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Immersive Virtual Reality Cognitive Training for Older Adults with Mild Cognitive Impairment: Interactive Media Design and Pilot Evaluation of a Spatial Memory Serious Game

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ABSTRACT: Mild cognitive impairment (MCI) is a transitional stage between normal aging and dementia in which memory decline, attentional reduction, and difficulty with complex daily tasks may appear before severe functional impairment. Traditional cognitive training methods, such as paper-and-pencil tasks and two-dimensional computerized exercises, are useful but often lack ecological context, bodily interaction, and sustained engagement for older adults.
This study proposes and pilots an immersive virtual reality (VR) serious game for MCI-oriented spatial memory training. The system was developed around a familiar household scene in which older users observe a virtual room, interactively place furniture, save layouts, and then complete an off-device recall task. The research integrates cognitive reserve theory, spatial memory training, VR interaction design, and human-centered media design principles.
A pilot evaluation with five older participants or cognitive-risk users was conducted using MMSE screening, VR task performance, researcher observation, and post-experience interviews. Results showed an average MMSE score of 25.6 (SD = 1.14), mean item recall accuracy of 80.0% (SD = 8.94), mean spatial recall accuracy of 57.8% (SD = 8.75), and mean recall time of 86.8 seconds (SD = 11.3). Observation and interview results indicated positive engagement, low perceived pressure, and good acceptance of the game-like interaction.
The findings suggest that household-based immersive VR can provide a feasible and acceptable interactive media approach for spatial memory stimulation in older adults with MCI risk. Although the sample size was limited and clinical efficacy cannot be inferred, the prototype demonstrates how everyday spatial memory tasks can be translated into an embodied, recordable, and repeatable VR training paradigm.

KEYWORDS: Mild Cognitive Impairment, Virtual Reality, Serious Game, Spatial Memory, Interactive Media Design, Older Adults, Cognitive Training.

1. INTRODUCTION

Population aging has intensified the need for early, acceptable, and repeatable cognitive intervention methods for older adults. Mild cognitive impairment (MCI) is commonly understood as a condition in which cognitive performance declines beyond normal aging while daily living functions are largely preserved. Petersen et al. (1999) described MCI as a clinically important stage because it may precede Alzheimer-type dementia, and later work reported that some MCI populations convert to dementia at substantially higher annual rates than cognitively normal older adults (Petersen, 2000). As a result, MCI has become a major target for non-pharmacological interventions that aim to maintain memory, attention, executive function, and independence before irreversible functional decline occurs.

Cognitive training has been widely applied to older adults through paper-and-pencil exercises, computerized cognitive training, group activities, and rehabilitation-oriented daily tasks. These methods can improve specific cognitive outcomes, particularly memory strategy use and task-based performance (Sisco et al., 2013; Belleville et al., 2018). However, many conventional interventions remain abstract, repetitive, and weakly connected to everyday life. A figure-copying task, a digital maze, or a word-list exercise may measure cognitive ability efficiently, but it does not always reproduce the spatial, social, and emotional conditions under which older adults actually use memory in their homes.

Virtual reality provides an opportunity to redesign cognitive training as an embodied and situated media experience. The three classic characteristics of VR - immersion, interaction, and imagination - suggest that users can perceive, manipulate, and reconstruct virtual scenes as if they were meaningful environments rather than flat test interfaces (Burdea & Coiffet, 2003). In the context of older adult cognitive training, this means that a virtual household can transform abstract visual memory tasks into daily-life scenarios, such as remembering where furniture is placed, navigating a room, or organizing objects in relation to other objects.

The present study develops an immersive VR serious game for spatial memory training in older adults with MCI or cognitive-risk characteristics. The project is positioned as an interactive media design study rather than as a clinical treatment trial. It uses a familiar home scene, furniture-object interaction, memory reconstruction, and postexperience verbal recall to explore whether VR can improve engagement and provide measurable behavioral data. The prototype was developed with a Meta Quest headset platform and Unity-based XR interaction architecture. The training task follows a cycle of observing a room arrangement, placing furniture in VR, removing the headset, and recalling both objects and spatial positions.

The contribution of this study is threefold. First, it translates traditional visual-spatial memory training into an immersive household task that may be more familiar to older adults. Second, it proposes a design framework that combines cognitive training goals, interaction simplicity, fatigue awareness, and automatic behavioral logging. Third, it reports pilot data from five older users, including MMSE screening, recall accuracy, spatial recall accuracy, recall time, researcher observation, and post-experience interviews. The study therefore provides a foundation for future multi-scene, multi-modal, and longitudinal VR cognitive training research.

2. LITERATURE REVIEW

2.1 Mild Cognitive Impairment, Spatial Memory, and Daily-Life Function

MCI is generally regarded as an intermediate stage between normal cognitive aging and dementia. Individuals with MCI may show memory decline, attention difficulties, and reduced performance in complex instrumental activities, while basic daily activities remain largely preserved. The Mini-Mental State Examination (MMSE) is frequently used for global cognitive screening (Folstein et al., 1975), while the Montreal Cognitive Assessment (MoCA) was designed to improve sensitivity for MCI detection (Nasreddine et al., 2005). In applied design research, such measures help identify whether a proposed system should be designed for cognitive-risk users, MCI users, or users with more advanced impairment.

Spatial memory is especially relevant for older adults because it connects directly with daily behaviors such as locating objects, remembering room layouts, shopping, route planning, and managing domestic routines. Traditional visual memory assessments, including complex figure copying and recall, evaluate visual construction, non-verbal memory, attention, planning, and spatial organization. However, these assessments often occur on paper and may feel test-like. For older users who are anxious about cognitive decline, ecological and low-pressure training scenarios may be more acceptable than abstract tasks.

2.2 Cognitive Reserve and Non-Pharmacological Cognitive Training

Cognitive reserve theory suggests that learning, social participation, and sustained cognitive activity may help individuals cope with age-related or pathological brain changes (Stern, 2002). From this perspective, cognitive training is not only a set of exercises but also a structured way of maintaining active engagement. Programs that train memory strategies, attention, processing speed, or executive function can produce measurable improvements, although their transfer to everyday functioning and long-term maintenance remains inconsistent (Belleville et al., 2018; Zhang et al., 2019).

The project documentation reviewed for this study identified several common intervention types: paper-and-pencil training, computerized cognitive training, group cognitive intervention, and activity-based cognitive stimulation. Paper tasks are easy to administer but may feel monotonous and disconnected from daily life. Computerized cognitive training increases repeatability and data capture but is usually limited by two-dimensional display and mouse or touch interaction. Group-based activities provide social opportunity but may lack individualization. Activity-based training, such as cooking, singing, drawing, or craft tasks, is more familiar but often lacks precise behavioral data. These limitations motivate the development of immersive, ecological, and trackable systems.

2.3 Virtual Reality Serious Games for Cognitive Rehabilitation

VR has been increasingly explored in older adult rehabilitation because it can combine perceptual immersion, interactive manipulation, and controlled repetition. Liao et al. (2020) reported that VR-based training may improve cognitive function and daily-life-related abilities among older adults with MCI. A recent systematic review and metaanalysis of randomized controlled trials found that VR interventions for older adults with MCI showed improvements in memory, attention and information processing speed, and executive function, although the quality of evidence varied and further rigorous studies were recommended (Yang et al., 2025).

For media design, the value of VR lies not only in outcome scores but also in the way cognitive tasks are represented. A serious game can make training more meaningful by embedding the task in a believable scene, giving users immediate feedback, and allowing the system to record interaction behavior. In the present project, the household scene was deliberately simplified to reduce visual distraction, while still preserving enough realism to support spatial association. This design choice reflects a balance between ecological validity and cognitive load control.

2.4 Older-Adult Interaction Design and Research Gap

Older-adult VR systems require special attention to readability, fatigue, dizziness, controller learning, and task pacing. A cognitively meaningful environment can become ineffective if the user interface is confusing or if the interaction sequence produces anxiety. Therefore, the prototype emphasizes large visual elements, clear furniture icons, limited scene interference, short adaptation, simple grabbing and placing operations, and an option to reset or save layouts. These choices are aligned with the project objective of making the experience feel like a manageable game rather than an examination.

Existing VR cognitive training studies often evaluate clinical indicators but provide less detail about media design logic, task ecology, and the transformation of traditional memory assessment into a daily-life scenario. There is also a need for pilot studies that combine quantitative task data with qualitative observation and participant feedback. The current study addresses this gap by designing a household spatial memory serious game and evaluating it through recall performance, observation, and post-experience interviews.

3. MATERIALS AND METHODS

3.1 Research Design

This study adopted a design-based pilot evaluation approach. The purpose was not to establish clinical efficacy, but to construct a working immersive VR cognitive training prototype and examine its feasibility, acceptability, and preliminary task performance with older users. The research questions were: (1) How can a traditional spatial memory task be transformed into an immersive, daily-life VR interaction? (2) Can older users complete the observeplace-recall loop with acceptable engagement and comfort? (3) What preliminary performance patterns are observable in item recall, spatial recall, and recall time?

The overall design follows a mixed evidence logic. System design evidence was collected through prototype construction and task workflow refinement. Quantitative evidence was collected through MMSE scores and VR recall task data. Qualitative evidence was collected through researcher observation and post-experience interviews. The combination of these data sources was intended to support a balanced interpretation of cognitive training feasibility from an interactive media perspective.

3.2 Participants and Screening

Five older participants or cognitive-risk users were recruited for the pilot implementation. The target population was defined as adults aged approximately 60 to 75 years who could safely wear a VR headset and follow basic task instructions. The screening logic included basic demographic questions, self-reported memory difficulty, vision and hearing status, household support, and the MMSE. The project documentation reported that a representative participant obtained a total MMSE score of 25 out of 30, interpreted as mild cognitive impairment or borderline mild impairment. Across the five pilot participants, the mean MMSE score was 25.6 with a standard deviation of 1.14.

Participants were required to have corrected vision and hearing sufficient for the task, basic mobility for seated or standing VR use, and no severe dizziness, epilepsy risk, or other conditions that would make VR unsafe. Users with likely moderate-to-severe cognitive impairment were not targeted in the current prototype because the interaction sequence required comprehension of observation, placement, and recall instructions.

Table 1: Participant Screening and Experimental Context

Variable	Value
Target user group	Older adults with MCI or cognitive-risk characteristics
Pilot sample	Five participants
Age range guideline	60-75 years
Screening measure	MMSE and basic information interview
Representative case	MMSE = 25 / 30, interpreted as mild cognitive impairment or borderline mild impairment
VR device platform	Meta Quest headset platform
Development environment	Unity-based XR interaction system
Training scenario	Household spatial memory and furniture placement task

3.3 Ethical Considerations

The pilot implementation followed basic human-subjects protection principles for design research with older adults. Participants received an explanation of the experiment before participation, and informed consent was obtained. Privacy and data security were considered during recording and reporting; participant identities are not disclosed in this manuscript. Because older adults and users with cognitive risk can be considered a vulnerable group, the experiment emphasized risk-benefit balance, short task duration, and the right to stop at any time. Researchers monitored signs of fatigue, dizziness, anxiety, or discomfort during the VR session.

3.4 System Design and Development Environment

The VR serious game was developed as a household spatial memory training environment. The virtual room provides a familiar domestic context, including walls, floor, door, lighting, and furniture objects. The scene was optimized to reduce distraction: unnecessary decorative elements were minimized, furniture shapes were made legible, and visual materials were kept clear without excessive brightness. The intention was to make the spatial relationships between furniture and room boundaries easy to perceive while maintaining an immersive sense of place.

The interaction architecture included headset-based viewing, controller-based object selection, grabbing, moving, rotation, placement, layout saving, layout reading, room reset, and application exit. The interface allowed users to select furniture such as a table, sofa, chair, microwave oven, tea table, refrigerator, cabinet, bed, box, plant, and bookshelf. The system was designed to record item placement, completion time, and recall-related performance so that future versions can support longitudinal tracking.

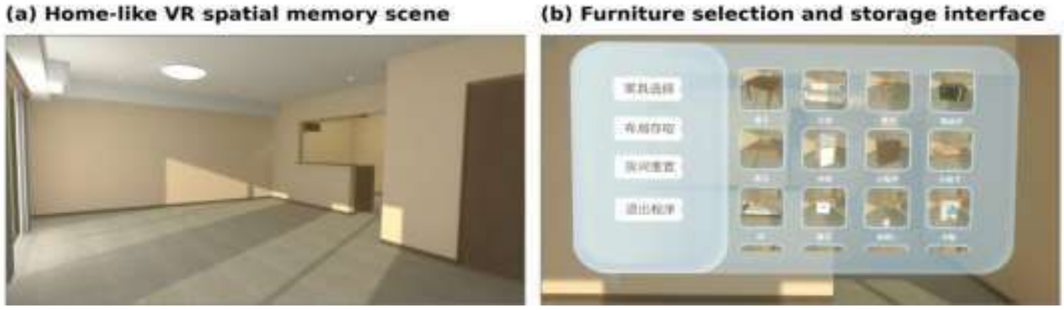

Figure 1: VR Home-Scene Prototype and Furniture Interaction Interface

Table 2: Prototype Design Goals and Interaction Principles

Design Dimension	Operational Meaning in the Prototype
Cognitive training goal	Stimulate spatial memory, visual memory, attention, and recall organization through a household layout task
Experience goal	Make training feel game-like, familiar, and low-pressure rather than examlike
Interaction principle	Use direct object manipulation: grab, move, rotate, place, save, read, and reset
Readability principle	Use clear object forms, large interface elements, simple room structure, and limited scene distractions
Fatigue and safety	Provide short adaptation, dizziness warnings, researcher monitoring, and the option to pause or stop
Data collection	Record accuracy, spatial position descriptions, recall time, task completion, and observation notes

3.5 Gameplay Workflow and Task Procedure

The task cycle was designed as a simplified daily-life memory challenge. First, the participant received instructions and completed a short adaptation period. Second, the participant observed the virtual room and target furniture arrangement. Third, the participant interacted with furniture objects in VR, placing them in the room according to the task prompt or memory. Fourth, the participant removed the headset and verbally recalled what furniture items were shown and where they were located. Finally, researchers recorded recall accuracy, spatial accuracy, time, observation notes, and post-experience feedback.

The off-device recall phase is important because it prevents the task from becoming only a virtual manipulation exercise. By requiring participants to describe items and positions after removing the headset, the system connects immersive perception with memory retrieval. The design therefore adapts the logic of traditional visual recall tests into a more ecological household scenario.

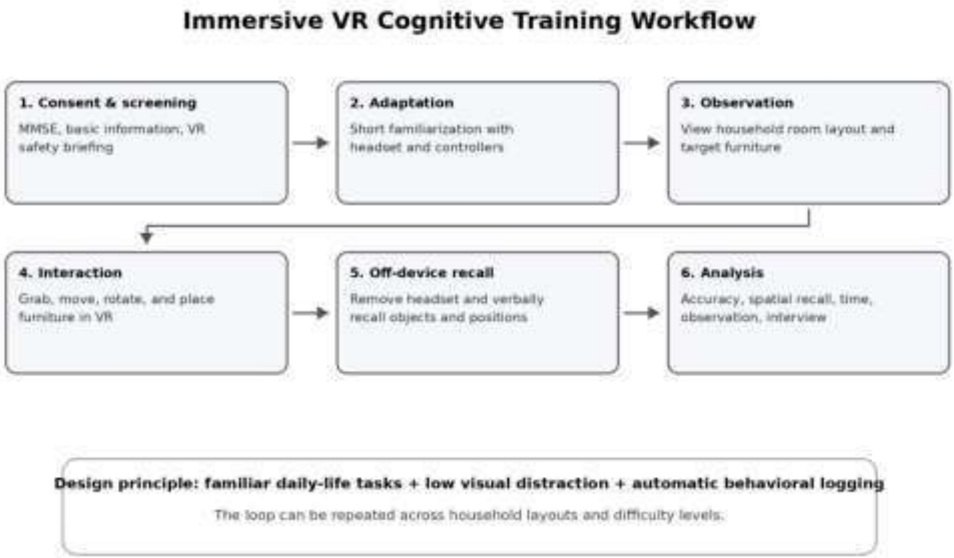

Figure 2: Experimental Workflow for VR-Based Spatial Memory Training

3.6 Measures and Data Analysis

The evaluation used four categories of data. The first category was basic cognitive screening, represented by MMSE score. The second category was task performance, including number of furniture items presented, correctly recalled items, item recall accuracy, correct position descriptions, spatial recall accuracy, and recall time in seconds. The third category was observational engagement, including attention level, task engagement, emotional response, and researcher notes. The fourth category was subjective feedback collected after the VR experience.

Due to the small pilot sample, statistical analysis was descriptive. Means and standard deviations were calculated for MMSE score, item recall accuracy, spatial recall accuracy, and recall time. Participant-level data were also retained because case-by-case patterns are important in early design evaluation. The results should be interpreted as feasibility and design evidence rather than as clinical proof of cognitive improvement.

4. RESULTS

4.1 Prototype Implementation Results

The prototype successfully implemented the main interaction modules required for the study: VR scene entry, furniture object selection, object manipulation, room reset, layout storage, layout reading, and task exit. The system also included safety and comfort guidance before the formal task. Compared with a paper-based complex figure or clock-drawing task, the prototype presented a more familiar domestic context and allowed participants to use bodily interaction to construct a spatial layout. The field testing scene showed that older participants were able to wear the headset and complete the interaction under researcher supervision.

Figure 3: Field Implementation of the Immersive VR Cognitive Training Task

4.2 Spatial Memory Recall Performance

All five participants were able to recall multiple furniture items after the VR experience. The number of furniture items presented in the task was nine for each participant. Item recall accuracy ranged from 66.7% to 88.9%, with a mean of 80.0% and a standard deviation of 8.94. Spatial recall accuracy ranged from 44.4% to 66.7%, with a mean of 57.8% and a standard deviation of 8.75. Recall time ranged from 72 to 101 seconds, with a mean of 86.8 seconds and a standard deviation of 11.3.

These results suggest that participants not only remembered the existence of objects but also retained part of the spatial relationship between objects and the virtual room. Spatial recall was lower than item recall, which is expected because position reconstruction is more demanding than item recognition. Participant P3 showed lower item and spatial recall than the others and was observed to show some confusion, while P2 and P5 demonstrated higher recall and stronger engagement.

Table 3: Spatial Memory Recall Performance after VR Experience

ID	Items Presented	Items Recalled	Item Recall (%)	Positions Recalled	Spatial Recall (%)	Recall Time (s)	Observation
P1	9	7	77.8	5	55.6	85	Minor hesitation
P2	9	8	88.9	6	66.7	72	Highly engaged
P3	9	6	66.7	4	44.4	96	Some confusion
P4	9	7	77.8	5	55.6	101	Needed more thinking time
P5	9	8	88.9	6	66.7	80	Positive engagement

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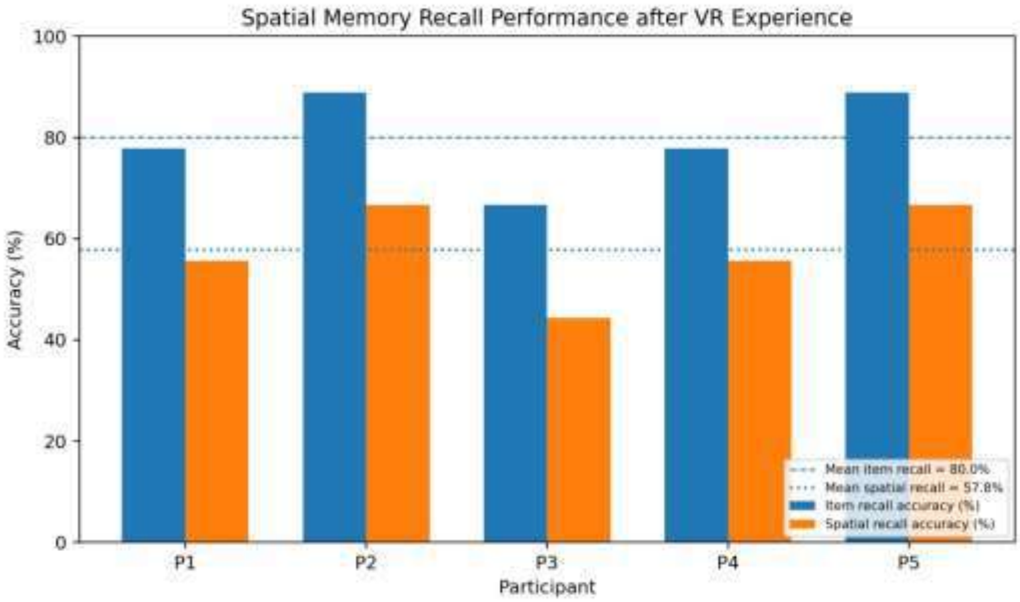

Figure 4: Comparison of Item Recall and Spatial Recall Accuracy by Participant

Table 4: Summary Statistics of Memory Recall Performance

Measure	Mean	Standard Deviation
MMSE Score	25.6	1.14
Item Recall Accuracy (%)	80.0	8.94
Spatial Recall Accuracy (%)	57.8	8.75
Recall Time (seconds)	86.8	11.3

4.3 Observational Engagement Assessment

The observational engagement data indicated that most participants maintained active attention and task involvement. Three participants were rated as having high attention, while two were rated as moderate. Task engagement was active or very active for four participants and moderate for one participant. Emotional responses were generally relaxed, positive, or neutral. No severe adverse response was reported during the documented pilot session.

Table 5: Observational Engagement Assessment

Participant ID	Attention Level	Task Engagement	Emotional Response	Notes
P1	High	Active	Relaxed	Showed curiosity
P2	High	Very Active	Positive	Smiled during task
P3	Moderate	Active	Neutral	Occasionally hesitant
P4	Moderate	Moderate	Neutral	Longer thinking time
P5	High	Very Active	Positive	Expressed interest

4.4 Post-Experience Subjective Feedback

Post-experience interviews showed that most participants described the interaction as simple and easy to operate. Several participants compared the task to playing a game rather than taking a test, which reduced the pressure commonly associated with traditional cognitive training. Some participants reported that the process was comfortable and that they would be willing to participate again. These responses indicate that the game-like structure and familiar household scene may support acceptance among older adults.

The subjective feedback also revealed design issues for future improvement. Some participants needed more time to think during the recall phase, and some hesitated during object placement. These observations suggest that difficulty should be adjustable, that instruction should remain concise, and that future versions should include progressive levels ranging from fewer objects and simple layouts to more complex spatial tasks.

5. DISCUSSION

5.1 From Abstract Cognitive Tasks to Ecological Spatial Memory Training

The study demonstrates one possible path for transforming traditional cognitive training into immersive interaction media. Instead of asking participants to reproduce abstract shapes, the prototype asks them to perceive, manipulate, and recall furniture in a household scene. This shift is important because daily memory problems in MCI often occur in situated contexts: remembering where objects are placed, recalling a room arrangement, or reconstructing spatial relationships after a short delay. The VR household scene therefore functions as an ecological bridge between clinical-style cognitive tasks and everyday memory use.

The pilot results support the feasibility of this approach. Participants achieved higher item recall accuracy than spatial recall accuracy, indicating that the task successfully separated object memory from spatial relationship memory. This distinction is useful for future training design because different difficulty parameters can be adjusted independently, such as number of objects, object similarity, spatial distance, room complexity, and recall delay.

5.2 Engagement, Embodiment, and Cognitive Participation

The observational and interview results suggest that immersive interaction may improve user engagement compared with conventional paper-based exercises. Participants described the experience as game-like, low-pressure, and interesting. This finding is consistent with the broader idea that interactive technology can provide cognitive stimulation, social connection, and compensatory support in older adulthood (Benge & Scullin, 2025). In the present prototype, interaction was not merely decorative; object manipulation was directly linked to memory encoding and retrieval.

Embodied interaction may also support attention. When users select, grab, rotate, and place virtual furniture, they must actively attend to the object, its orientation, and its relation to the surrounding space. This active manipulation could strengthen spatial encoding compared with passive viewing. However, the study did not include a control group, so this explanation remains a design interpretation rather than a confirmed causal mechanism. Future studies should compare VR observation-only conditions, VR interactive conditions, and traditional paper or screen-based conditions.

5.3 Design Implications for Older-Adult VR Cognitive Training

Several design implications can be drawn. First, familiar scenes may reduce learning barriers. A household room and common furniture objects are easier for older users to understand than abstract game spaces. Second, interface readability is essential. Large buttons, clear object images, and limited menu depth can reduce cognitive load. Third, task duration should be short and adjustable. Users with MCI risk may become fatigued or anxious if instructions are too long or if the scene is too complex. Fourth, behavioral logging should be integrated from the beginning because precise data on placement, time, and recall can support long-term individualized assessment.

The study also highlights the need to combine cognitive training with emotional and social considerations. Older adults may resist activities that feel like diagnostic examinations. A serious game can reframe training as exploration and play, potentially improving willingness to continue. In future versions, family members, caregivers, or therapists could participate in the training loop, turning spatial memory tasks into guided social interaction.

5.4 Limitations and Future Work

This study has several limitations. First, the pilot sample was small, with only five participants, and the evaluation used descriptive statistics. The results therefore cannot be generalized to the wider MCI population. Second, the study did not include a randomized control group, pre-post cognitive outcome comparison, or long-term follow-up. Third, the current prototype used a single household scene and a limited set of furniture objects. Fourth, the social interaction component remains underdeveloped, although it is important for long-term motivation and cognitive reserve.

Future work should expand the participant sample, include clinically confirmed MCI users, and compare the VR prototype with traditional cognitive training or non-immersive digital training. Additional scenes such as a supermarket, bus route, kitchen task, or medication management routine could increase ecological coverage. Adaptive difficulty, AI-generated task layouts, multimodal feedback, and long-term behavioral logging could further support individualized training. Usability assessment instruments and standardized cognitive measures should also be included to evaluate both user experience and cognitive outcomes.

6. CONCLUSION

This study proposed and piloted an immersive VR serious game for spatial memory training among older adults with MCI or cognitive-risk characteristics. The system transformed a conventional memory assessment logic into a familiar household scene in which users could observe room layouts, interact with furniture objects, and complete off-device recall. The design integrated cognitive training goals, immersive interaction, older-adult readability, fatigue awareness, and behavior data recording.

Pilot results from five participants showed an average MMSE score of 25.6, item recall accuracy of 80.0%, spatial recall accuracy of 57.8%, and recall time of 86.8 seconds. Observational and interview data indicated positive engagement and good acceptance. These findings suggest that immersive VR can provide a feasible and engaging medium for spatial memory stimulation, although clinical effectiveness must be examined through larger, controlled, and longitudinal studies.

Overall, the project contributes an interactive media design framework for MCI-oriented VR cognitive training. It demonstrates how domestic spatial memory tasks can be made embodied, repeatable, and measurable. Future development should expand scenes, increase sample diversity, integrate social interaction, and connect VR behavioral data with standardized cognitive evaluation.

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