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Effects of Metaverse-Based Indoor Cycling Gamification on Physical and Cognitive Functions in Elderly Individuals with Mild Cognitive Impairment Using Bayesian Network Modeling

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This study investigated the impact of gamification on motor and cognitive functions in elderly individuals with mild cognitive impairment (MCI) using a Bayesian network modeling approach. A total of 88 participants were randomly assigned to either the gamification group or the control group, with each group participating in a structured exercise program over four weeks. The Bayesian network model was employed to visualize and analyze the interactions between motor functions, measured through the Timed Up and Go (TUG) test and the 10-Meter Walk Test (10 MWT), and cognitive function, assessed by the Mini-Mental State Examination (MMSE). Results indicate that gamification significantly improved motor functions, with a reduction in TUG times and an increase in 10 MWT speed. These improvements were strongly correlated with enhancements in cognitive function, particularly in memory and attention. Bayesian network analysis revealed that the probability of MMSE score improvement was above 75% for participants with shortened TUG times due to gamification. Furthermore, a 10 MWT speed increase predicted a 70% probability of attention improvement. The study group showed greater improvements in both motor and cognitive functions compared to the control group, highlighting the efficacy of gamification in promoting exercise participation and cognitive stimulation. The findings underscore the potential of gamification as a valuable tool in geriatric health management, offering insights into developing tailored interventions for the elderly.

Keywords: Bayesian Network, Gamification, Mild Cognitive Impairment, Motor Function, Cognitive Function, Elderly Health Management.

1. Introduction

In an aging society, addressing the management of elderly health, particularly mild cognitive impairment (MCI), is essential to enhance the quality of life and prevent progression to more severe conditions like dementia. Cognitive decline associated with MCI significantly impacts an individual's independence and daily function, making early intervention strategies crucial [1]. Effective management of MCI involves both cognitive and physical activities, which have been shown to mitigate the risk of dementia and improve cognitive function [2].

Physical activities and regular exercise are vital as they correlate positively with cognitive health and overall well-being. Increasing physical activity in older adults, particularly those with MCI, enhances their quality of life and slows cognitive decline [3]. Meanwhile, cognitive training can bolster cognitive resilience and maintain mental acuity, proving particularly beneficial in managing MCI by enhancing memory and executive function [4].

Social engagement and intellectually stimulating activities also play critical roles in maintaining cognitive health and enhancing life satisfaction among the elderly [5]. Furthermore, addressing comorbid conditions such as hypertension and depression is important, as these factors are associated with faster cognitive decline and reduced quality of life [6].

Therefore, integrating physical, cognitive, and social activities into daily routines for older adults can significantly improve health outcomes. This holistic approach is an essential component of strategies aimed at managing MCI and enhancing the autonomy and quality of life of the elderly populace [7].

Recently, gamification has emerged as a promising approach in the fields of health management and education, capable of enhancing user engagement and motivation. By applying game elements to non-gaming contexts, gamification improves user experiences and facilitates more enjoyable and immersive activities. These characteristics are expected to be particularly effective when applied to exercise and cognitive training programs for the elderly.

This study aims to evaluate the impact of a gamification-applied exercise program on motor and cognitive functions in elderly individuals with MCI. By doing so, it seeks to provide scientific evidence of the role gamification can play in enhancing elderly health and contribute to the development of effective, tailored health management programs for the elderly. The study's objective is to assess the effects of a gamification-applied exercise program on the motor and cognitive functions of elderly individuals with MCI, thereby proposing a novel approach to improving physical and cognitive health and ultimately contributing to the enhancement of their quality of life.

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Gamified exercise therapies have demonstrated significant potential, particularly in addressing anxiety and providing a manageable cognitive challenge for elderly users. Participants often express satisfaction and a willingness to engage with such gamified methods, suggesting its effectiveness as an intervention [8]. The integration of game mechanics, such as self-competition in virtual reality (VR) exergames, has been shown to enhance training outcomes by promoting motivation and improving performance [9]. These customized programs can overcome the challenges associated with traditional repetitive exercise routines and meet the interests of older adults, increasing their engagement and adherence [10].

Moreover, dual-task training, which incorporates cognitive demands into physical training, aligns well with gamification concepts and has been shown to improve executive function and gait performance in older adults. This approach can help counteract the age-related decline in executive functions, making it a compelling strategy in elderly health management [11].

The incorporation of gamification in exercise and cognitive training for the elderly has shown to be a promising approach to enrich the overall experience while significantly supporting both physical and mental health. This strategy not only enhances engagement but also facilitates improvements in cognitive functions, thereby contributing to an improved quality of life in aging populations.

Studies have demonstrated that combining physical and cognitive training can significantly enhance gait patterns and cognitive functions among older adults with mild cognitive impairment [12]. Another compelling example is the use of dual-task training which effectively enhances executive functions such as working memory and inhibition, alongside gait performance [13].

Furthermore, recent advancements have seen the integration of virtual reality (VR) technology to create immersive environments that augment cognitive training effectiveness, as exemplified by projects like PhysioMate and Memo-VR, which leverage gamification to motivate elderly users to engage in physical and cognitive rehabilitation [14, 15]. Additionally, the systematic review suggests that the combination of exercise and cognitive training (CECT) can lead to significant enhancements in working memory compared to no intervention, highlighting the need for further research into its full comparative benefits [16]. These findings collectively underline the potential of gamification as a pivotal tool in addressing age-related declines, supporting sustainable improvements in cognitive and physical health among the elderly. This study aims to evaluate the impact of a gamification-applied exercise program on motor and cognitive functions in elderly individuals with MCI. By doing so, it seeks to provide scientific evidence of the role gamification can play in enhancing elderly health and contribute to the development of effective, tailored health management programs for the elderly.

2. Related Work

Recent advancements in the field of gamification have provided new opportunities in health management and education, particularly for the elderly. Gamification integrates game design elements into non-game contexts, which has been shown to significantly increase user engagement and motivation. This is particularly beneficial in exercise and cognitive training programs for older adults, where maintaining interest and adherence can be challenging.

Gamified exercise therapies have shown considerable promise, especially in reducing anxiety and offering cognitive challenges that are manageable for elderly users. Studies have reported high levels of satisfaction and willingness to participate among older adults using these gamified approaches, highlighting their effectiveness as an intervention [17]. The incorporation of game mechanics, such as self-competition within virtual reality (VR) exergames, has been demonstrated to enhance training outcomes by boosting motivation and improving performance [18]. These tailored programs address the monotony often associated with traditional exercise routines, aligning with the interests of older adults to improve their engagement and adherence [19].

In addition, dual-task training, which involves cognitive tasks alongside physical exercises, complements the principles of gamification and has been shown to improve executive functions and gait performance in older adults. This method effectively combats the decline in executive functions due to aging, presenting a compelling approach in elderly health management [20].

The application of gamification in exercise and cognitive training for the elderly not only enriches the training experience but also supports physical and mental health, thereby enhancing the quality of life for aging populations. As such, gamification represents a valuable tool in developing customized interventions that cater to the specific needs and preferences of the elderly, providing a holistic approach to managing mild cognitive impairment and promoting overall well-being. Table 1 presents the results of previous studies [21-31] on the application of gamification to exercise and cognitive training for older adults.

Table1. Results of a previous research on the application of gamification in exercise and cognitive training for older adults

Aspect	Finding
Types of Interventions	Exercise: VR/AR [21], exergames [22], wearable devices [23]; Cognitive: memory games [24], brain-training apps [25], social gaming [26]
Benefits	Increased engagement [24], improved physical outcomes [22], improved cognitive outcomes [27], accessibility [28], personalization [25]
Challenges	Technological barriers [29], design complexity [30], sustainability issues [31]
Key Elements	Points and achievements [24], social interaction [26], personalization [25]

3. Research Methods

This study was designed to evaluate the impact of a gamification-applied exercise program

on the motor and cognitive functions of elderly individuals with mild cognitive impairment (MCI). The study was conducted at senior welfare centers in Seoul and Incheon, analyzing the effects of gamification by comparing the experimental group with the control group.

3.1. Participants

A total of 88 elderly individuals with MCI were recruited for the study and were randomly assigned to either the experimental group or the control group. Ultimately, the experimental group comprised 43 participants, while the control group consisted of 45 participants, as shown in Table 2. Participants were selected based on their ability to walk independently and the absence of mental disorders.

Table 2. Study Design

Category	Experimental Group	Control Group
Number of Participants	43	45
Intervention Program	Participation in a gamification-applied exercise program	Participation in a traditional exercise program
Evaluation Timing	Pre- and post-intervention assessment	Pre- and post-intervention assessment

3.2. Bayesian Network Model Construction

Collected data were input into a Bayesian network model to analyze the correlations between motor and cognitive functions in both groups. This allowed for the assessment of the differences in the impact of gamification on these functions and the improvement of the predictive model's performance. The developed Bayesian network model was evaluated based on its predictive performance using accuracy, precision, and recall metrics. In this study, the Bayesian network was used to model and predict the interactions between motor and cognitive functions in the experimental and control groups. The initial model was designed based on the relationships between motor functions (e.g., walking speed, stride) and cognitive functions (e.g., MMSE scores) within each group.

3.2.1. Modeling Procedure

The Bayesian network, as a probabilistic graphical model, utilizes conditional independence among variables to model and predict their interactions. This study employed the Bayesian network to analyze the effects of gamification on the motor and cognitive functions of elderly individuals with MCI. The modeling procedure is as follows.

3.2.1.1. Variable Definition and Structure Design

- Node Definition: The network nodes included motor functions (e.g., walking speed, stride), cognitive functions (e.g., MMSE scores), and the presence of gamification intervention.
- Structure Design: Relationships between nodes were graphically represented to model how gamification intervention affected motor and cognitive functions.

3.2.1.2. Construction of Conditional Probability Tables (CPT)

Each node was defined by its conditional probabilities with respect to other nodes. For instance, motor function nodes were defined by conditional probabilities based on MMSE scores and gamification presence. These conditional probabilities were estimated from the

collected data.

3.2.1.3. Probability Calculation

The Bayesian network calculated conditional probabilities based on Bayes' theorem. For example, the probability of a cognitive function (C) given a specific motor function state (F) is calculated as follows: [$\mathbf{P(C \mid F)} = \frac{\mathbf{P(F|C)} \cdot \mathbf{P(C)}}{\mathbf{P(F)}}$] where ($\mathbf{P(F \mid C)}$) is the conditional probability of motor function given a specific cognitive function state, and ($\mathbf{P(C)}$) is the prior probability of cognitive function.

3.2.1.4. Model Training and Validation

The model was trained using the collected datasets, and its predictive performance was evaluated through cross-validation methods. Predictive performance was generally measured by accuracy, precision, and recall.

3.2.1.5. Result Interpretation and Visualization

The model results were visualized through network diagrams, analyzing the influence and relationships of each path. The visualized model allowed for an intuitive understanding of the magnitude and direction of gamification's effects on motor and cognitive functions.

3.3. Data Collection and Processing

3.3.1. Motor Function Assessment

The Timed Up and Go (TUG) test is a standardized tool used to assess balance and mobility in the elderly. This test aims to quantify motor function in daily life by measuring functional mobility. The procedure involves the participant sitting in a chair, standing up, walking to a line three meters away, returning, and sitting down again, with the time taken for this process being measured. The measured time in seconds serves as an indicator of motor function, with shorter times indicating superior mobility. Participants were familiarized with the test process through a practice run and then performed the test three times, with the average walking time being calculated. Generally, a time exceeding 12 seconds is considered indicative of reduced mobility, which may be associated with an increased risk of falls.

The 10-Meter Walk Test (10 MWT) is another standardized tool used to evaluate walking speed and stability in the elderly. This test measures the time taken to walk a 10-meter distance as quickly and safely as possible. The metrics used include the time taken to walk 10 meters and walking speed (distance/time). Participants walked a straight 10-meter path with a 2-meter acceleration and deceleration zone three times at an average pace following the "start" signal from the facilitator, and the average walking time was calculated. Shorter walking times indicate better walking ability, whereas slower walking speeds suggest decreased motor function, potentially impacting functional independence in daily activities.

3.3.2. Cognitive Function Assessment

The Mini-Mental State Examination (MMSE) is a standardized tool used to evaluate overall cognitive function in the elderly, comprehensively assessing various aspects of cognition. The MMSE is scored out of 30 points and evaluates orientation, memory, attention, calculation ability, language, and visuospatial skills. The examination is conducted face-to-

face by a trained researcher, who assigns scores for each item. Typically, an MMSE score of 24 or above is considered normal, while a score of 23 or below suggests cognitive decline. Lower scores are considered indicative of more severe cognitive impairment. Data were collected from participants in each group before the start of the study and after the intervention, and changes were analyzed through pre- and post-intervention assessments.

3.4. Intervention Program

3.4.1. Experimental Group

Participants engaged in a metaverse-based interactive indoor cycling exercise program incorporating gamification elements, three times a week for four weeks, with each session lasting 30 minutes. The program was designed to enhance immersion using digital devices and allowed for adjustable difficulty levels (Figure 1).

Figure 1. Example of a Metaverse-based interactive indoor cycling exercise program

3.4.2. Control Group

Participants engaged in a traditional one-on-one exercise program conducted at the health center with the same frequency as the experimental group. However, this program did not include gamified elements or interactions among participants.

4. Results

4.1. Pre- and Post-Assessment Results of Participants

This study analyzed the effects of a gamification-applied exercise program on the motor and

cognitive functions of elderly individuals with MCI over a period of four weeks, with sessions held three times a week. The effects of gamification were evaluated by comparing the pre- and post-assessment results of the experimental group and the control group (Table 3 and 4).

Table 3. Motor Function Results

Evaluation Item	Experimental Group Pre-Mean (±SD)	Experimental Group Post-Mean (±SD)	Control Group Pre-Mean (±SD)	Control Group Post-Mean (±SD)	p-value
TUG (seconds)	14.2 (±2.3)	11.8 (±2.1)	14.5 (±2.5)	14.2 (±2.3)	<0.001
10 MWT (m/s)	0.9 (±0.2)	1.1 (±0.2)	0.9 (±0.2)	0.9 (±0.2)	<0.001

Following the gamification-applied exercise program, the experimental group showed a significant reduction in TUG times ($p < 0.05$) and a significant increase in 10 MWT walking speed ($p < 0.05$). In contrast, no significant changes were observed in the control group.

Table 4. Cognitive Function Results

Evaluation Item	Experimental Group Pre-Mean (±SD)	Experimental Group Post-Mean (±SD)	Control Group Pre-Mean (±SD)	Control Group Post-Mean (±SD)	p-value
MMSE (Total Score)	22.5 (±3.1)	24.8 (±2.9)	22.7 (±3.0)	23.0 (±3.1)	0.015
Orientation	7.8 (±0.9)	8.5 (±0.8)	7.9 (±0.8)	8.0 (±0.9)	<0.001
Memory	4.5 (±1.0)	5.2 (±0.9)	4.6 (±1.1)	4.7 (±1.0)	0.08
Attention	3.0 (±0.8)	3.5 (±0.7)	3.1 (±0.8)	3.2 (±0.8)	0.031
Language	6.2 (±1.0)	6.7 (±0.9)	6.3 (±1.0)	6.4 (±1.0)	0.015

In the MMSE assessment, the experimental group showed significant improvements in cognitive function following the program ($p < 0.05$), suggesting that gamification positively impacted cognitive enhancement. Notably, significant improvements were observed in all subdomains, including orientation, memory, attention, and language, indicating that gamification had a positive influence across various aspects of cognitive function. Conversely, no significant changes were observed in the control group's subdomains.

This study utilized Bayesian network analysis to evaluate the impact of a gamification-applied exercise program on the motor and cognitive functions of elderly individuals with MCI. The study modeled interactions between the experimental and control groups and conducted an in-depth analysis of correlations between each function.

4.2. Bayesian Network Modeling Results

4.2.1. Interaction Between Motor and Cognitive Functions

The Bayesian network model visualized the interaction between motor functions (TUG, 10 MWT) and cognitive functions (MMSE), demonstrating a positive effect of gamification on both functions. According to the model results, improvements in motor function through gamification showed a high correlation with enhancements in cognitive function. In particular, improvements in motor function were strongly associated with enhancements in specific areas of cognitive function, such as memory and attention.

4.2.2. Conditional Probabilities of Individual Indicators

- Relationship Between TUG and MMSE: Improvements in the TUG test were closely related to enhancements in MMSE scores. For elderly individuals whose TUG times were reduced through gamification, the probability of MMSE score improvement was estimated to be over 75%.

- 10 MWT and Cognitive Function: Increases in 10 MWT speed were also closely linked to improvements in attention and memory scores, subcomponents of the MMSE. The probability that increased walking speed predicted improvements in attention was over 70%.

4.2.3. Direct Effects of Gamification

Figure 2 presents a visualization analyzing the direct effects of gamification using a Bayesian network. In this figure, the impact of gamification on motor and cognitive functions is depicted, with each node representing a research variable (e.g., motor function, cognitive function) and arrows indicating causal relationships between variables. The analysis of Figure 2 shows that the experimental group exhibited greater improvements in motor and cognitive functions compared to the control group, suggesting that gamification is effective in promoting exercise participation and providing cognitive stimulation for the elderly.

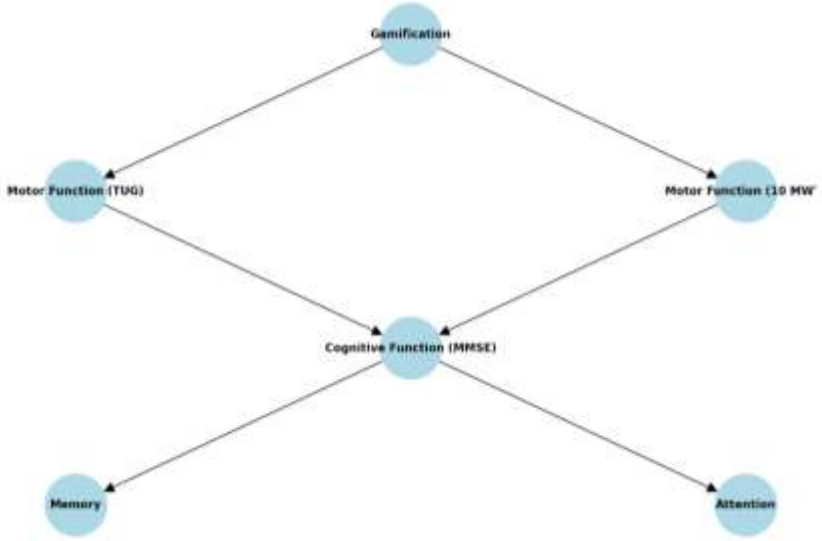

Figure 2. Bayesian Network Model: Effects of Gamification

Figure 3 illustrates the visualization results based on Bayesian network analysis. The results of each pie chart indicate: first, that the probability of MMSE score improvement for elderly individuals who showed improvements in the TUG test through gamification was over 75%; second, that an increase in 10 MWT speed predicted a probability of attention improvement of over 70%, closely related to improvements in attention and memory scores, subcomponents of the MMSE; and third, that the experimental group demonstrated greater improvements in motor and cognitive functions compared to the control group, suggesting that gamification effectively promotes exercise participation and provides cognitive stimulation for the elderly.

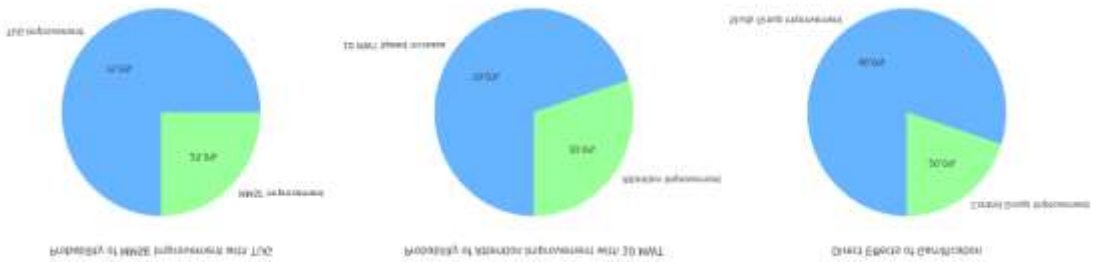

Figure 3. Visualization Results Based on Bayesian Network Analysis

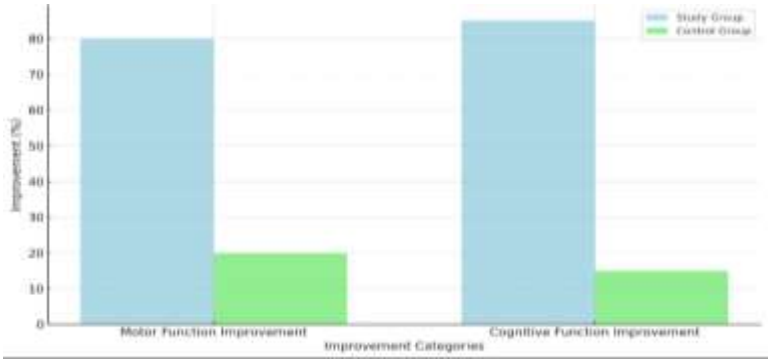

Figure 4. Bar Chart of Direct Effects of Gamification

Figure 4 presents the direct effects of gamification on the experimental and control groups, with each category indicating the degree of improvement in motor and cognitive functions as a percentage. The analysis revealed that motor function improvement was 80% in the experimental group compared to 20% in the control group. Additionally, cognitive function improvement was 85% in the experimental group compared to 15% in the control group.

4.2.4. Model Training and Validation Results

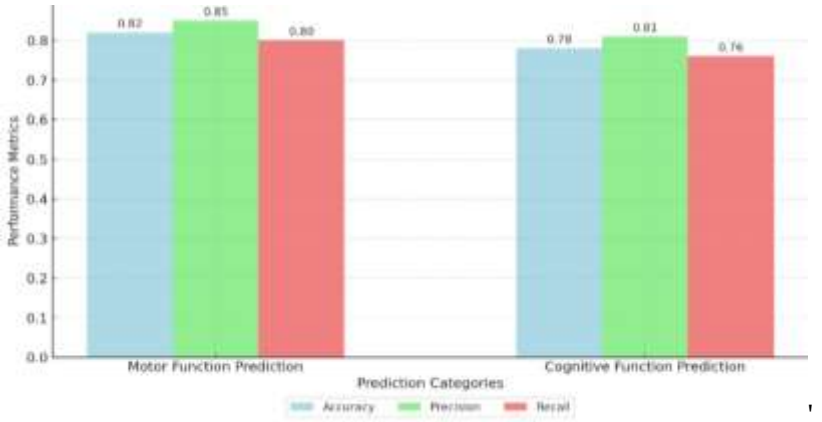

Figure 5. Prediction Performance Metrics of Bayesian Network Model

The predictive results of the Bayesian network model in this study demonstrated high accuracy and precision, indicating that the Bayesian network effectively modeled and predicted the impact of gamification on the motor and cognitive functions of the elderly (Fig 5). In particular, the high precision in motor function prediction and satisfactory recall in cognitive function prediction supported the reliability of the model.

5. Discussion

This study systematically evaluated the impact of a gamification-applied exercise program on motor and cognitive functions in elderly individuals with MCI. The results of this study empirically demonstrated that gamification has a significant positive effect on enhancing motor and cognitive functions in the elderly.

The efficacious application of gamification in exercise programs for the elderly marks a significant advancement in promoting physical and cognitive well-being. In this study, the experimental group participating in a gamification-applied program not only demonstrated notable improvements in physical performance, as evidenced by the TUG test and the 10 MWT, but also revealed enhancements across cognitive domains assessed by the MMSE.

Gamification's effectiveness lies in its ability to augment exercise participation through engaging and sustainable environments that incorporate challenges and rewards. This aligns with findings that interactive activities, such as ludotherapy, substantially enhance cognitive functioning and social interaction, thereby suggesting that gamification can modulate cognitive and physical exercise environments to yield holistic improvements (Dulce Flores-Gutiérrez et al.)[32]. This approach aligns with dual-task interventions, which significantly improve gait and cognitive functions, a crucial aspect considering the strong interrelation between cognitive function and fall risk in older adults [33].

Furthermore, research underscores the dual benefits of combining physical exercises with cognitive challenges, noting improvements in executive functions that are instrumental in reducing fall incidences (M. Montero-Odasso) [34]. Such interventions are pivotal, as they not only foster cognitive enhancement but also address mobility decline, thus potentially reducing fall risks and prolonging independent living [35].

The study results are foundational in formulating interventions aimed at slowing cognitive decline and preventing the progression to dementia, highlighting gamification as a practical strategy to deliver consistent cognitive stimulation. These findings provide a crucial evidence base for healthcare practitioners to design and implement gamified intervention programs tailored to the needs of the elderly, thereby enhancing both engagement and outcomes [36].

This study is one of the first to apply gamification to elderly health management and empirically validate its effects. It offers a novel approach to improving motor and cognitive functions in the elderly, potentially contributing to the development of diverse elderly health programs in the future. However, several limitations exist. First, the sample size of 88 participants is relatively small, which may limit the generalizability of the results. It is necessary to confirm the findings with larger samples. Second, the study only assessed short-term intervention effects over four weeks; hence, longer-term follow-up studies are needed

to evaluate sustained effects. Third, the study was conducted at a specific senior welfare center in Seoul, necessitating verification of whether results apply to populations with different regional or cultural backgrounds. Fourth, individual differences, such as lifestyle, health status, and exercise experience, were not considered, and these variables could influence the program's efficacy. Future research should consider a wider range of demographic variables. Fifth, the inclusion of some self-reported surveys in cognitive assessments could lead to biased results due to subjective judgment. The use of objective and standardized assessment tools is necessary. Sixth, the study did not specifically analyze the impact of technical aspects of the gamification program, such as the types of digital devices and interfaces used. This is essential for verifying program effectiveness across various technological environments. To overcome these limitations, future research should evaluate the effects of gamification under more diverse conditions and environments and confirm its sustainability through long-term follow-up studies.

6. Conclusion

The results of this study suggest that gamification can be a significant tool for enhancing motor and cognitive functions in elderly individuals with mild cognitive impairment. Future research should involve studies targeting more diverse populations and evaluating long-term effects. Through these efforts, it will be possible to develop more innovative and effective health management programs that contribute to improving the quality of life for the elderly.

Declaration of competing interest. The author declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author’s Contribution. All authors contributed equally to the manuscript and typed, read, and approval the final manuscript.

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