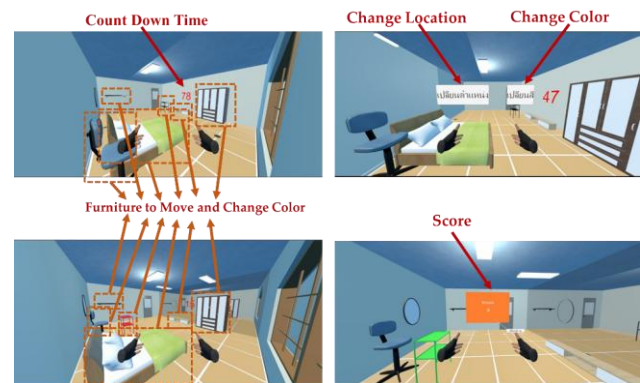


Fig. 5. Decor Detective: Furniture Challenge. This game requires users to identify and place virtual objects according to given instructions, supporting cognitive skills related to memory, attention, and spatial reasoning. The figure illustrates how elderly users interact with objects in the immersive environment as part of the cognitive rehabilitation tasks.

2.2.4.2. Veggie Quest: Harvest Challenge



Fig. 6. Veggie Quest: Harvest Challenge. This game engages users in object recognition and categorization by prompting them to select and collect specific items. The activity promotes cognitive processes such as decision-making, visual discrimination, and task comprehension, demonstrating how the VR environment supports structured cognitive training.

The objectives of this game are to enhance object memory, numerical memory, spatial awareness, social skills, emotional interactions, and relationships. The game can be played by a single elderly player or two elderly players. To start, the player needs to log in to their account to track progress and scores and choose a suitable game level.

The game begins with an assignment displayed on the board, indicating the type and quantity of vegetables to be collected. The elderly player must carefully read and understand the assignment. They then navigate the farm to collect the specified vegetables and return them to the collection box. In the two-player mode, communication between the elderly players is essential to efficiently divide the tasks of vegetable collection.

Scores are awarded based on the accuracy of the collected vegetable types and the quantity collected. Additionally, completing the task in a shorter time frame results in higher scores. The example game images are shown in Fig 6.

2.2.4.3. Balloon Busting Challenge

The objectives of this game are to improve color memory, spatial awareness, emotional interactions, and relationships. The game can be played by a single elderly player or multiple elderly players. To begin, the player needs to log in to their account to track progress and scores, and they can choose the game level that suits their preferences.

The game starts by releasing balloons of various colors into a large glass and then releasing them onto the playground. The elderly player must use the stick in their hand to hit the balloons that match the color they initially selected. Successfully hitting the correct color balloon earns them points. However, if they hit balloons of a different color or black balloons, they lose points. The elderly can choose to play the game as a single player or in multiplayer mode, either as a team or in a competitive format. The example game images are shown in Fig. 7.

The Large Glass and Balloons



Hit the Balloon with the Stick.



Fig. 7. Balloon Busting Challenge. This game involves popping moving balloons within a virtual environment, encouraging hand-eye coordination, reaction time, and focused attention. The figure highlights the platform's ability to incorporate dynamic and interactive tasks that stimulate cognitive and motor responses in elderly users.

2.3. Virtual Reality Rehabilitation Platform Experiment

To assess the effectiveness of the Virtual Reality Rehabilitation Platform, an experiment was conducted as part of the study titled "Assessment of Acceptance and Initial Efficacy of an Online Rehabilitation Platform for Elderly Individuals with Cognitive Impairment Utilizing

Virtual Reality via 5G Wireless Networks." This study was carried out within the Department of Psychiatry at the Faculty of Medicine, Chulalongkorn University. The experiment took place from June to October 2023.

This study focuses on evaluating the feasibility, usability, and user acceptance of the proposed metaverse-based VR rehabilitation platform. It does not aim to measure cognitive improvement or therapeutic efficacy. Therefore, no pre- and post-intervention cognitive assessments such as MMSE or MoCA were administered. The purpose of this early-stage investigation is to determine whether elderly users with cognitive impairment can comfortably use the system, understand the tasks, and interact within the metaverse environment. Clinical cognitive outcomes will be evaluated in future controlled trials once the system is fully validated for routine use.

The participants in this study were elderly individuals from the Elderly Center at Chulalongkorn Hospital. A total of 18 elderly participants took part in the experiment, with ages ranging from 59 to 79 years. Among these participants, 12 were male and 6 were female, with educational backgrounds ranging from Secondary 3 to Master's degrees. All participants had previously engaged in traditional cognitive training programs and provided informed consent under the supervision of physicians and therapists.

Participant Recruitment and Eligibility Criteria:

Participants were recruited according to the following screening criteria under the IRB-approved protocol.

Inclusion criteria: (1) age 50–85 years; (2) diagnosed with Mild Cognitive Impairment (MCI) through structured clinical cognitive assessment by physicians; (3) able to sit, stand, and walk independently; (4) able to communicate effectively in Thai; and (5) completion of an initial screening session including history taking and cognitive evaluation.

Exclusion criteria: (1) diagnosis of moderate-to-severe dementia; (2) major psychiatric disorders (e.g., major depression, psychosis); (3) neurological conditions affecting cognition such as stroke or Parkinson's disease; (4) significant visual, auditory, or motor impairments that could interfere with the safe use of VR; and (5) known intolerance to VR, including severe dizziness or motion sickness. All participants completed a screening session comprising medical interview, detailed cognitive testing, and safety assessment before enrollment.

The study was conducted over a five-week period, during which each participant used the VR rehabilitation platform once per week under therapist supervision. Each session lasted approximately 20–30 minutes and included orientation, device familiarization, and completion of the designated VR cognitive tasks. No control group or baseline comparison with traditional cognitive rehabilitation was included, as the primary objective of this study was to assess feasibility, usability, and user acceptance rather than therapeutic efficacy.

Each of the participants was provided with Oculus Quest 2 VR devices, which were preloaded with the Virtual Reality Rehabilitation Platform. Over the course of 5 weeks, the participants had the flexibility to utilize the platform and engage in the games at their convenience. However, should they wish to partake in multiplayer mode, they were responsible for scheduling gaming sessions with their friends or therapists independently. Additionally, participants were requested to return to Chulalongkorn Hospital for assessment purposes during the third and fifth weeks of the study. This evaluation at the hospital allowed for a thorough examination of the outcomes and progress achieved through the utilization of the Virtual Reality Rehabilitation Platform.

The evaluation of the Virtual Reality Rehabilitation Platform involves two key assessments. Firstly, medical professionals assess the effectiveness of the new technique called “A Metaverse Approach” in treating Mild Cognitive Impairment. Secondly, it examines how convenient and suitable the Virtual Reality Rehabilitation Platform is for treating Mild Cognitive Impairment in elderly individuals. Since the main goal of this research is to measure how well the Virtual Reality Rehabilitation Platform performs in assisting with the treatment of Mild Cognitive Impairment in the elderly, the focus will be solely on assessing its suitability for this purpose.

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3. Results

To comprehensively evaluate the platform's effectiveness for elderly users, a three-part evaluation strategy was implemented:

Elderly Satisfaction Surveys:

Tailored surveys were administered to assess user-friendliness, accessibility, content relevance, and overall satisfaction. These quantitative results, summarized in Table 1, provide insight into how well the platform aligns with the needs of elderly users.

In addition to mean scores, Table 1 also reports standard deviations and score ranges to illustrate variability among participants. The SD values (approximately 0.6–0.9 across most items) indicate moderate variation in user responses, suggesting that although overall satisfaction was generally positive,

Table 1. Elderly Satisfaction Surveys (n = 18).

Topics	Average Score [0-5]	SD Score	Range [Min-Max]
Satisfaction with the Platform	3.28	0.669	[2-4]
Satisfaction of VR Device Size	3.44	0.616	[2-4]
Satisfaction of VR Device Weight	3.00	0.907	[1-4]
Satisfaction with Wearing the VR Device	3.00	0.767	[1-4]
Convenience of VR Device Usage	3.22	0.808	[1-4]
Satisfaction of VR Environment	3.61	0.916	[2-5]
Satisfaction of VR Scenes	3.72	0.669	[3-5]
Satisfaction of VR Audio	3.39	0.850	[2-5]
Satisfaction of VR Motion	3.22	0.647	[2-4]
Satisfaction of the Usage in the Future	3.33	0.686	[2-5]

Table 2. Game Evaluation Surveys (n = 18).

Topics	Decor Detective: Furniture Challenge			Veggie Quest: Harvest Challenge			Balloon Busting Challenge		
	Average Score [0-5]	SD Score	Range [Min- Max]	Average Score [0-5]	SD Score	Range [Min- Max]	Average Score [0-5]	SD Score	Range [Min- Max]
Level Difficulty	2.40	0.594	[1-3]	2.00	0.485	[1-3]	1.67	0.594	[1-3]
Overall Satisfaction	3.56	0.616	[3-4]	3.61	0.698	[3-5]	3.44	0.511	[3-4]
Rule Understanding	3.39	0.669	[3-5]	3.67	0.686	[3-5]	3.56	0.856	[2-5]
Game Comfortability	3.44	0.698	[2-4]	3.44	0.984	[2-5]	3.28	0.752	[2-4]
Game Content Understanding	3.61	0.850	[2-5]	3.67	0.767	[2-5]	3.72	0.752	[2-5]
Game Interest	3.44	0.808	[2-4]	3.44	0.616	[2-4]	3.22	0.808	[2-4]
Game Attractiveness.	3.56	0.916	[2-5]	3.44	0.984	[2-5]	3.22	0.878	[2-5]

individual users experienced different levels of comfort and familiarity with VR technology. Higher variability in items such as device weight and VR environment reflects differences in physical comfort and immersion perception among elderly participants.

Game Evaluation Surveys:

A detailed assessment of the three VR games available on the platform was conducted to examine engagement, entertainment value, ease of play, and suitability for elderly users. The evaluation results are presented in Table 2.

As shown in Table 2, standard deviations were included to highlight the dispersion of game evaluation scores. Difficulty ratings demonstrated modest variability ($SD \approx 0.48 - 0.59$), with the Balloon Busting Challenge identified as the most difficult. Other dimensions—such as rule understanding, comfortability, and overall satisfaction—showed moderate variability, reflecting differences in user preferences and interaction abilities. Notably, Veggie Quest exhibited relatively higher SD values in comfortability and attractiveness, indicating that certain gameplay elements were perceived differently across participants.

Focus Group Sessions:

To complement the quantitative analysis, focus group sessions were conducted with selected elderly participants to gather qualitative insights. These open discussions provided deeper understanding of user experiences, challenges, and suggestions for improvement, highlighting nuances that numerical scores alone could not capture.

This combined evaluation approach—integrating quantitative satisfaction data, game-specific assessments, and qualitative feedback—ensures a holistic understanding of the platform's performance and supports ongoing enhancements in usability, content relevance, and overall acceptance among elderly users.

3.1. Focus Group

Based on the feedback gathered during the focus group survey, participants expressed predominantly positive sentiments towards the platform, highlighting several aspects they found appealing:

Engaging and Attractive Games: Participants appreciated that the games offered on the platform were not only interesting but also visually appealing. The combination of entertainment and aesthetics contributed to their overall positive experience.

Varied Levels of Difficulty: The availability of games with diverse levels of difficulty was well received. Participants found this aspect of the platform engaging, as it allowed them to select games that matched their skill and comfort levels.

Novelty of the Platform: The novelty factor of the platform was a significant draw for participants. Its innovative nature piqued their curiosity and motivated them to engage with the platform and explore its offerings.

Content Clarity: Participants found the platform's content to be easily understandable. This clarity contributed to their overall enjoyment, as it ensured that they could readily grasp the concepts and objectives of the games.

However, participants also voiced specific concerns and suggestions for improvement, indicating areas where they felt the platform could be enhanced:

Immersive VR Environment: Some participants desired a more immersive virtual reality environment. They suggested improvements to make the gaming experience even more captivating and transportive.

Reduced VR Device Weight: Concerns were raised regarding the weight of the VR device. Participants suggested that reducing the weight would enhance comfort during extended gaming sessions.

Smoother VR Motion: Participants experienced motion sickness in some instances due to less-than-smooth VR motion. They emphasized the importance of smoother transitions to mitigate discomfort.

Ease of Initial Use: Some participants found the platform challenging to use initially. They recommended enhancing user-friendliness to minimize any learning curve.

Familiarization Time: Acknowledging the novelty of the technology, participants noted that it required time to become familiar with the platform. They highlighted the need for patience and practice in adapting to this innovative form of entertainment.

In conclusion, the feedback from the focus group survey revealed a strong overall positive sentiment towards the platform, with participants lauding its engaging games, varied difficulty levels, novelty, and content clarity. At the same time, constructive feedback provided valuable insights into areas for improvement, such as enhancing immersion, reducing device weight, optimizing motion, and further enhancing user-friendliness. These comments serve as valuable input for developers to refine and advance the platform, ensuring a more enjoyable and accessible experience for elderly users.

4. Discussion

The results of this study show that elderly participants were able to use the VR rehabilitation platform with generally positive levels of usability and satisfaction. Participants reported improved engagement, clear task understanding, and enjoyable interaction through the metaverse-based VR environment.

Compared with prior VR-based cognitive training systems, which predominantly focus on single-user gameplay and are typically deployed in controlled hospital or laboratory settings, the proposed platform

introduces a metaverse-oriented architecture that supports persistent multi-user environments, avatar-based interaction, and therapist co-presence. Through its MQTT-based real-time monitoring channel, therapists can remotely observe gameplay events, adjust tasks, and supervise users with low latency—capabilities that are rarely addressed in existing VR rehabilitation tools. Furthermore, the networked design of the platform allows remote in-home usage over high-speed wireless communication, including 5G-ready infrastructure, providing a level of scalability and accessibility beyond that of conventional VR cognitive intervention systems. This integrated combination of social interaction, continuous therapist oversight, and remote deployment meaningfully differentiates our platform from previous VR rehabilitation approaches.

4.1. Virtual Reality Rehabilitation Platform Satisfaction

To allow for a more rigorous interpretation of the survey results, predefined scoring benchmarks were used when analyzing participant satisfaction. Scores in the range of 1-2 were classified as indicating low satisfaction, a score of 3 was considered moderate satisfaction, and scores of 4-5 were interpreted as high satisfaction. These benchmarks follow common practices in Likert-scale usability assessments and provide a consistent framework for interpreting both platform-level and game-level results in this study.

The satisfaction survey results provide valuable insights into participants' experiences with the Virtual Reality Rehabilitation Platform, aligning with the platform's objectives. The results can show the important aspects.

Satisfaction with the Platform: Participants' satisfaction with the overall platform garnered an average score of 3.28, suggesting moderate satisfaction. The standard deviation (SD) of 0.669 indicates relatively consistent responses, and the range (2 to 4) demonstrates a moderate level of variability. Overall, the platform has achieved a reasonable level of satisfaction among users. However, there is potential for enhancement to further improve overall satisfaction.

VR Device Ergonomics and Convenience: Participants' satisfaction with the VR device's size, weight, comfort, and overall convenience received moderate ratings. The average scores for VR device size (3.44), VR device weight (3.00), wearing the VR device (3.00), and convenience of VR device usage (3.22) collectively indicate moderate satisfaction levels. These aspects are closely related to the physical comfort and usability of the VR device. While there is room for improvement in terms of device weight and comfort during usage, participants generally found the device size and convenience to be acceptable. The SD values and ranges reflect moderate consistency in responses and varying degrees of user experiences within this key feature.

Satisfaction with VR Environment and Elements: Participants expressed moderate to moderately positive satisfaction with the VR environment (average score: 3.61), VR scenes (average score: 3.72), VR audio (average score: 3.39), and VR motion (average score: 3.22). The SD values indicate relatively consistent responses, and the ranges show moderate variability. These results suggest that participants generally appreciated the quality of the VR environment, scenes, audio, and motion. However, there may be opportunities to enhance these aspects to further improve user satisfaction.

Usage in the Future: Participants expressed their willingness to use the platform in the future, with an average score of 3.33. The SD of 0.686 suggests relatively consistent responses, and the range (2 to 5) indicates variability. This implies that most participants are open to using the platform again in the future, reflecting a positive outlook.

In summary, participants' satisfaction with VR device ergonomics and convenience, along with their overall platform satisfaction, suggests a moderate level of contentment. While certain aspects within these categories received higher satisfaction ratings, such as the VR environment and scenes, there are areas where improvements could enhance user satisfaction. The relatively consistent responses and moderate variability in the results provide valuable insights for refining the platform's physical and usability aspects. The average scores, SD values, and range collectively inform future efforts to optimize user experience.

4.2. Game Satisfaction

This section discusses and compares the results of the three games within the Virtual Reality Rehabilitation Platform, focusing on overall satisfaction, level difficulty, rule understanding, game comfortability, game content understanding, game interest, and game attractiveness.

Overall Satisfaction and Level Difficulty: The study found that all three games, “Decor Detective: Furniture Challenge,” “Veggie Quest: Harvest Challenge,” and “Balloon Busting Challenge,” received moderate overall satisfaction levels. Despite variations in perceived difficulty levels, participants consistently expressed satisfaction, indicating consistent enjoyment and engagement across all three games.

Rule Understanding, Game Comfortability, and Game Content Understanding: One strength of the Virtual Reality Rehabilitation Platform is the games' comprehensibility. Participants reported clear rule understanding, comfort in gameplay, and a good grasp of the game's content across all three games. This consistency ensures accessibility and enjoyment for elderly users with varying levels of technological familiarity.

Game Interest and Attractiveness: While player perceptions of interest and attractiveness varied among the games, all received moderate ratings. Participants found each game engaging and visually appealing. “Decor Detective” and “Balloon Busting Challenge” had

similar interest scores, slightly higher than “Veggie Quest.” Attractiveness scores also varied slightly, reflecting user preferences. Nevertheless, all three games maintained a moderate level of appeal, ensuring user captivation in the virtual reality experience.

In summary, the study's results indicate that the three games offered within the Virtual Reality Rehabilitation Platform were well-received by elderly participants. These games effectively engaged elderly individuals in rehabilitation activities within a virtual reality environment. Participants consistently expressed satisfaction, emphasizing the platform's effectiveness in delivering engaging and comprehensible rehabilitation exercises. Variation in player interest and attractiveness scores highlights the platform's ability to cater to diverse preferences while maintaining a moderate level of engagement. These findings underscore virtual reality's potential as a valuable tool for enhancing the well-being and cognitive abilities of elderly individuals.

4.3. Focus Group Surveys

To strengthen the analysis of qualitative feedback, a basic thematic coding procedure was applied to categorize the comments collected from the focus group sessions. User feedback was grouped into four recurring themes: (1) usability, referring to clarity of instructions, ease of navigation, and the ability to operate VR controls; (2) immersion, including perceptions of realism, engagement in the virtual scenes, and enjoyment of interaction; (3) comfort, covering physical comfort while wearing the headset and any motion-related sensations; and (4) motivation, referring to users' interest in continuing to use the system and their perceived cognitive or emotional benefits. These themes provided structure for interpreting participant experiences and enhanced the rigor of the qualitative analysis.

The focus group feedback underscores the platform's strengths in delivering engaging and adaptable content to elderly users. At the same time, it provides crucial guidance for further enhancing the platform's immersive qualities, usability, and overall user comfort. These insights are invaluable for developers, allowing them to refine the platform to better support the cognitive rehabilitation needs of elderly individuals and ultimately improve their well-being.

Although the platform demonstrated good levels of usability, engagement, and user acceptance, it is important to clarify that this study does not evaluate cognitive improvement or clinical efficacy. No pre- and post-intervention cognitive assessments (such as MMSE or MoCA) were performed, as the objective of this work was to investigate feasibility, usability, and user experience rather than therapeutic outcomes. Similarly, no control group or baseline comparison with traditional cognitive rehabilitation was included, as this study was intentionally designed as an early-stage feasibility evaluation aimed at determining whether elderly users with cognitive impairment could comfortably operate the

system, understand the interaction flow, and engage in metaverse-based activities. Future research will incorporate standardized cognitive assessments and controlled experimental designs to evaluate therapeutic effectiveness and compare the metaverse-based VR rehabilitation platform with conventional cognitive training approaches.

5. Conclusion

This study presented a metaverse-inspired Virtual Reality Rehabilitation Platform designed to support cognitive engagement, social interaction, and remote therapist supervision for elderly individuals with Mild Cognitive Impairment (MCI). The platform incorporates three key innovations that differentiate it from conventional VR-based cognitive training systems: (1) a persistent multi-user environment that enables avatar-based communication and therapist co-presence; (2) an MQTT-based real-time monitoring channel that allows therapists to observe user performance and adjust rehabilitation tasks with low latency; and (3) a networked architecture that enables remote in-home usage over high-speed wireless communication, including 5G-ready infrastructure. These features collectively provide a level of accessibility, scalability, and social connectedness that is not addressed in traditional single-user VR rehabilitation tools.

The usability study conducted with 18 elderly participants demonstrated positive levels of user engagement, acceptance, and task comprehension, indicating that the metaverse-based approach is feasible for real-world community deployment. Participants expressed that the immersive environments, simplified interaction mechanisms, and social features were supportive and motivating for cognitive exercise. However, this study did not evaluate cognitive improvement or clinical efficacy, and no pre- or post-intervention assessments (such as MMSE or MoCA) were performed. The findings should therefore be interpreted strictly as evidence of usability and feasibility rather than therapeutic effect.

Future work will focus on expanding therapist-patient interaction capabilities, integrating cloud-based and edge-computing infrastructure for large-scale deployment, and conducting controlled clinical trials to assess the platform's impact on cognitive outcomes. With further development, the proposed metaverse-based VR rehabilitation system has the potential to become a scalable and accessible tool for cognitive health support in aging populations.

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References

- [1] P. Wongboonsin, Y. Aungsuroch, and N. Hatsukano, "The Ageing Society and Human Resources to Care for Older People in Thailand," in *Human Resources for the Health and Long-Term Care of Older Persons in Asia*, 1st ed., pp. 104, 2020.
- [2] N. N. Chuakhamfoo, P. Phanthunane, S. Chansirikarn, and S. Pannarunothai, "Health and long-term care of the elderly with dementia in rural Thailand: A cross-sectional survey through their caregivers," *BMJ Open*, vol. 10, no. 3, pp. e032637, Mar. 2020.
- [3] J. Griffiths, L. Thaikrue, N. Wongpakaran, and P. Munkhetvit, "Prevalence of mild cognitive impairment in rural Thai older people, associated risk factors and their cognitive characteristics," *Dement. Geriatr. Cogn. Dis. Extra.*, vol. 10, no. 1, pp. 38–45, Jan. 2020.
- [4] P. Thaipisuttikul, K. Jaikla, S. Satthong, and P. Wisajun, "Rate of conversion from mild cognitive impairment to dementia in a Thai hospital-based population: A retrospective cohort," *Alzheimer's Dement (Transl Res Clin Interv)*, vol. 8, no. 1, pp. e12272, 2022.
- [5] Y.-C. Tsao, C.-C. Shu, and T.-S. La, "Development of a Reminiscence Therapy System for the Elderly Using the Integration of Virtual Reality and Augmented Reality," *Sustainability*, vol. 11, no. 4792, 2019. doi: 10.3390/su11174792.
- [6] R. Soonthornchaiya, "Resilience for psychological impacts of COVID-19 pandemic on older adults in Thailand," *HSOA J. Gerontol. Geriatr. Med.*, vol. 6, pp. 053, 2020.
- [7] T. N. Aung, M. N. Aung, S. Moolphate, Y. Koyanagi, S. Supakankunti, and M. Yuasa, "Caregiver burden and associated factors for the respite care needs among the family caregivers of community-dwelling senior citizens in Chiang Mai, Northern Thailand," *Int. J. Environ. Res. Public Health*, vol. 18, no. 11, pp. 5873, 2021.
- [8] S. Jongsiriyanyong and P. Limpawattana, "Mild cognitive impairment in clinical practice: A review article," *Am. J. Alzheimers Dis. Other Dement.*, vol. 33, no. 8, pp. 500–507, 2018.
- [9] N. Scarmeas, C. A. Anastasiou, and M. Yannakoulia, "Nutrition and prevention of cognitive impairment," *Lancet Neurol.*, vol. 17, no. 11, pp. 1006–1015, 2018.
- [10] K. Ritchie, "Mild cognitive impairment: an epidemiological perspective," *Dialogues Clin. Neurosci.*, vol. 6, no. 4, pp. 401–408, 2004.
- [11] S. Jirayucharoensak, P. Israsena, S. Pan-Ngum, S. Hemrungron, and M. Maes, "A game-based neurofeedback training system to enhance cognitive performance in healthy elderly subjects and in patients with amnesic mild cognitive impairment," *Clin. Interv. Aging*, vol. 14, pp. 347–360, 2019.
- [12] S. Kasper, C. Banche, A. Eckert, H. Förstl, L. Frölich, J. Hort, A. D. Korczyn, R. W. Kressig, O. Levin, and M. S. Palomo, "Management of mild cognitive impairment (MCI): the need for national and international guidelines," *World J. Biol. Psychiatry*, vol. 21, no. 8, pp. 579–594, 2020.
- [13] S. L. Kletze, P. Sood, A. Negm, P. C. Heyn, S. Krishnan, J. Machtinger, X. Hu, and H. Devos, "Effectiveness of brain gaming in older adults with cognitive impairments: a systematic review and meta-analysis," *J. Am. Med. Dir. Assoc.*, vol. 22, no. 11, pp. 2281–2288, 2021.
- [14] C. Cutler, B. Hicks, and A. Innes, "Does digital gaming enable healthy aging for community-dwelling people with dementia?" *Games Cult.*, vol. 11, pp. 104–129, 2016.
- [15] H. Jo and E. Son, "The effect of reminiscence therapy on depression, quality of life, ego-integrity, social behavior function, and activities of daily living in elderly patients with mild dementia," *Educ. Gerontol.*, vol. 41, pp. 1–13, 2015.
- [16] P. Subramaniam, B. Woods, and C. Whitaker, "Life review and life story books for people with mild to moderate dementia: A randomized controlled trial," *Aging Ment. Health*, vol. 18, pp. 363–375, 2014.
- [17] E. Fujiwara, K. Otsuka, A. Sakai, K. Hoshi, S. Sekiai, M. Kamisaki, and F. Chida, "Usefulness of reminiscence therapy for community mental health," *Psychiatry Clin. Neurosci.*, vol. 66, pp. 74–79, 2012.
- [18] S.-L. Huang, C.-M. Li, C.-Y. Yang, and J.-J. J. Chen, "Application of reminiscence treatment on older people with dementia: A case study in Pingtung," *Nurs. Res.*, vol. 17, pp. 112–119, 2009.
- [19] S. C. Sellers and P. B. Stork, "Reminiscence as an intervention: Rediscovering the essence of nursing," *Nurs. Forum*, vol. 32, pp. 17–23, 1997.
- [20] R. Coppola, M. Morisio, and M. Torchiano, "Mobile GUI testing fragility: a study on open-source android applications," *IEEE Trans. Reliab.*, vol. 68, no. 1, pp. 67–90, 2018.
- [21] M. Quest, *Oculus Quest2*. Facebook Technologies, LLC, 2022.

- [22] H. Koziolk, S. Grüner, and J. Rückert, “A comparison of MQTT brokers for distributed IoT edge computing,” in *Softw. Archit., ECSA 2020, Lect. Notes Comput. Sci.*, vol. 12292, pp. 352–368, 2020.
- [23] A. Al-Fuqaha, M. Guizani, M. Mohammadi, M. Aledhari, and M. Ayyash, “Internet of Things: A survey on enabling technologies, protocols, and applications,” *Technovation and IEEE Commun. Surv. Tutor.*, vol. 17, no. 4, pp. 2347–2376, 2015.
- [24] M. Poongothai, P. Muthu Subramanian, and A. Rajeswari, “Design and implementation of IoT-based smart laboratory,” in *2018 5th Int. Conf. Ind. Eng. Appl.*, pp. 169–173, 2018.
- [25] R. Chanchaen and G. Phanomchoeng, “The Telepresence Laboratory for a New Campus Life Since the COVID-19 Crisis,” *Int. J. Eng. Educ.*, vol. 38, no. 5, pp. 1523–1535, 2022.



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