Design and Development of Cognitive Training Systems Based on Extended Reality and BCI Technology

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***Abstract*—Dementia is considered a Mild Cognitive Impairment (MCI), representing a blurred transition from normal cognitive function to dementia. MCI might be a precursor to dementia being caused by various neurodegenerative diseases, including Alzheimer's disease, stroke, metabolic disorders, and mental health conditions. According to the World Health Organization (WHO), over 55 million people worldwide are suffering from dementia, with nearly 10 million new cases each year. This number is expected to rise to 78 million by 2030. Numerous studies have proposed various training methods targeting specific cognitive domains in dementia. For instance, reminiscence therapy encourages individuals to recall buried memories, while reality orientation therapy focuses on strengthening orientation cues to help patients with dementia establish a stronger sense of control. With aging, changes occur in cognitive and physical functions. Research suggests that memory functions can be improved through training. Therefore, the primary goal of this study was to develop an Extended Reality (XR) cognitive system to assist MCI patients in enhancing logical thinking, increasing independence in daily life, and improving response accuracy. The application of extended reality technology in the medical field is expanding, covering areas such as surgical assistance, medical consultation, disease treatment, and medical training. We integrated mixed reality devices with brain-computer interface (BCI) equipment. By detecting brainwave signals in the frontal region of the brain through sensors, neural activity was quantified, and digital brainwave data was transmitted to the system. This data was then visualized on screen in real-time to analyze changes in brainwave data during training. Through multifaceted task training, the system enhanced cognitive response and sensory perception, stimulating brain activity with the goal of strengthening cognitive functions.**

Keywords—extended reality (XR), brain-computer interface (BCI), mild cognitive impairment (MCI), Electroencephalography (EEG), cognitive training

I. Introduction

Cognitive functions and physical abilities change with age, and related studies have indicated symptoms including deterioration in brain function, hand-foot coordination, memory, responsiveness, concentration, spatial perception, and logical thinking. These symptoms affect patients' family relationships, social skills, and work capabilities, increasing the burden on caregivers.

In this study, cognitive dysfunction was explored, targeting conditions such as attention deficits, memory decline, and loss of judgment in cognitive diseases as the primary development goals. A cognitive training system has been developed including immersive cognitive games for user training. Brainwave technology is used to integrate visualized EEG data into the system for real-time analysis of user brainwave activity to assess the effectiveness of the training process. Considering the need for Telemedicine Education, we developed an Azure-based cloud platform to support applications such as mixed reality, remote medical assistance, and rehabilitation instruction and established a shared virtual space for multiple users. For the study, we used the Microsoft Mesh technology platform equipped with HoloLens 2.

XR encompasses a wide range of technologies including virtual and real elements such as Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR). Today, XR is associated with entertainment visual applications and has evolved into the new generation of the Metaverse, connecting interpersonal communication, retail economy, gaming entertainment, and film and art. In the application of medical care, it has been used for MetaHealth [13] in which remote consultations and post-treatment Telemedicine Education are conducted through wearable devices. Patients are familiarized with the online mode gradually [1]. Social healthcare and intelligent medical services have been emerging in recent years with countries investing many resources in the research and development of healthcare software and hardware.

XR technology is widely used in digital medicine, providing visualized motion learning training. Scholars have explored how virtual images created by VR redefine the relationship between the patient's brain and the motor nervous system [12] and how the neural feedback of brainwaves through VR devices helps patients in real situations. VR games can refine various cognitive enhancements through games, and a virtual rehabilitation system simulates real situations [3]. Clinical research and analysis have shown that XR-based rehabilitation methods have advantages in terms of usability, entertainment, user motivation, and improved patient training performance. Therefore, to enhance the effectiveness of cognitive training research, we applied brain electrical neural feedback technology in XR to analyze changes in the user's left and right brain during the training process. The system was developed using Unity equipped with the HTC Vive virtual reality device and the Looxid Link EEG sensor to transmit brainwave signals from the frontal lobe area to the system for visualization in the VR display [4]. We designed four cognitive training programs including the Stroop Effect, which refers to the interference effect between word meaning and font color [18], the Shulte Grid, indicating intermittent, repetitive concentration training [6], the Eureka effect, referring to the use of the brain's intuitive thinking [7], and the Soma cube, aimed at enhancing spatial thinking and analytical abilities [15]. These functions were designed to strengthen brain function and visual perception responses and train users to gradually master hand-eye coordinated cognitive responses for different difficulty levels of tasks. Brain activity was stimulated to increase imagination and logical thinking and prevent MCI [11]. The results can be applied to develop the Telemedicine system.

II. Related Work

XR technology has been widely applied in medicine. Hospitals use XR for international medical surgeries, consultations, and training [17]. Numerous studies have highlighted its ability to improve treatment adherence and alleviate patient fatigue and anxiety. Thus, the integration of related technologies [16] into the healthcare and wellness sector benefits the medical system.

Dementia is a neurodegenerative disease that causes cognitive abilities, personality changes, behavioral disorders, and problems with daily functions. Cognitive deficits include impairments in memory, attention, executive function, language, and visuospatial abilities, leading to overall cognitive dysfunction and impaired functional independence. For patients with mild MCI, cognitive stimulation is used as an intervention measure. Studies have shown that VR-based cognitive stimulation impacts the overall cognitive function of MCI patients. Interventions for cognitive domain stimulation, such as reminiscence therapy, prompt people to recall memories of events, people, and places [9], and reality orientation therapy (ROT) reinforces orientation information to help patients have a greater sense of control. It further enhances creative thinking, functional independence, and activity identification. The elderly in medical care institutions generally accept the use of VR serious games for cognitive impairment training and show positive outcomes [2]. Electroencephalography (EEG) is effective in assessing the VR cognitive training process as it records changes in EEG brainwaves synchronously [5]. Brainwaves are divided into five types from high to low frequency: beta waves, alpha waves, theta waves, delta waves, and gamma waves. EEG is used to detect data from various regions of the cerebral cortex, including the frontal lobe, temporal lobe, parietal lobe, and occipital lobe. The frontal lobe is responsible for cognitive functions and motion control and allows users to concentrate on making decisions. It receives information from the body and decides body movements. Human intelligence, concentration, personality, behavior, and emotions are related to the frontal lobe. The frontal lobe of the brain is responsible for higher cognitive functions and judgment of personality. The temporal lobe is the location of the primary and secondary auditory cortices, central to processing auditory information. Wernicke's area, located at the edge of the parietal lobe, is significantly related to language comprehension, while Broca's area is associated with language production. Damage to this area may lead to aphasia. Therefore, the observation and analysis of brainwave activity are required to explore the brain changes during VR operations.

We established the system for the requirements of Telemedicine Education for patients and doctors using HoloLens 2 to assist in delivering Telemedicine Education services including data analysis, image assistance, and instructional training. The system provides a management solution that integrates virtual and real elements to implement telemedicine for patients with mobility issues [10]. Literature has been reviewed for the use of this device for medical treatment to aid patients with mobility issues [8]. Research results indicated that when using MR devices for direct clinical care, the contact time between medical staff and patients was reduced by 51.5%, and the use of Personal Protective Equipment (PPE) was decreased by 83.1% [14]. The HoloLens 2 was used to establish a virtual classroom where learners participated in clinical teaching meetings remotely and shared, interacted, and discussed relevant result images. The system represents a novel evolution in the traditional clinical teaching model.

III. System Architecture

We employed the Unity development environment with the HTC Vive to provide users with an immersive Virtual Reality (VR) experience. To detect and analyze brainwave changes during training sessions, we integrated the Looxid Link EEG device for real-time brainwave data detection. This data was synchronized with the VR display and presented on the system interface for real-time neurofeedback visualization. It is crucial to understand users' cognitive load, focus, and emotional state during cognitive tasks. Therefore, by analyzing these real-time data, we adjusted and optimized cognitive training methods to offer personalized training strategies to improve users' cognitive abilities and overall experience. Additionally, to design telehealth services, the HoloLens 2 Mixed Reality (MR) device was used as a framework for implementing Telemedicine Education for healthcare professionals. The system architecture is illustrated in Fig. 1.

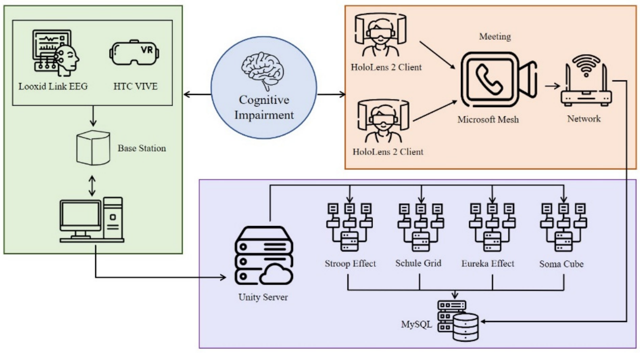
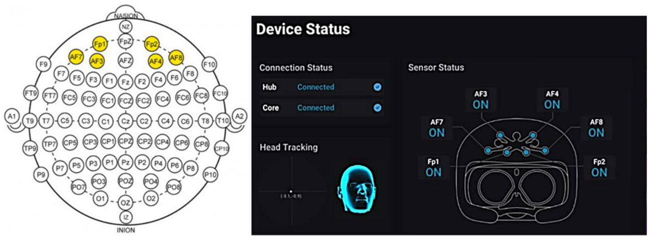


Fig. 1. System architecture.

The Looxid Link brainwave monitoring device enabled VR users to instantly view their brainwave data in real-time. This device detects brainwave changes in the frontal lobe areas, including positions on the left frontal side such as Fp1, AF7, AF3, and on the right side such as Fp2, AF8, and AF4. Therefore, an overview of the activities in the left and right hemispheres of the brain was reflected. This data is used to indicate the user's level of focus and relaxation. Figure 2(a) shows the International 10–20 EEG system with the yellow dots marking the brainwave sensing positions in the cerebral cortex of the frontal lobe. This region plays a key role in regulating emotions, concentration, and decision-making processes. In the Looxid Link device, these measurement points are used to collect brainwave data to monitor brain activities in real-time in a VR environment. Figure 2(b) illustrates the interaction between the brainwave monitoring device and the user interface, displaying whether the sensors monitoring the frontal lobe areas are active for subsequent data analysis.



(a) (b)

Fig. 2. (a) International 10-20 EEG system (b) Looxid link connection status and sensor status.

Regarding the brainwave data from the six electrode nodes on the frontal lobe, alpha (α) are most easily detected during relaxation, while beta (β) waves are more readily detected during tension. Theta (θ) and delta (δ) waves appear in the states of light consciousness or unconsciousness, and gamma (γ) waves are high-amplitude frequency waves that play important roles in concentration, working memory, learning, and awareness. These data are applied to a broader range of fields to improve learning efficiency and athletic performance and promote mental health. The VR cognitive training tasks developed in this study include the Schulte Grid, Eureka Effect, Stroop Test, and Soma Cube, integrating a brain-computer interface for real-time analysis of the user's response times and progress in training. The content of the cognitive training tasks for each item is explained as follows.

A. Stroop Effect

The Stroop Effect is a classic phenomenon in cognitive psychology, revealing the automatic nature of human information processing. When people process congruent information such as the color and the meaning of a word being the same (e.g., the word RED displayed in red color), recognition is swift. Conversely, incongruent information interferes with normal cognitive processes and necessitates more time to respond when the meaning of a word and its presented color is mismatched (e.g., the word GREEN displayed in red). Through training in this cognitive task, an increase in beta (β) wave values was observed in participants' brainwaves when answering such questions. This increase shows that participants discern the question and search for corresponding color options. In task completion, an elevation in alpha (α) wave values indicates that participants enter a relaxed state. This training enhances the participant's concentration and improves the brain's ability to process information conflicts, further enhancing cognitive flexibility and efficiency.

B. Shulte Grid

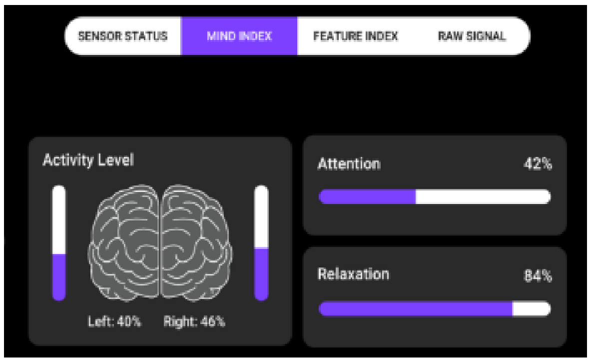
The Schulte Grid involves visual tracking and identification control. The system randomly generates a series of numbers, updating them with each training session. Participants use the handheld controller of the HTC Vive to make selections, and locate and click on squares in numerical order from 1 to 26 swiftly and accurately. The shorter the completion time, the more it reflects the participant's state of attention. To evaluate the effectiveness of the training precisely, brainwave data are processed and analyzed in real-time through the Looxid Link Core. When participants focus on clicking numbers, an increase in beta β wave activity in their brainwaves indicates an enhancement in attention. During the intervals of searching for the next target number, an increase in α wave activity suggests that the participant is in a state of relaxation, open to new information (Fig. 3(a)). This training enhances participants' response time and attention.

C. Eureka Effect

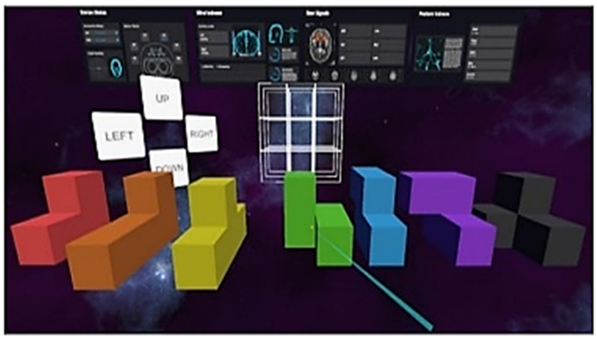
The Eureka effect, also known as the insight effect, refers to the experience of the sudden understanding of the core concept or solution to a problem during the problem-solving process. This task is designed for a Constellation Puzzle game themed on the 12 zodiac signs. Participants are required to connect scattered points within a time limit to gradually construct a complete constellation image. In this design, speed, imagination, and logical thinking abilities are tested to stimulate brain function through visual-perceptual cues and promote cognitive enhancement. It is beneficial for memory, spatial recognition, and problem-solving abilities. When players complete the connections of a constellation, they experience a moment of sudden comprehension of the entire pattern, which is the effect of this training.

D. Soma Cube

The Soma cube is a classic intellectual game composed of seven distinctively shaped polyhedra. The goal is to assemble these polyhedra into a complete cube, serving as an effective tool for enhancing visual and spatial cognition. This task applies the concept of the Soma cube in a 3 × 3 × 3 cubic space, where participants are required to use their imagination and spatial awareness to reassemble a specified cube. With 240 different possible solutions, this task fosters users' creativity and problem-solving abilities.



(a)



(b)

Fig. 3. (a) Looxid link mind index (b) Recognition training with Soma Cube.

Participants need to adjust the orientation and angles of each polyhedron using the controller, as well as their rotation within the cubic space as depicted in Fig. 3(b). In this process, participants' brainwave changes are recorded to provide real-time feedback on cognitive load, attention, and emotional state.

E. Telemedicine Education

For Multiplayer Telemedicine Education services for medical professionals and patients, we used Microsoft Mesh to allow users to connect remotely without spatial limitations and expand the scope and efficiency of Telemedicine Education services (Fig. 4). For a virtual meeting, the system generated a virtual space where participants could share images or 3D models, synchronously engaging in discussions. Objects in this space were updated in real-time. This approach enhanced visual aids for medical communication and educational processes, making users engaging and dynamic in discussion. Consequently, it provided an efficient and interactive environment for learning.

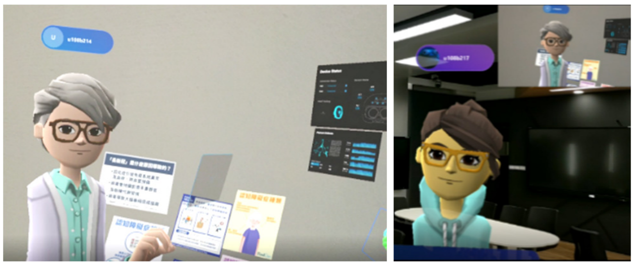


Fig. 4 Telehealth service using HoloLens 2.

IV. Conclusions

In this study, we designed four innovative training systems by using VR technology to provide cognitive training and help patients improve their symptoms. The system implemented cognitive training and assessed patients' brain activity in training using the combination of VR and EEG technologies. It resulted in comprehensive training effects. Hololens 2 technology was used to improve multi-user Telemedicine Education to expand medical services in remote areas. Using such methods, professional medical knowledge and resources can be available in areas where medical resources are relatively scarce. To enhance the effectiveness of the training and application of the technology, more research is required to develop the effectiveness of physical rehabilitation and apply it for long-term and smart home healthcare, thereby providing more effective and personalized care solutions.

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