



Cognitive training with adaptive algorithm improves cognitive ability in older people with MCI

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Abstract

Recent discoveries indicating that the brain retains its ability to adapt and change throughout life have sparked interest in cognitive training (CT) as a possible means to postpone the development of dementia. Despite this, most research has focused on confirming the efficacy of training outcomes, with few studies examining the correlation between performance and results across various stages of training. In particular, the relationship between initial performance and the extent of improvement, the rate of learning, and the asymptotic performance level throughout the learning curve remains ambiguous. In this study, older adults underwent ten days of selective attention training using an adaptive algorithm, which enabled a detailed analysis of the learning curve's progression. Cognitive abilities were assessed before and after CT using the Mini-mental State Examination (MMSE) and the Montreal Cognitive Assessment (MoCA). The findings indicated that: (1) Initial performance is positively correlated with Learning amount and asymptotic performance level, and negatively correlated with learning speed; (2) Age is negatively correlated with learning speed, while it is positively correlated with the other three parameters. (3) Higher pre-training MMSE scores predicted higher post-training MMSE scores but less improvement; (4) Higher pre-training MoCA scores predicted higher post-training MoCA scores and less improvement; (5) The parameters of the learning curve did not correlate with performance on the MMSE or MoCA. These results indicate that: (1) Selective attention training using adaptive algorithms is an effective tool for cognitive intervention; (2) Older individuals with poor baseline cognitive abilities require more diversified cognitive training; (3) The study supports the compensation hypothesis.

Keywords CT · Adaptive algorithm · Cognitive ability · Learning curve · Compensation assumption

Introduction

Cognitive training (CT) is a structured program of mental exercises designed to preserve or enhance cognitive abilities that facilitate daily activities and promote independent living [9]. The foundation of CT lies in the brain's neuroplasticity—the ability of its structure and neural pathways to adapt and change [6, 7]. CT has been extensively utilized

to mitigate cognitive decline in aging populations [1] and to enhance cognitive function in individuals with mild cognitive impairment (MCI) [11, 21]. Nevertheless, Early intervention during the MCI stage is more effective than improving cognitive status in older individuals with dementia. The MCI stage represents a critical juncture in the gradual progression from normal cognitive function to dementia [8]. Effective intervention during this stage can significantly postpone the advancement of this transition [24].

Older people can benefit significantly from CT, as the brain retains a considerable capacity for plasticity well into old age [20]. An intriguing question arises: who stands to gain the most from CT? This question touches upon the debate between two competing hypotheses—the magnification account [14] and the compensation account [12, 18]. The magnification account proposes that individuals possessing stronger baseline abilities are inclined to reap greater benefits from cognitive training, displaying a trend similar to the Matthew Effect. More precisely, those with higher baseline levels tend to excel

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in training, showing steeper learning curves and consequently benefiting more from cognitive interventions. Conversely, the compensation account suggests that those with poorer cognitive abilities will benefit more, as their brains have greater potential for learning. Research into this matter could not only deepen our understanding of human plasticity but also illuminate the development of tailored CT protocols.

Upon a careful review of the literature, we discovered that researchers have yet to chart the CT learning curve for the older population diagnosed with MCI. Indeed, the learning curve is crucial for scrutinizing the detailed time course of the learning process, including initial performance, the volume of learning, learning speed, and the asymptotic performance level. By investigating the correlation between these factors, we can elucidate whether individuals with MCI who exhibit better initial performance learn more or less and achieve a superior final performance during CT. We can also determine who learns at a faster or slower pace. Furthermore, this method aids in deepening our understanding of the progression from cognitively unimpaired (CU) to MCI.

In the present study, an adaptive staircase method was employed to monitor the learning process. The threedown/one-up staircase procedure converged to 79.4% correct responses [10], resulting in a moderate level of difficulty for the cognitive task, neither overly easy nor excessively challenging. According to the universal theory of education, individuals achieve the best learning effects when engaging in tasks at a moderate level of difficulty. From a different perspective, maintaining consistent accuracy in CT can circumvent the ambiguity associated with the trade-off between speed and accuracy.

In this study, we examined the impact of CT using an adaptive method on older individuals with MCI. Their cognitive function was evaluated using the Mini-Mental State Examination (MMSE) and the Montreal Cognitive Assessment (MoCA) both before and after CT. Attention serves as a prerequisite for individuals to engage in the majority of tasks, and it can be improved through training [17]. Considering that selective attention occupies a key position within attentional functions, it is selected as the focus of CT. The investigation had two objectives: (1) to differentiate between magnification and compensation theories based on the characteristics of the learning curve, and (2) to observe whether the benefits of selective attention training transfer to other major cognitive functions as assessed by the MMSE and MoCA tests.

Method

Subjects

Sixty older individuals diagnosed with MCI (31 males and 29 females, aged between 60 and 95) volunteered to

Table 1 Basic information for two groups

Item	Training group (n = 28)	Control group (n = 30)	χ^2	P value
Gender	14	16	0.064	0.8
Male	14	14		
Female				
Diploma	9	11	0.131	0.717
>7 years	19	19		
<7 years				
Occupation	8	10	0.153	0.695
Mental labor	20	20		
Manual labor				

participate in the current study. The inclusion criteria for research subjects with MCI were as follows: (1) Age 60 and above; (2) Normal hearing and vision; (3) MCI patients were diagnosed with MCI in accordance with the standards set by the International MCI Working Group and the diagnostic criteria of the European Alzheimer's Disease Consortium MCI Working Group [16]: a. The primary complaint was memory loss within the past year, while general cognitive function remained normal. b. Did not meet the diagnostic criteria for dementia as outlined in DSM-IV (Diagnostic and Statistical Manual of Mental Disorders, Fourth Edition). c. Based on the Montreal Cognitive Assessment (MoCA), patients with MCI were identified using the evaluation criteria from the study [13]. Specifically, illiterate individuals had a MoCA score of ≤ 14 , Those with 1–6 years of education had a MoCA score ≤ 20 points; And those with 7 or more years of education had a MoCA score ≤ 25 points.

Exclusion criteria for research participants: a. Functional or organic mental disorders; b. Language communication barriers; c. Exclusion of other diseases or factors that may lead to a decline in brain function (including physical diseases, depression, stroke, traumatic brain injury, drug and alcohol poisoning, and the use of psychiatric medications); d. Unhealthy behaviors (such as insomnia, alcoholism, etc.). Prior to our study, all participants signed informed consent forms prior to the experiment. The Institutional Review Board of the First People's Hospital of Yueyang approved the current study, which also adhered to the principles of the Declaration of Helsinki. Sixty participants were randomly assigned to the training (n = 30) and control groups (n = 30). Due to the decision of two participants in the training group to withdraw from the experiment, only twenty-eight remained. The ages of the two groups were comparable (all, $P > 0.1$). All screenings were conducted collectively by the research team Table 1.

Apparatus

The experiment was run by MATLAB with PsychToolbox extensions [2]. The screen has a meanluminance of 41 cd/m², a refresh rate of 60 Hz, and a resolution of 1366 × 768 pixels.

Stimuli and procedure

The selective attention task comprised twenty-seven images, each featuring one of three colors (red, green, blue), one of three shapes (square, triangle, circle), and one of three interior structures (hollow, nested, solid). Each trial commenced with a 200-ms blank screen, followed by the random selection of two images from the set of twenty-seven to serve as targets. Participants were tasked with determining whether these two images shared the same color (Fig. 1A) or not (Fig. 1B), using the buttons on a game controller. Participants were instructed to disregard the shape and interior structure of the images. A brief beep signaled the accuracy of their response immediately after they responded. Following their response, the targets vanished, and a 500-ms blank screen appeared. Throughout the experiment, a fixation cross remained centered on the screen.

The three down one up staircase method was employed to regulate the display duration of images and monitor the temporal progression of selective attention training, as per the subjects' responses. Within the realm of perceptual learning, the up-down staircase method is commonly utilized to determine the threshold required to attain a particular percentage of correct responses. This is achieved by adjusting the stimulus level (such as contrast, luminance, etc.) according to the subject's responses [23], 25. Prior to training, the experimenter typically establishes an initial stimulus level

based on pilot data. Subsequently, the stimulus level is modified, either increased or decreased, using adaptive or fixed step sizes, contingent upon the subject's performance in each trial. The estimated threshold for a series of trials is calculated at intervals of 60 to 80 trials, and the learning curve is charted using these estimated thresholds across several blocks. The method functions by decreasing the presentation time by 10% (to 90% of its previous value) after the subject has made three consecutive correct responses, and by increasing it by 10% (to 110% of its previous value) following each incorrect response. A reversal or end point was defined by the trial after which presentation time was increased or decreased. The initial four (for an even total number of reversals) or five (for an odd total) reversals were omitted. The threshold for distinguishing the color of the two images was determined by averaging the subsequent reversals. The initial presentation duration for each staircase was established close to the anticipated threshold, as inferred from preliminary testing. The mean accuracy rate was 79.3%.

Design

The experiment was divided into three distinct stages: a pre-test phase, a selective attention training phase, and a post-test phase. During the pre-test, participants' cognitive functions were evaluated using MMSE and MoCA. The training phase consisted of subjects completing 10 days of training over a span of two weeks, with each day's training comprising two separate blocks. Following the training phase, the post-test was conducted, where cognitive functions were once again assessed using the MMSE and MoCA. The training group underwent all three stages, whereas the control group only took part in the pre- and post-tests.

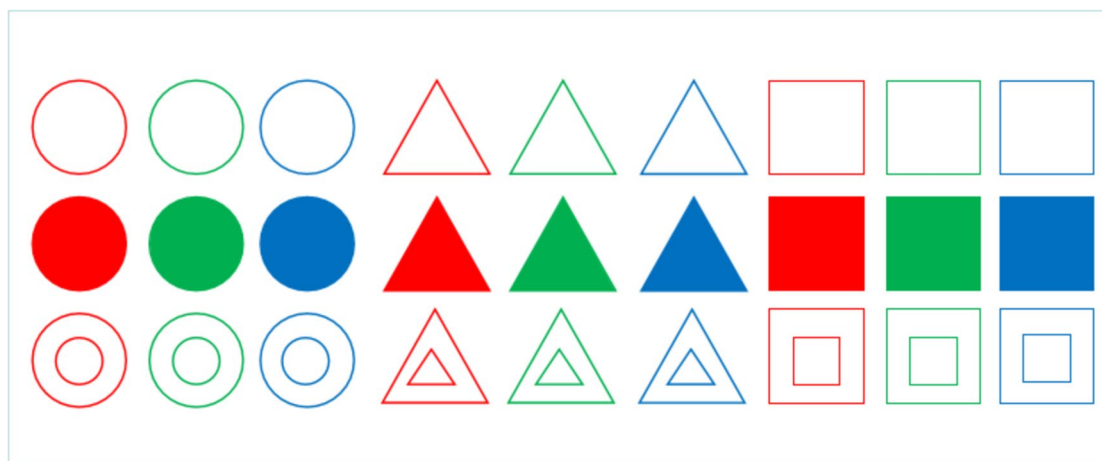


Fig. 1 Pictures in selective attention training

The learning curve was modeled by a single exponential function:

$$T(n) = \alpha \times \exp\left(\frac{-n}{\beta}\right) + \gamma \quad (1)$$

where T is the threshold, n is the training blocks. Learning amount, learning speed, and asymptotic performance level was denoted by α , β , and γ , respectively. Thus, $\alpha + \gamma$ indicated the initial performance. For β , the large value referred to a slow learning speed and vice versa. For α and γ , the large value referred to poor threshold and vice versa.

Results

Training group

The exponential function was applied to the block thresholds of each participant. The average goodness of fit (r^2) for each participant was $63.52 \pm 4.27\%$, and the mean values for α , β , γ , and $\alpha + \gamma$ across all participants were 8.29 ± 1.27 (mean \pm standard deviation), 8.12 ± 2.01 , 1.89 ± 0.11 , and 9.48 ± 1.34 , respectively. These results suggest that participants in the training group experienced significant learning gains. Subsequently, a Pearson correlation analysis was conducted on the four parameters of the learning curve. Initially, the initial threshold was positively correlated with the amount of learning and the asymptotic performance level, but negatively correlated with learning speed. This suggests that participants who performed poorly baseline Abilities exhibited a greater amount of learning and faster learning speeds, yet had a poorer asymptotic performance level. Secondly, the amount of learning was negatively correlated with learning speed, but positively correlated with the asymptotic performance level. This indicates that a larger amount of learning is associated with faster learning speeds and a poorer asymptotic performance level. Thirdly, learning speed was negatively correlated with the asymptotic performance level, suggesting that participants with faster learning speeds were likely to have a poorer asymptotic performance level. The correlation matrix is detailed in Table 2.

Meanwhile, The learning progress of 28 participants is plotted in Fig. 2.

From Tables 3 and 4 the MoCA and MMSE scores were (14.82 ± 4.81) and (20.07 ± 3.67) in the pre-test, respectively; and were (21.36 ± 3.70) and (25.00 ± 2.11) in the post-test, respectively. A paired T-test revealed that the differences between pre- and post-test scores were significant for both MoCA ($P < 0.05$) and MMSE ($P < 0.05$). The improvements in MoCA and MMSE scores were (6.39 ± 2.96) and (4.93 ± 2.54) , respectively. There was no significant correlation between age and either MoCA or

MMSE scores. The MoCA score in the pre-test was positively correlated with that in the post-test, as well as with its improvement. Similarly, the MMSE score in the pre-test was positively correlated with that in the post-test, and with its improvement. Additionally, the improvements in MoCA and MMSE scores were positively correlated. These results suggest that subjects with poor cognitive abilities experienced greater benefits from the selective attention training. Furthermore, the four parameters of the learning curve were not correlated with the scores of MoCA or MMSE in either the pre- or post-tests, nor with their improvements.

Control group

The MoCA and MMSE scores were (14.00 ± 3.35) and (19.67 ± 2.73) in the pre-test, respectively; and were (15.17 ± 3.24) and (20.37 ± 2.59) in the post-test, respectively. A paired T-test revealed that the differences between the pre- and post-test scores were significant for both MoCA ($P < 0.05$) and MMSE ($P < 0.05$). However, the improvements in MoCA and MMSE scores were minimal: (1.17 ± 1.05) and (0.70 ± 0.70) , respectively.

Comparison between two groups

The age, MoCA, and MMSE scores in the pre-test were comparable between the two groups ($P < 0.05$). However, the MoCA scores in the pre-test for the training group were significantly higher than those in the control group ($t = 8.833$, $P < 0.01$). The improvement in MMSE scores was also greater for the training group, which were significantly higher than those in the control group ($t = 8.519$, $P < 0.01$). These results indicated that the training group gained cognitive ability after the selective attention training, and there was a practice effect on the MoCA and MMSE.

Discussion

In the present investigation, we assessed the impact of CT utilizing an adaptive approach on selective attention among individuals with MCI. Additionally, we explored its transfer effects on other cognitive functions through the use of MMSE and MoCA assessments. The findings indicated that: (1) Initial performance is positively correlated with Learning amount and asymptotic performance level, and negatively correlated with learning speed; (2) Age is negatively correlated with learning speed, while it is positively correlated with the other three parameters. (3) Higher pre-training MMSE scores predicted higher post-training MMSE scores but less improvement; (4) Higher pre-training MoCA scores predicted higher post-training MoCA scores and less

Table 2 Correlation matrix

	Age	Moca In pre-test	Moca In post-test	Mmse In pre-test	Mmse In post-test	MoCA gain	MMSE gain	Learning amount	Learning speed	Asymptotic performance level	Initial performance
Age	1	0.311	0.158	0.130	0.191	-0.327	-0.029	0.565**	-0.435*	0.548**	0.584**
Moca in pre-test	0.311	1	0.817**	0.916**	0.756**	-0.641**	-0.696**	-0.069	0.011	-0.071	-0.071
Moca in post-test	0.158	0.817**	1	0.783**	0.754**	-0.080	-0.506**	-0.276	0.141	-0.208	-0.280
Mmse in pre-test	0.130	0.916**	0.783**	1	0.742**	-0.541**	-0.830**	-0.298	0.153	0.004	-0.284
Mmse in post-test	0.191	0.756**	0.754**	0.742**	1	-0.303	-0.242	-0.138	0.078	-0.153	-0.144
MoCA gain	-0.327	-0.641**	-0.080	-0.541**	-0.303	1	0.530**	-0.248	0.168	-0.155	-0.250
MMSE gain	-0.029	-0.696**	-0.506**	-0.830**	-0.242	0.530**	1	0.317	-0.157	-0.133	0.292
Learning amount	0.565**	-0.069	-0.276	-0.298	-0.138	-0.248	0.317	1	-0.648**	0.541**	0.998**
Learning speed	-0.435*	0.011	0.141	0.153	0.078	0.168	-0.157	-0.648**	1	-0.466*	-0.656**
Asymptotic performance level	0.548**	-0.071	-0.208	0.004	-0.153	-0.155	-0.133	0.541**	-0.466*	1	0.596**
Initial performance	0.584**	-0.071	-0.280	-0.284	-0.144	-0.250	0.292	0.998**	-0.656**	0.596**	1

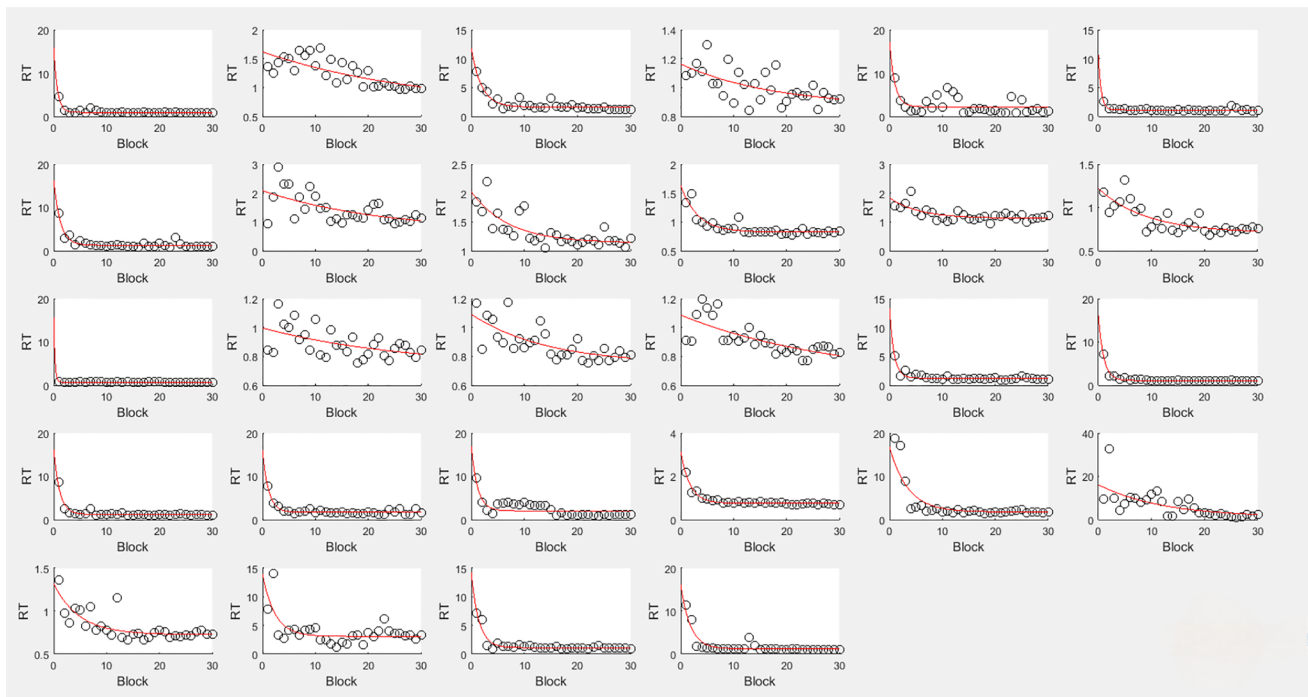


Fig. 2 Individual learning curve

Table 3 Comparison of MOCA Scores Between Two Groups Before and After the Intervention(mean ± sd)

Group	Participants	Pre-test (MOCA)	Post-test (MOCA)	Average progress	T value	P value
Experimental	28	14.82 ± 4.81	21.36 ± 3.70	6.39 ± 2.96	12.431	0.000
Control	30	14.00 ± 3.35	15.17 ± 3.24	1.17 ± 1.05	6.067	0.000
T value		0.750	6.788	8.833		
P value		0.457	0.000	0.000		

Table 4 Comparison of MMSE scores between two groups before and after the intervention (mean ± sd)

Group	Participants	Pre-test (MOCA)	Post-test (MOCA)	Average progress	T value	P value
Experimental	28	20.07 ± 3.67	25.00 ± 2.11	4.93 ± 2.54	10.277	0.000
Control	30	19.67 ± 2.73	20.37 ± 2.59	0.70 ± 0.70	5.46	0.000
T value		0.474	7.435	8.519		
P value		0.638	0.000	0.000		

improvement; (5)The parameters of the learning curve did not correlate with performance on the MMSE or MoCA.

Based on the previous discussion, among the four parameters involved in the learning curve, the initial performance is related to baseline ability. A higher initial scores indicates poorer baseline ability of the participants, whereas a lower initial scores suggests better baseline ability. The asymptotic performance level is associated with the final performance that participants can achieve through cognitive learning. A higher asymptotic performance level indicates poorer final performance achieved through cognitive learning, whereas a lower asymptotic performance level suggests better final

performance. Learning speed represents the time taken by participants to progress from the initial performance to the final performance through training, while learning amount represents the magnitude of cognitive learning.

Current research shows that the initial performance is positively correlated with learning amount and negatively correlated with learning speed. This indicates that within a certain range, poorer baseline ability leads to a greater amount of learning, and this learning occurs at a faster speed. This suggests that older adults with poorer baseline abilities have a greater need for cognitive training, and the training effects are both rapid and significant. However, the

longevity of these benefits is currently uncertain. Nonetheless, this is a path worth pursuing in the future. This outcome strongly supports the compensation hypothesis, which posits that aging individuals with diminished attentional capacities will experience more significant learning gains during training. Our results align with those of previous studies [15, 22]. For instance, Borella et al., [1] discovered that healthy older adults with lower working memory and vocabulary scores prior to testing benefited more from the training program. An advantage of our study is the broad age range of the MCI subjects, spanning from 62 to 95 years. Consequently, our findings are more universally applicable.

The initial performance is positively correlated with the asymptotic performance level. This reflects that older adults with poorer baseline abilities tend to achieve poorer final performances, whereas those with better baseline abilities, despite having smaller learning amounts, can achieve superior final performances through cognitive learning. This implies that older adults with poorer baseline abilities may require more diversified training programs to achieve the same training effects as those with better baseline abilities. Research has also found that age is positively correlated with initial performance, asymptotic performance level, and learning amount, but negatively correlated with learning speed. This suggests that as age increases, cognitive baseline abilities decline. This indicates that age is associated with cognitive levels and, to a certain extent, suggests that the probability of developing Alzheimer's disease increases with age. This result is consistent with some previous neurological studies, such as those by Depp et al., [3], which found age-dependent structural defects in myelin that directly or indirectly promote the formation of A β plaques, a risk factor for amyloid deposition.

The Mini-Mental State Examination (MMSE) is a widely used short cognitive screening test, initially developed to detect Mild Cognitive Impairment (MCI) and dementia in medical and psychiatric patients. However, the MMSE and the Montreal Cognitive Assessment (MoCA), a more recent test created in a memory clinic setting, have distinct target functions. The MMSE allocates 24 out of 30 points to memory, language, and orientation, and only 1 point to visuoconstructive function, making it less sensitive to milder forms of cognitive impairment [19]. In contrast, the MoCA dedicates 14 out of 30 points to visuospatial, attentional, and executive functions.

In the current study, both tests were employed to assess the cognitive function of subjects experiencing normal aging. The results indicated that both groups benefited from the tests, suggesting that the transfer effect of selective attention training is robust. A practice effect for the MMSE and MoCA was also noted in the control group of this study, a phenomenon that has been documented in the literature. For instance, [5] observed slight increases in MMSE and MoCA

scores after repeated measurements. In the present study, the training group showed improvements of 4.39 and 6.79 on the MMSE and MoCA, respectively, compared to the control group's improvements of 0.70 and 1.17. Consequently, we believe that our observed transfer effect is quite reliable. The reason may be that the brain is an organic whole, and any training of a function is not independent, but requires the close cooperation of several brain regions to complete. This has been verified in neurobiology, such as Engvig et al., [4], who found that cognitive training can change the activation state of some brain regions related to the training task.

In summary, we found that selective attention training with adaptive methods effectively enhanced the selective attention of subjects experiencing MCI, and that this improvement could transfer to other major cognitive abilities measured by the MMSE and MoCA. Furthermore, initial performance was found to predict learning amount, learning speed, and asymptotic performance levels. Subjects with poorer initial performance often learned faster and more extensively, yet their final performance remained lower than those who started with better initial abilities. Looking ahead, we plan to expand our training initiatives to reach a broader audience, including individuals recovering from strokes and those in the early stages of Alzheimer's disease. We will tailor our training programs to various groups, incorporating targeted exercises such as those focusing on executive function and spatial orientation. Once we have established significant outcomes, our aim is to implement more user-friendly approaches, such as creating mobile applications that can be easily accessed on smartphones, thereby facilitating the dissemination of our research findings to communities that lack extensive training resources.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s40520-024-02913-5>.

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Author contributions Chenxi Li: Organize, write programs, coordinate experiments, design experiments, and write. Funding acquisition-Meiyun Li: Experimental design, data analysis, and writing Yunfeng Shang: Ethics, experimental design, writing, data analysis, and Funding acquisition, review & editing.

Data availability All data supporting the findings of this study are available within the paper and its Supplementary Information.

Declarations

Conflict of interest The authors declare no competing interests.

Human and animal rights The human subjects involved in this study have strictly adhered to the ethical principles of human medical research as outlined in the Helsinki Declaration and its subsequent amendments. All participants were fully informed of the research purpose, methods, expected outcomes, potential risks, and personal pri-

vacy protection measures before participating in the study, and signed an informed consent form. This study has been approved by the Ethics Committee of Yueyang Central Hospital, ensuring the legality, ethics, and protection of the rights and interests of the subjects in the research activities. This article does not contain any studies with animals performed by any of the authors.

Informed consent The autonomy of the subjects was studied and respected, and all participants and their families signed informed consent forms.

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