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VR Technology Based on AI Models Enhances Memory Enhancement in Cognitive Patients

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Abstract. Cognitive impairment creates a significant burden of disease worldwide, and traditional rehabilitation methods have limitations in terms of accessibility, personalization, and cost. The integration of artificial intelligence and virtual reality technology provides an innovative intervention approach for memory enhancement in patients with cognitive impairment. This paper systematically expounds the core synergistic mechanism of AI-VR technology to enable memory enhancement, and reviews its application in major types of disorders such as mild cognitive impairment and dementia. The study found that this technology shows significant potential in autobiographical memory stimulation and daily living ability training by creating immersive scenarios and driving personalized adaptive interventions. However, its development also faces multiple challenges, such as technical cost, insufficient strength of clinical evidence, and data ethics. The study points out that promoting the clinical translation, standardization, and ethical framework construction of technology is the key to unlocking its enabling potential and improving the future of cognitive impairment rehabilitation.

Keywords: artificial intelligence, virtual reality, cognitive impairment, memory enhancement, cognitive rehabilitation.

1. Introduction

Cognitive impairment, including mild cognitive impairment (MCI) and dementia (such as Alzheimer's disease), has become a major global public health challenge. According to statistics, more than 50 million people worldwide are affected by cognitive decline, and its prevalence is expected to increase dramatically [1]. Cognitive impairment not only seriously affects the patient's ability to live independently and quality of life, but also brings a heavy care and financial burden to the family and society. In the face of this problem, it is very important to develop effective prevention, assessment, and intervention strategies.

Traditional cognitive rehabilitation methods are limited by high costs, inconvenient implementation, lack of personalization, and disconnection from real life, which gives rise to the urgent need for innovative rehabilitation technology.

In recent years, the rapid development of information technology has provided new possibilities for breaking through the above limitations. Among them, virtual reality (VR) technology can create

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a safe, controllable, and immersive simulation environment, which enables cognitive training to be carried out in highly simulated daily scenes, thus greatly improving the ecological validity of training and users' willingness to participate. At the same time, artificial intelligence (AI) technology, especially machine learning and deep learning, provides impetus for the "intelligent" upgrading of the rehabilitation process. AI can analyze data from many aspects, and then realize real-time personalized adjustment of the intervention scheme, accurate prediction of the curative effect, and generate new interactive content.

The integration of AI and VR, through the synergy of data and intelligence, can transform static scenes into intelligent environments that can be perceived and responded to in real time. This opens up a new path for the development of personalized and adaptive cognitive rehabilitation programs, especially in memory enhancement [1]. This paper aims to systematically review the research status, core mechanism, application, and challenges of this cross-field in order to provide a reference for future research and practice.

2. The core mechanism of AI and VR technology, enabling memory enhancement

2.1. Immersive scenario simulation and ecological memory coding

A key advantage of VR technology is that it can build a highly immersive three-dimensional environment simulating the real world, thus bringing unprecedented ecological validity to the encoding and retrieval of memory [2]. Unlike the traditional pen and paper exercise or two-dimensional screen training, VR can provide rich environmental stimuli through multiple sensory channels, such as vision, hearing, and even touch, that may be integrated in the future [1]. This multi-sensory immersive experience can significantly improve users' motivation and participation. Its internal mechanism is that it is closer to the natural process of memory formation in daily life, so it helps to promote the consolidation of memory traces and generalize the learned skills to the real world [1].

Research has confirmed that VR based scene simulation (such as "virtual store" shopping task) can not only be used for memory assessment, but also its ecological validity makes it an effective memory training tool [2]. When users perform tasks closely related to daily life (such as spatial navigation and memory items) in VR, this situational learning method can more effectively activate brain networks related to autobiographical memory and episodic memory, so as to enhance the ability of memory and recall [1].

2.2. Generative content generation and personalized memory cue reconstruction

The enhancement of memory, especially autobiographical memory, largely depends on clues closely related to personal experience. In this regard, generative artificial intelligence (such as large-scale language models and image generation models) has played a revolutionary role [3]. Its core mechanism is that it can transform the patient's oral or written description of past experience into highly personalized and visual memory scenes.

Specifically, the system will first use natural language processing technology to understand and optimize the user's description of the memory segment, and then generate detailed images to generate prompt words. Subsequently, the system uses generative AI, such as a diffusion model, to create visual images that are both consistent with the description and can cause emotional resonance [3]. This process transforms abstract and fuzzy memory fragments into concrete and vivid visual stimuli, which provide powerful clues for memory retrieval. Although the current technology still

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has the risk of generating stereotype images or missing details, it has preliminarily verified the feasibility of generating personalized content through AI to activate specific neural pathways and promote memory [3]. This intervention method, customized according to personal history, directly targets the impaired autobiographical memory system in dementia and other diseases [3].

2.3. Adaptive difficulty adjustment and cognitive load optimization

Static and fixed rehabilitation programs are often difficult to match patients' dynamic cognitive ability, which is also a key reason for the limited effect of many traditional digital therapies. In contrast, the adaptive system driven by artificial intelligence can dynamically adjust the difficulty of the challenge and provide instant feedback by analyzing the user's response time, accuracy, and other data in real time. In this way, the training can always be maintained within the "best load" range that meets the user's personal ability. This dynamic adjustment not only helps to maintain users' motivation and participation, but more importantly, it can build a continuous optimization closed loop of "evaluation adjustment re evaluation", so that the intervention measures can really keep up with the progress of users' ability.

A double-blind randomized controlled trial conducted by the Graessel team provided direct evidence for this [4]. This study compared the individualized computerized cognitive training (ICCT) with machine learning function with the basic non-adaptive computerized cognitive training (BCCT). After 6 months of intervention, the score of the intervention group using ICCT on the Montreal Cognitive Assessment (MoCA) scale increased by an average of 2.2 points (95% CI [1.4, 2.9]), which was significantly better than that of the control group using bcct (0.9 points, 95% CI [0.2, 1.7]), and the interaction effect between groups was significant (P=0.029) [4]. In addition, 51% of the participants in the intervention group improved their cognitive status to the range of non-mild cognitive impairment (MCI), which was also significantly higher than 29% in the control group (P=0.033) [4]. These quantitative results show that AI-enhanced personalized cognitive training is significantly better than the traditional non-adaptive methods in improving the overall cognitive function of patients with mild cognitive impairment.

2.4. Multimodal biofeedback and neural loop regulation

The introduction of wearable devices and biosensor technologies (such as EEG and eye tracking) enables the rehabilitation system to collect deep physiological data beyond behavioral performance. The core role of artificial intelligence is multimodal data fusion. It can integrate and analyze behavior data, physiological signals, and virtual reality environment parameters, so as to achieve a more comprehensive and objective evaluation of users' cognitive state and intervention effect. This "behavior physiology environment" multidimensional data closed loop provides the possibility of precise intervention from external behavior improvement to internal neural function remodeling. For example, by analyzing the EEG activity characteristics of users in a VR memory task in real time, an AI algorithm can determine the intensity of their attention or memory coding, and dynamically adjust the task difficulty based on it, so as to realize closed-loop neural feedback training. This idea has been strongly confirmed in the research of Andrade et al. His team successfully identified specific EEG biomarkers and key brain regions that can predict the treatment response of patients with Alzheimer's disease by using resting state EEG and machine learning methods [5]. This study not only provides a direct basis for screening potential beneficiaries and realizing personalized treatment before intervention, but also lays a key neuroscience foundation for the future design of VR cognitive tasks with clear neural targeting and the development of the next generation of

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intelligent rehabilitation systems that can be adjusted adaptively based on real-time EEG biomarkers.

3. Application of the AI-VR system in the main types of cognitive impairment

Traditional drug and non-drug interventions have limitations in delaying the decline and improving the quality of life. Based on the integration technology of AI and VR, it opens up an innovative path for the care and rehabilitation of patients with dementia by providing a highly personalized, safe, and controllable intervention environment with emotional resonance.

3.1. Autobiographical memory and nostalgic therapy

Autobiographical memory is the core of maintaining self-identity and emotional connection. Traditional nostalgia therapy is often limited by a single physical medium, and the combination of generative artificial intelligence and virtual reality brings the possibility of Paradigm Innovation in this field. Its theoretical basis is that the immersive familiar environment can effectively trigger emotion and memory. Appel et al's review pointed out that virtual reality can activate the relevant memory and improve the happiness of patients with dementia by presenting familiar scenes and sounds, which provides a basis for the development of digital nostalgia therapy [6]. Wang and Zhang's team further integrated generative AI and VR technologies and developed a system that can transform personal text descriptions into personalized immersive scenes. A technical verification shows that the accuracy rate of matching the image generated by the system with the key elements described by the user reaches 85%, which preliminarily proves the feasibility of this path [3]. This indicates that nostalgia therapy has moved from using general materials to a highly personalized intervention that dynamically generates visual scenes based on the patient's personal experience. Although the current technology still faces challenges such as the possibility of generating stereotyped images, and the actual curative effect on patients still needs clinical verification, it undoubtedly provides a promising modern way for the direct rehabilitation of memory and visuospatial skills.

3.2. Scenario simulation training of daily living ability

In the care of dementia, maintaining the independence of patients is the core goal. Virtual reality (VR) technology enables patients to practice daily life activities such as shopping and cooking without risk by building a safe, controllable, and repeatable high-simulation environment. When artificial intelligence (AI) is integrated, the training is upgraded from static simulation to a dynamic adaptive process. The system can analyze the user performance in real time, dynamically adjust the task difficulty (such as increasing or decreasing shopping list items or environmental interference) through the algorithm, and provide personalized tips and feedback, to create an intelligent training environment that can evolve in real time with the change of the patient's ability, and help maintain its functional independence to the greatest extent under the premise of safety [2]. Existing studies have provided an empirical basis for this. For example, Oliveira et al's randomized controlled trial showed that after VR cognitive intervention using simulated instrumental activities of daily living (IADL), the overall cognitive function (MoCA score) of patients with mild to moderate Alzheimer's disease was significantly improved (2.2 points in the intervention group vs. 0.9 points in the control group), $p=0.029$ [7]. The feasibility study of Manera et al. Further confirmed that the IADL performance (average score from 19.7 to 22.0) and cognitive function (ADAS cog score from 14.7

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to 15.7) of patients with Alzheimer's disease and mild cognitive impairment who used the virtual kitchen cooking game showed significant improvement only one week later [8]. In addition, the pilot study of Fasilis et al. Found that after 4-5 weeks of serious game VR training, the score of patients' memory retention (Babcock story recall test) increased from 2.30 to 4.65 (p=0.009), Executive function and many other cognitive areas have been significantly improved [9]. These studies jointly verified the effectiveness of cognitive rehabilitation based on highly structured, life-friendly virtual task templates and provided a solid practical framework for future AI technology to realize scene personalization and difficulty adaptation, so as to build a more intelligent rehabilitation path.

4. Discussion and analysis

Although AI-VR technology shows great potential in the field of memory enhancement in cognitive impairment, it still faces a series of technical, clinical, and ethical challenges from experimental research to wide clinical and family applications. Based on the existing literature, these limitations are mainly reflected in the following three levels.

4.1. Technical level

The popularity of the current AI-VR system is first restricted by the hardware and technical threshold. Equipment cost is the primary obstacle: high-performance VR head displays, computers supporting real-time rendering, and necessary sensors (such as EEG equipment for neural feedback) constitute a considerable initial investment, which poses economic challenges to individual users, communities with limited resources, and small and medium-sized medical institutions [2]. Secondly, simulator motion sickness is a significant usability problem. An immersive VR experience may lead to dizziness, nausea, and disorientation in some users (affecting about 20% of users), which not only reduces the comfort and acceptance of users but also may limit the duration of a single training, thus affecting the continuity and effect of the intervention [2]. Finally, equipment and technical literacy requirements limit the range of users. The operation and maintenance of the system and the understanding of AI interaction (such as inputting an effective memory description) require users or caregivers to have certain technical adaptability. For elderly users or people with low digital literacy, this constitutes an additional use barrier [2]. In addition, many current systems have the problem of "device transparency", that is, due to the compatibility of device specifications or software closeness, it is difficult to migrate and integrate between different platforms

4.2. Clinical and practical aspects

From the perspective of clinical evidence and promotion practice, this field is still at an early stage. The most prominent problem is the lack of large-scale, high-quality randomized controlled trials. Many existing studies (such as many trials reviewed in literature 2) have small sample sizes and methodological limitations, such as inadequate distribution and concealment, and difficulty in implementing blind methods, resulting in low levels of evidence and questionable external validity and universality of conclusions [10]. Secondly, the intervention program lacks standardization. Different studies have huge differences in VR scene design, AI algorithm model, training intensity, frequency, and cycle, which makes it difficult to directly compare and conduct meta-analysis of research results, and hinders the establishment of best practice guidelines [1]. Third, the long-term efficacy and disease modification are unknown. Most studies focus on the effect of cognitive

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improvement in the short term (weeks to months), but there is still a lack of sufficient longitudinal data to support whether AI-VR intervention can maintain cognitive benefits in the long term, and even whether it can delay or change the transformation path of mild cognitive impairment to dementia [10]. Finally, the clinical integration path is vague. How to seamlessly integrate such technologies into the existing health care and rehabilitation service system, how to train therapists to effectively use and interpret system data, and how to determine the expense reimbursement mechanism are all unsolved practical problems [1].

4.3. Ethics and privacy

In terms of ethics and privacy, the medical application of AI-VR technology has raised a series of profound concerns. The fairness of the algorithm bears the brunt. The judgment and generation quality of its model are highly dependent on the training data. If the data are not sufficiently representative, it may produce evaluation bias or intervention effect differences for specific groups [1]. Secondly, the personal memory description, behavior trajectory, and physiological data collected during the operation of the system are extremely sensitive, and their safe storage, compliant use, and leakage prevention are serious challenges that must be overcome, while the relevant regulatory framework is not yet perfect [1,2]. In addition, over-reliance on technology may affect the patient's autonomy and reality connection, and the "memory" generated by AI also touches the ethical boundary of self-narrative authenticity [1]. Finally, for people with cognitive impairment, ensuring the adequacy and effectiveness of the informed consent process is also a complex link that must be carefully designed in practice [1].

5. Conclusion

This study systematically reviewed the existing literature and discussed the effect and value of the fusion technology of artificial intelligence and virtual reality on memory enhancement in patients with cognitive impairment. The integration of artificial intelligence and virtual reality technology is opening up a new path full of possibilities for the field of memory rehabilitation of cognitive impairment. This paper discusses how this technology can simulate daily life scenes by constructing an immersive and interactive environment and realizing the personalized adaptation of training with the help of intelligent algorithms. Existing studies have shown that the combination of individualized cognitive training for mild cognitive impairment and initial application in autobiographical memory recall and life skill simulation shows the potential to improve patient participation and intervention pertinence. However, its development is still in the early stage, facing many practical challenges such as insufficient clinical evidence, high technology cost, and data ethics.

Looking forward to the future, the maturity and popularization of this technology depend on the joint promotion of many aspects. Technically, lighter and cheaper hardware devices and intelligent algorithms that can more naturally understand users' intentions are needed to improve the experience and accessibility. At the scientific research level, it is urgent to design a rigorous, large-scale, long-term study to verify its real efficacy in improving cognitive function and delaying disease progression, and establish a standard application scheme. At the same time, building an ethical framework to protect users' privacy and rights, and exploring its integration path and cost-effectiveness in the existing medical system are the keys to transforming laboratory innovation into truly benefiting patients. Only through the continuous cooperation of technology developers, clinical researchers, ethicists, and policy makers can it overcome the current bottleneck, make the intelligent

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immersive rehabilitation from a cutting-edge perspective to gradually grow into a reliable, accessible and warm daily support means, and effectively improve the quality of life of people with cognitive impairment.

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