Environment-Integrated Adaptive Cognitive Training System Based on Augmented Reality and Intelligence

Yuqi Zhang [1], Chyan Zheng Siow [2], Wenbang Dou[3], Takenori Obo[4] and Kubota Naoyuki[5]

[1] Tokyo Metropolitan University, Department of System Design School ,Tokyo, Japan
(Tel : +81-080-7508-1996; E-mail: zhang-yuqi1@ed.tmu.ac.jp)
[2] Tokyo Metropolitan University, Department of System Design School ,Tokyo, Japan
(E-mail: siow-chyanzheng@ed.tmu.ac.jp)
[3] Tokyo Metropolitan University, Department of System Design School ,Tokyo, Japan
(E-mail: dou-wenbang@ed.tmu.ac.jp)
[4] Tokyo Metropolitan University, Department of System Design School ,Tokyo, Japan
(E-mail: t.obo@tmu.ac.jp)
[5] Tokyo Metropolitan University, Department of System Design School ,Tokyo, Japan
(E-mail: kubota@tmu.ac.jp)

Abstract. As the population ages, it is important to maintain the cognitive health of elderlies, which can reduce the cost of care by millions. Through cognitive training can significantly improve or maintain memory, attention, and problem-solving abilities in the elderly. However, traditional cognitive training (non-digital media) methods face issues of low engagement, insufficient motivation, limited accessibility, and scalability. To address these challenges, researchers have developed serious games as a solution. However, current serious games lack personalization and are out of touch with the user environment. Therefore, this paper introduces an adaptive, personalized augmented reality escape game system for cognitive training that addresses these issues. First, we employ a Q&A system to obtains the estimation of the cognitive abilities for the user. Next, we request user to take photo of his current environment. Based on the cognitive abilities and environment, we employ fuzzy system to determine the suitable game programs for the user. Empirical experiments conducted with individuals in their twenties demonstrate that this system can customize cognitive tasks, adapt to the environment, and maintain high user engagement and positive feedback.

Keywords: Adaptive Cognitive training, Applications of Artificial Intelligence, Human-Computer Interaction, Augmented Reality

1 Introduction

1.1 Background

According to Wortmann's findings in the 2012 World Health Alzheimer's Report, dementia, encompassing a variety of conditions, including memory loss and decreased problem-solving skills, is predominantly caused by brain function impairments[1]. This condition is rapidly growing in prevalence globally. The report predicts a surge in dementia cases, estimating that numbers will escalate from 35.6 million currently to 66 million by 2030 and further to 115 million by 2050[2]. The incidence and prevalence of Alzheimer's disease and other dementias increased by 147.95 and 160.84%, respectively, from 1990 to 2019[3]. This increase is attributed to the aging population worldwide. The impact of dementia extends beyond the health of individuals; it poses significant economic and psychological burdens. Caregivers, often family members, face considerable stress, and many countries still lack adequate awareness and support systems for this growing issue[4].

Studies have shown that appropriate cognitive training can effectively slow the deterioration of cognitive abilities, especially in the elderly. Research on the effectiveness of cognitive training in older adults presents mixed findings. Ballesteros (2018) and Bonnechère (2020) both found that certain types of cognitive training, such as video game interventions and commercially available computerized cognitive games, can improve cognitive function in older adults[5][6][7].

1.2 Related Work

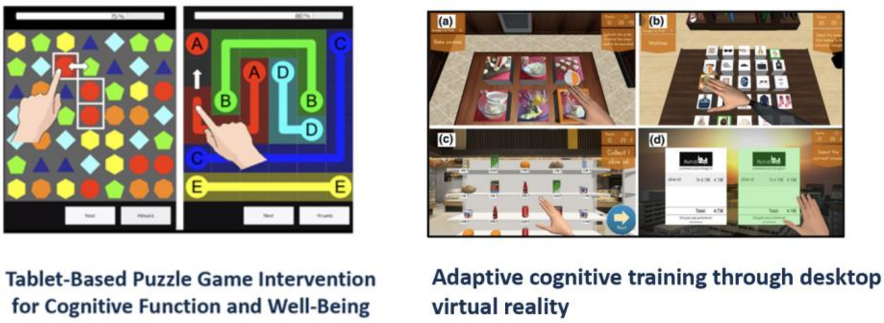

Fig. 1. Serious Games For Cognitive Training.

Serious Games represent an innovative blend of educational and recreational approaches, particularly suited to addressing the challenges faced by traditional cognitive training methods in maintaining participant engagement and ensuring widespread accessibility (see Fig. 1). These games stand out by integrating educational content with engaging gaming mechanics, such as challenges and reward systems, offering a stark contrast to traditional methods. This integration not only enhances the learning experience but also promotes long-term user participation through enjoyable and competitive elements [8][9]. The immediate feedback provided by these games is crucial for users to monitor their progress and foster a sense of achievement, thereby maintaining sustained interest.

Although cognitive training serious games has been proven effective in addressing Cognitive Decline, Rehabilitation, and Mental Health, it faces several problems:

limitations of assessment tools. Assessment tools that necessitate in-person interaction and professional oversight often face limitations. These tools typically rely on fixed content, which can hinder their ability to effectively monitor changes in an individual's cognitive abilities over time. This rigidity restricts adaptability, making it challenging to accommodate evolving needs or to tailor assessments to suit varying cognitive profiles. Moreover, the reliance on professional administration may introduce delays and logistical constraints, impacting the timely evaluation and intervention needed for cognitive development [10] [11].

Lack of Real-World Application (Ecological validity). Another significant challenge lies in the ecological validity of cognitive training programs, affecting their real-world application. Often, these programs fail to integrate cognitive exercises seamlessly into everyday environments, limiting their effectiveness in practical scenarios. This gap between training content and real-life contexts diminishes the transferability of learned skills, undermining the potential benefits of cognitive training in enhancing functional abilities necessary for daily living. Addressing these limitations requires innovative approaches that bridge the gap between training exercises and real-world challenges, ensuring that cognitive improvements translate effectively into meaningful outcomes [12] [13].

2 Method

2.1 System Architecture.

In response to these challenges, this study propose an Adaptive Cognitive Training program that allows for automatic assessment and integrates real-world environments with training content to enhance ecological validity. The core of this research references the adaptive Cognitive Training Framework. The advantage of these cognitive training tasks, which are based on cognitive tests, lies in their ability to target, and effectively improve an individual's specific cognitive abilities, as they are based on specific assessments (see Fig. 2).

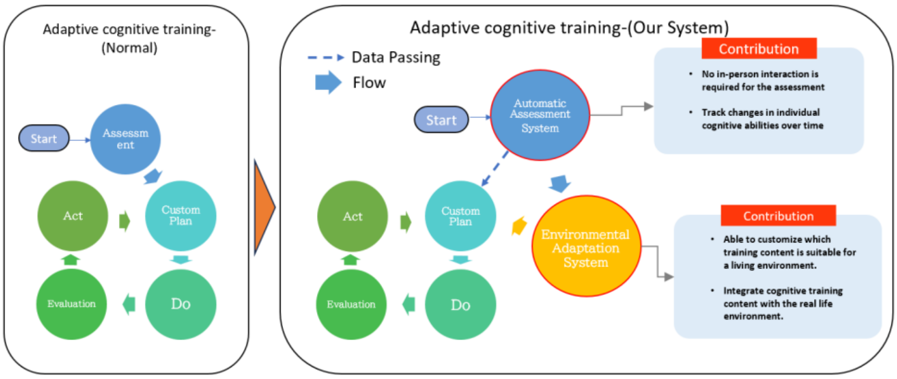

Fig. 2. Adaptive Cognitive Training Framework (Left-Tradition, Right-Our System).

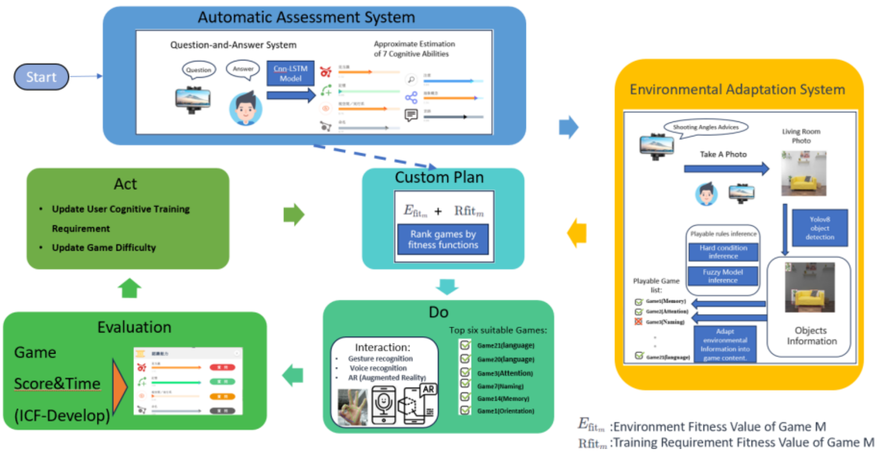

Fig. 3. System Architecture.

Following this approach, the overall flowchart of the system is designed as shown in see (Fig. 3). The system structure is broadly divided into three main modules. The first module is the Question-and-Answer System, which functions to conduct initial assessments and provide personalized customization according to the user's training needs. The second module is the Environmental Adaptation System, which identifies objects in a room, analyzes which games can be selected for play, and adapts the information about the room's items into the game content. The third module is the Escape Game System, which performs training and records, performance evaluations, and feedback and adjustments.

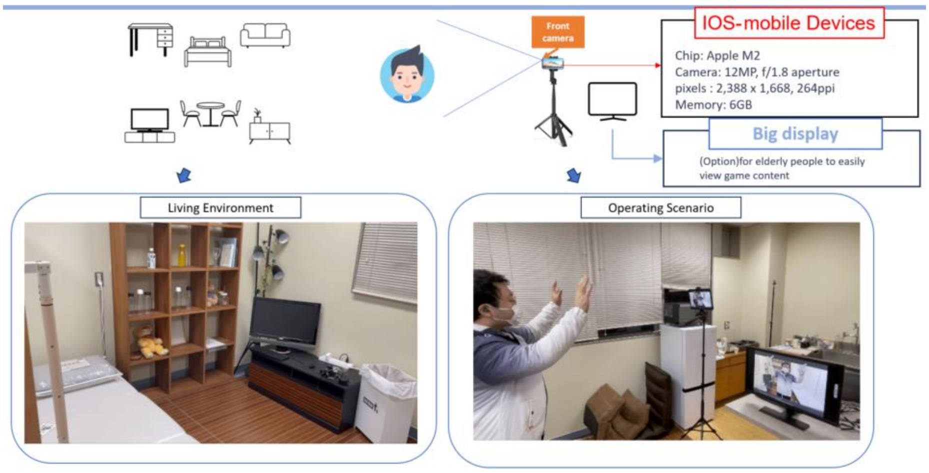

Fig. 4. Real Machine Operation Example

The system's real machine operation is shown in (see Fig 4). It runs on the iOS platform and only requires an iOS Mobile Device equipped with a front-facing camera and microphone. However, for the convenience of playing, a tripod is needed to stabilize the Mobile Device.

2.2 Escape Game Design

Continuous player engagement is essential, especially in health game programs that depend on voluntary participation [14]. Effective and sustainable programs require ongoing player involvement, achieved through iterative cycles of goal setting, planning, action, and outcome evaluation, enhanced by timely feedback. Engaging players in thinking, feeling, and acting is vital for integration into the game's dynamics. The game's design motivates elderly players through cognitive tasks to unlock treasure chests containing gem fragments, leading to the assembly of a gem for a virtual key to escape the room, thus boosting user motivation in the escape game (see Fig 5).

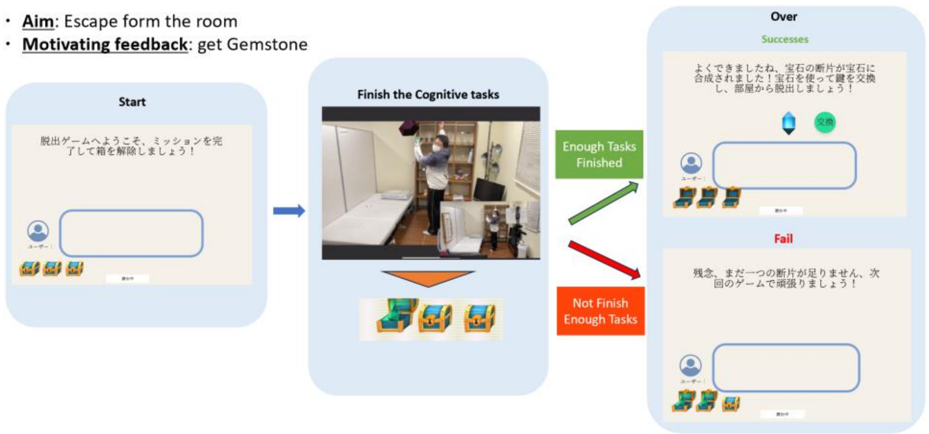

Fig. 5. Escape game Flowchart

The MoCA cognitive test categorizes cognitive abilities into seven areas: orientation, memory, visual-spatial abilities, naming, attention, abstract concepts, and language [15]. Based on these, 21 cognitive test-based games have been developed for an elderly-focused 'escape game'. In this game, elderly users play in a living room setting, blending cognitive challenges with physical activity. The game features augmented reality (AR) objects that unlock as players progress, offering visual feedback and stimulating interest through task completion. This design aims to actively engage elderly players in cognitive training, thereby improving their cognitive skills and quality of life (see Fig.6).

Fig. 6. Cognitive task for visual-spatial, Users move AR object according to task content.

2.3 Question-and-Answer Assessment System

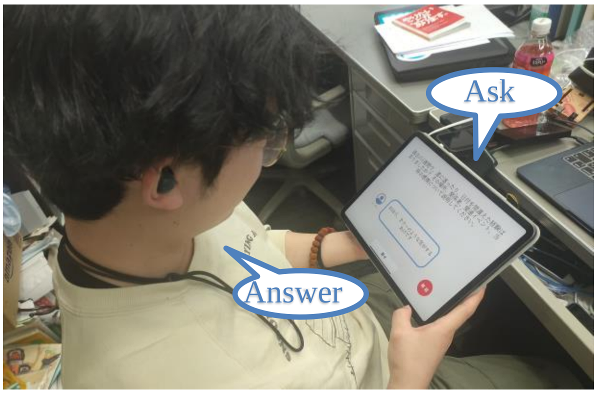

Fig. 7. Working Environment of the Question-and-Answer Evaluation System

This system evaluates elderly cognitive abilities in seven areas: Orientation, Memory, Visual-Spatial Abilities, Naming, Attention, Abstract Concept Understanding, and Language, through a question-and-answer format. It's designed for initial estimations, not precise measurements, to identify potential cognitive issues for planning training and interventions. The core involves an assessment model processing participants' response, generating values reflecting their performance in each cognitive domain (see Fig 7).

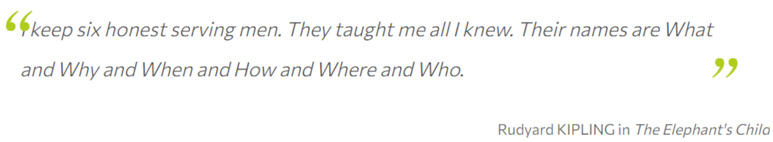

Fig. 8. Kipling Method

To facilitate critical and constructive analysis, we use open-ended questions, following the 5W1H (Kipling Method) approach, to gather comprehensive data. This method involves asking What, Who, Where, When, Why, and How, to understand the user's situation in detail and identify the true nature of the problem (see Fig 8). This approach helps in precisely defining problems and discerning the relationship between questions and answers, enhancing our understanding of the user's current situation.

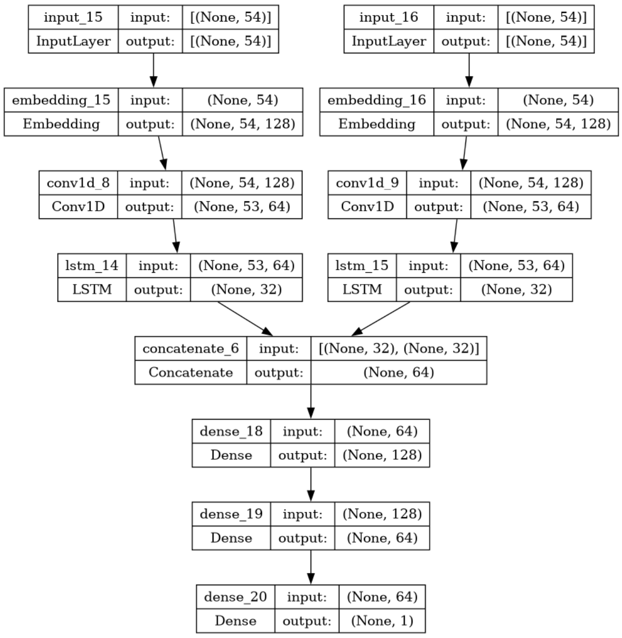

Fig. 9. Question-and-Answer Model architecture

We propose a neural network model tailored for evaluating answers in a cognitive ability assessment. This involves preprocessing Japanese text into tensors using Word2Vec, which turns words into vector forms capturing their semantic relationships. The model combines CNN (Convolutional Neural Network) for recognizing local text patterns with LSTM (Long Short-Term Memory) for understanding long-term dependencies (see Fig 9). This structure efficiently processes complex and structured dialogues, like those in the 5W1H format. The final output, ranging from 0 to 1, indicates cognitive ability, with values below 0.6 suggesting potential issues. The model's architecture effectively correlates questions and answers to assess cognitive abilities.

2.4 Environmental Adaptation System

The system comprises an object recognition system and a conditional judgment system for cognitive training tasks.

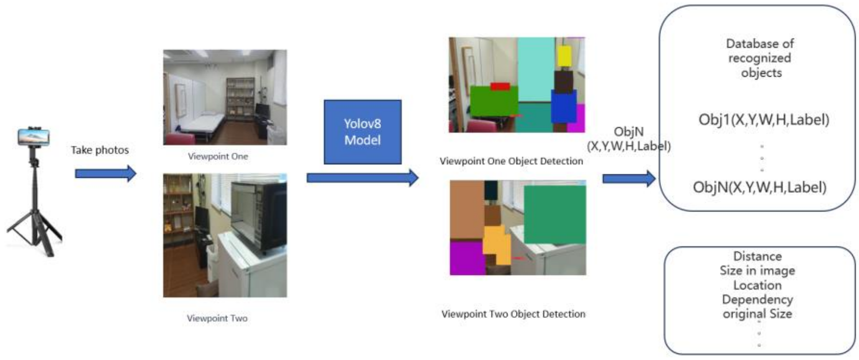

Fig. 10. Yolov8 Object Detection Model Training process.

Initially, the object recognition part, using YOLOv8, identifies items and gathers room information from photos taken by users following specific shooting angle advice. This data informs the conditional judgment system, which defines tasks based on rigid criteria and fuzzy conditions, aided by a genetic algorithm and a defuzzification process using a suitability algorithm. This results in a prioritized list of suitable cognitive training tasks for the specific scene (see Fig 10). YOLOv8's high accuracy in object detection was confirmed by training on 400 living room images, achieving 98% accuracy. However, for new scenes, additional photographing and annotation of objects are required for accurate recognition.

Table 1. Some examples of game content.

Game Number	Hard Condition	Fuzzy Condition	Game Content
1	if (None).	if (None).	(Orientation) "What is today's date?"
2		if (None).	(Orientation) "What is the current space?"
…	…	…	…
5	if (more than 2 objects detected).	if (two objects' original size is high). 2. if (taller detected object is high) 3. if (taller object is mid, object's size in image should be low).	(Visual-Spatial) "Move an AR object from below … to above …"
…	…	…	…
21	if (object "floor" detected).	1. if (floor object's size in image is mid or high). 2. if (center x of floor is mid). 3. if (center y of floor is low).	(Language) "Please make the corresponding gesture based on the read number."

Fuzzy rules based on fuzzy reasoning determine whether a game is suitable for a specific scenario. Depending on the game's requirements, a game may contain multiple such rules (Table 1).

Generally, using simplified fuzzy reasoning, these fuzzy IF-THEN rules can be described as follows：

$$\textbf{IF } x_1 \text{ is } A_{i1} \text{ and ... and } x_j \text{ is } A_{ij}$$
$$\textbf{THEN} \text{ game } m \text{ is playable.}$$

In this context, "m" represents the m-th game in the list of candidate games. "I" refers to the category of the membership function, such as low, medium, or high. Meanwhile, "j" denotes the j-th rule among all the rules in the m-th game. The simplified fuzzy inference is described based on these definitions. The simplified fuzzy inference is defined by：

$$\mu_{Ai,j}(x_j) = exp\left(-\frac{\left(x_j - \alpha_{i,j}\right)^2}{\beta_{i,j}^2}\right) \tag{1}$$

Where$\alpha i, j$ and $\beta i, j$ are the central value and the width of the membership function Ai, j . Through fuzzy rules, we match the rules in the prepared game library.

2.5 Fitness Function

This part using an Environmental Fitness Function (Efit) and a Training requirement Fitness Function (Rfit) to select the most suitable games for users.

Uses a defuzzification process and the suitability equation Efitm" stands for environmental suitability,The expression $A \setminus \{\mu Aij(xj)\}$ denotes the sum of the values of all membership functions other than μAij. The value of Efit ranges from 0 to 1.0. When Efit approaches 0, it indicates that the membership function is initially determined to be in that category, typically at the intersection point of two membership functions. When Efimt approaches 1, it signifies the maximum judgment point of the membership function, which is the center of the membership function (Equation 2).

$$\begin{cases} E_{fitm} = \frac{1}{n}\sum_{j=1}^{n}\left(\exp\left(-\frac{(x_j-\alpha_{ij})^2}{\beta_{ij}^2}\right) - A\setminus\{\mu_{Aij}(x_j)\}\right) \\ E_{fitm} \approx 1, \text{ if } (X_{ij} < \alpha_{ij\text{-low}} \text{ or } X_{ij} > \alpha_{ij\text{-high}}) \end{cases} \tag{2}$$

However, when a user's cognitive ability value falls below 0.8, the system focuses on increasing the weight of Rfitm in game 'm'. A Tanh function is used here， Equations (3.4), taking (1-Ck) as its input. When the input value is close to 0, the function's value also approaches 0. Conversely, when the value of (1-Ck) is near 0.2, the function's value rapidly rises to close to 2. The value of the expression[1+tanh(10×((1−Ck)−0.2))] ranges from 0 to 2. The factor 10 is used to accelerate the speed at which the function approaches 2 when it is close to 0.2(Equation 3).

$$R_{fitm}(1-C_k) = (1-C_k) + [1 + \tanh(10 \times ((1-C_k) - 0.2))]$$

$$R_{fitm}(1-C_k) = (1-C_k) + \left[1 + \frac{e^{10\times((1-C_k)-0.2)} - e^{-10\times((1-C_k)-0.2)}}{e^{10\times((1-C_k)-0.2)} + e^{-10\times((1-C_k)-0.2)}}\right] \tag{3}$$

For the game m, the play priority is primarily influenced by Efitm and(1-Ck). when the user's training demand (1-Ck) is less than 0.2. When it exceeds 0.2, according to formula 3.5, the play priority is predominantly affected by Rfitm. The final fitness function Ffitm is the sum of Efitm and Rfitm, (Equation 4). Through this equation, and after passing through the first two modules of the game, the most suitable game play priority ranking can ultimately be generated.

$$F_{fitm} = E_{fitm} + R_{fitm} \tag{4}$$

2.6 Interactive System Design.

Although all elements of the gaming system contribute to defining players' willingness to play, excellent game activities and core mechanics are crucial for initiating and maintaining player engagement [16]. This article introduces four main interactive technologies and will elaborate on these technological elements and their implementation methods in this chapter.

Voice recognition & Generation System. The system incorporates 'Undertone,' an offline voice recognition tool for Unity applications, offering robust capabilities for voice control and interaction in games and VR/AR environments. It allows custom voice commands and operates well in internet-limited settings. Speech recognition accuracy is set at 95% for keyword utterances and 80% for paraphrased text. Additionally, the system uses Google's Text-to-Speech (TTS) technology for natural voice output, creating an advanced and interactive user experience by combining 'Undertone' with TTS.

Gesture recognition System. The system uses MediaPipe's hand skeleton recognition to detect 17 points on the hand, training a model on ten numeric hand gestures with 99% accuracy. Users can convey numeric answers from 0 to 99 through hand gestures, recognized and interpreted by the system. Successful gestures are displayed on-screen using Augmented Reality (AR) numeric models, enhancing interaction and usability, particularly in educational settings. This integration of AR and gesture recognition creates an engaging, effective learning environment and fosters interactive digital content control.

AR Interaction System. The AR Interaction module combines hand gesture and object recognition to inter-act with models in the Unity environment. Users manipulate Unity models through hand movements, tracked and translated into model movements. This intuitive interaction enhances user engagement by allowing direct interaction with digital elements as though they were tangible. The system enhances interaction by using object recognition to accurately position Unity models on the screen. Users can place real-world objects, which the system identifies to align digital models correspondingly in the Unity environment. This feature is vital for applications requiring precise spatial placement of digital elements.

These features combine to offer a highly interactive AR experience, transforming users from passive viewers to active participants. They control and manipulate digital content, mirroring real-world interactions, which is particularly beneficial in educational, training, or gaming applications. The blend of hand gesture and object recognition bridges the physical and digital worlds, fostering creativity and practicality in AR applications.

3 Experiments

3.1 Question-and-Answer System Empirical Experiment

Experiment outline. The objective of this experiment is to evaluate whether the model can make reasonable predictions in response to users' answers within a real-world question-and-answer scenario. The experiment will involve eight volunteers, all in their twenties. Prior to the experiment, participants will be briefed about the 5W1H (Who, What, When, Where, why, How) conversational structure of the dialogue system. They will be asked to describe, following this format, any cognitive conditions or relevant experiences they encountered during the past week. Then, we will analyze the responses of the volunteers and obtain an expected prediction through Experience Judgment. Finally, we will compare this with the prediction of the question-and-answer model.

The ratings in this context employ the International Classification of Functioning, Disability and Health (ICF)'s 5-stage rating methodology as outlined in Chapter 2. They categorize the cognitive ability of game m, specifically the value of the k-th cognitive ability Ck (obtained from the question-and-answer initial assessment), into five levels ranging from 0 to 4. The distribution of these levels is illustrated in (see Table-2).

Table 2. The predicted value of User answers.

Evaluation level	Cognitive Ability Value Distribution	Evaluation Description
0	(0.8 , 1.0]	No problem
1	(0.6 , 0.8]	Mild problem
2	(0.4 , 0.6]	Moderate problem
3	(0.2 , 0.4]	Severe problem
4	[0.0 , 0.2)	Complete problem

Experiment result.

Table 3. The correct value of User answers.

	orientation,	memory	visuospatial	naming,	attention,	attention,	abstract	language
Subject1	0	0	0	0	0	0	0	0
Subject2	0	0	1	0	1	0	0	0

Subject3	0	0	0	0	0	0	0	2
Subject4	0	0	0	0	0	0	0	0
Subject5	0	0	3	0	0	0	0	1
Subject6	0	0	0	0	0	0	0	0
Subject7	1	0	0	0	0	0	0	0
Subject8	0	0	0	0	0	0	0	3

Table 4. System predicted values.

	orientation,	memory	visuospatial	naming,	attention,	attention,	abstract	language
Subject1	0	0	4	0	0	0	0	0
Subject2	0	0	1	0	2	0	0	0
Subject3	0	0	0	0	0	0	0	4
Subject4	0	0	0	0	0	0	0	0
Subject5	0	0	3	0	0	0	0	2
Subject6	0	0	0	0	0	0	0	0
Subject7	0	0	0	0	0	0	0	1
Subject8	0	0	0	0	0	0	0	3

In the results, a total of 56 predictions were made, among which 52 were consistent. Two predictions were completely incorrect, marked in red in the table. There were two near-accurate predictions, marked in yellow (see Table-3,4). These errors in voice recognition caused a discrepancy between the input and the original intention of the user, leading to inaccurate recognition results.

The two near-accurate predictions were also considered within the acceptable range for system processing. Overall, we believe that this system can predict users' general cognitive abilities and identify potential issues in real-world conversational environments.

3.2 Cognitive Training Effectiveness Empirical Experiment

Experiment outline. The goal of this experiment is to validate the effectiveness of cognitive game training. The experiment involves 8 volunteers, for whom the most needed cognitive training content is determined through a series of steps and prioritized accordingly. The entire experiment consists of 6 different cognitive games, forming an escape game, with the first two games set as the highest priority to play. Volunteers will first play the game with the highest priority, and record and evaluate it. Then, they will play the remaining games in order according to the ranking. After completing these six games, volunteers will play the games again. To reduce the impact of training with the same content repeatedly on the evaluation, some changes will be made to the content in the second tour games. The performance in each game is scored according to the International Classification of Functioning, Disability and Health (ICF) standards, ranging from 0 to 4, across five levels. After the volunteers complete these 6 games (First Tour), the system regenerates the initial game, but with altered content (Second Tour). This design aims to train and assess the cognitive abilities of volunteers through a continuous gaming process and changes in the content, thereby evaluating the effectiveness of cognitive game training.

Experiment result.

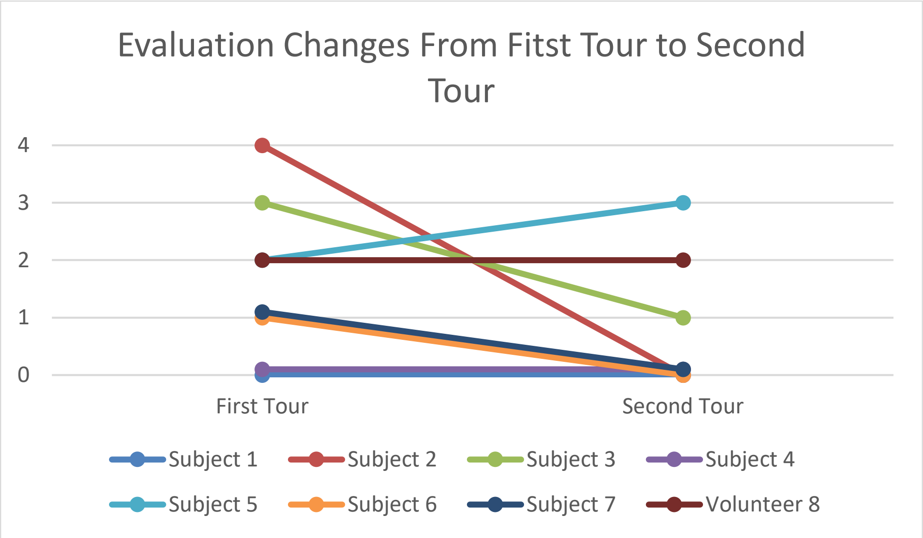

Fig. 11. Cognitive ability Evaluation Changes from First Tour to Second Tour

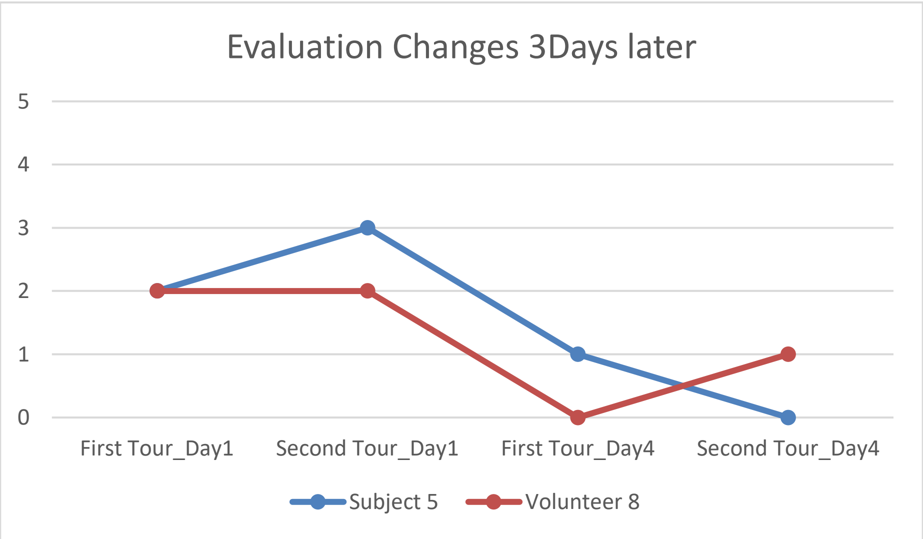

Fig. 12. Cognitive ability Evaluation Changes From First Tour_Day1 to Second Tour_Day4

Based on the results, we found that most volunteers showed an improvement in cognitive ability assessment after their second training session, likely due to initial unfamiliarity with the cognitive testing games causing delays. However, some volunteers, specifically Subject 5 and Subject 8, did not show any improvement(see Fig.11). To further validate, we had Subject 5 and Subject 8 undergo another game content test three days later (during which we required them to perform at least two adaptive cognitive training sessions per day) with similar but slightly altered content. The results, as shown in (see Fig. 12), generally indicated a downward trend. In conclusion, we believe that our cognitive training system can enhance cognitive abilities in the short term.

4 Conclusion & Future work

4.1 Summary

This study addresses two major challenges in serious games for cognitive training: the disconnect between training content and real-world environments (Real-World Application) and the lack of automatic adaptation to individual cognitive abilities (Personalization). The research team developed an innovative system based on a structured cognitive training framework derived from assessments, effectively enhancing specific cognitive abilities. The system consists of three modules: the Question-and-Answer System for initial assessment and customization, the Environmental Adaptation System to integrate real-world objects into game content, and the Escape Game System for training and feedback. Operating on iOS devices, experimental validation confirmed its effectiveness in personalization and real-world application, enhancing cognitive abilities in the short term.

4.2 Future Work

In future work, we will focus on addressing the varying needs of different age groups in cognitive training games. While the current system targets the elderly, feedback suggests it may not fully engage younger users in their 20s. This highlights the need to diversify game content for broader appeal. Personalization features for different age groups will be integrated to enhance effectiveness.

Additionally, research will explore the duration of cognitive training, as preliminary results suggest longer training may yield significant improvements. We will investigate extended sessions to understand the long-term impacts on various age groups.

Improving interaction methods, especially in voice recognition and UI design, is also crucial. Users reported negative experiences, necessitating optimization. Future iterations will enhance voice recognition accuracy and refine the UI for a more user-friendly experience. Overall, our aim is to create a more inclusive, personalized, and engaging cognitive training platform.

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