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Effects of Tablet-Based Cognitive Training in Cognitively Unimpaired Older Adults: A Randomized Controlled Trial

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Objective This study aimed to evaluate the neurophysiological and cognitive effects of a tablet-based cognitive training program in cognitively unimpaired (CU) older adults, in order to explore its potential as an accessible intervention for promoting cognitive health in aging populations.

Methods In a single-center, rater-blind randomized controlled trial, 40 CU older adults were assigned to either a 10-week tablet-based cognitive training intervention or a passive control group. Resting-state quantitative electroencephalography was conducted to assess spectral power and functional connectivity (FC) across cortical regions. Cognitive outcomes were measured using seven tests from the Cambridge Neuropsychological Test Automated Battery, covering memory, attention, and executive function domains.

Results Compared to the control group, participants in the intervention group showed significant increases in absolute power in beta1–3, theta, and gamma frequency bands, particularly in frontal and central regions. FC analysis revealed enhanced coherence in fronto-temporal and occipital regions following the intervention. Cognitive assessment demonstrated significant improvements in memory tasks, including delayed matching to sample, paired associates learning, and pattern recognition memory, in the intervention group. No significant changes were observed in attention or executive function domains.

Conclusion Tablet-based cognitive training was associated with measurable neurophysiological changes and selective improvements in memory performance among CU older adults. These findings support the potential of digital cognitive training as a non-pharmacological intervention to promote cognitive resilience and neural efficiency in aging. Further large-scale and long-term studies are warranted to confirm the durability and underlying mechanisms of these effects. Psychiatry Investig 2025;22(11):1319-1333

Keywords Cognitive training; Electroencephalography; Brain mapping; Neuroplasticity; Aged.

INTRODUCTION

The global aging population is projected to increase significantly, leading to growing concerns about age-related cognitive decline.[1] Given this trend, maintaining cognitive health is critical for preserving quality of life and independence among older adults. Among non-pharmacological strategies, cognitive training has emerged as a promising strategy to enhance cognitive function and mitigate decline.[2] Recent advances in digital technology, particularly tablet-based platforms, have made cognitive training more accessible, scalable, and engaging for older adults.[3] These interventions can overcome traditional barriers such as high cost, and geographic limitations.[4] Importantly, technology-driven training can be tailored to individual abilities and offer real-time feedback, enhancing adherence and motivation.[3] A key theoretical basis for cognitive training is the concept of cognitive reserve, the brain's adaptive capacity to compensate for age-related neural changes by optimizing existing networks or recruitment of alternative pathways.[5,6] This framework underpins cognitive interventions aimed at enhancing neural efficiency and resilience. Evidence suggests that cognitively stimulating activities may increase reserve and delay the onset of clinical symptoms in neurodegenerative diseases.[7] The cognitive benefits of digital cognitive training are also well-documented using standardized cognitive assessments. Previous randomized controlled trials

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(RCT) have demonstrated the efficacy of these interventions in improving processing speed, episodic memory, executive function, and working memory among cognitively unimpaired (CU) older adults and those with subjective memory complaints.[8,9]

Beyond cognitive improvements, digital cognitive training may also promote neuroplastic changes, particularly in attention and memory-related networks.[4,10] Electroencephalography (EEG), which captures real-time neural dynamics, enables the assessment of training-induced changes in functional connectivity (FC) related to cognitive performance.[11] Prior research has linked EEG frequency band activity and connectivity patterns to various cognitive functions, including working memory, attention, perceptual speed, and memory performance.[12-15] Emerging studies have further demonstrated that digital cognitive training can modulate EEG-based FC patterns across cognitive networks.[16]

In addition to EEG findings, previous neuroimaging studies using functional magnetic resonance imaging (fMRI) and positron emission tomography (PET) have also demonstrated neuroplastic effects following cognitive training. For instance, fMRI studies have shown increased activation and FC in fronto-parietal and hippocampal networks, regions crucially involved in executive functions and memory.[17,18] PET studies have similarly reported training-induced metabolic changes, reflected as improved glucose metabolism in cortical and subcortical areas associated with attention and episodic memory.[19] These fMRI and PET findings align with EEG-based connectivity results, collectively highlighting enhanced activation in cognitive control networks following cognitive training. However, EEG uniquely captures rapid temporal dynamics that other imaging modalities might miss, as it directly measures electrical brain signals rather than relying on indirect hemodynamic or metabolic proxies. Moreover, EEG is non-invasive, portable, and cost-effective, allowing for repeated measurements over short intervals. This is an essential advantage for detecting neurophysiological changes during relatively brief interventions such as our 10-week cognitive training. These features make EEG particularly suitable for evaluating both the immediate and cumulative neural effects of digital cognitive training in older adults.

In this context, we investigated the effects of tablet-based cognitive training in CU older adults using both neurophysiological measures (quantitative EEG) and cognitive assessments by Cambridge Neuropsychological Test Automated Battery (CANTAB). Based on prior research,[20,21] we hypothesized that participants in the cognitive training group would exhibit increases in EEG spectral power, particularly in the beta, theta, and gamma bands, along with enhanced FC in fronto-temporal networks, compared to a passive control group. We also expected the cognitive training group to show superior cognitive improvements relative to controls.

METHODS

Study design

This was a prospective, single-center, rater-blind, and RCT, which conducted from August 23, 2024 to November 21, 2024 at the Memory Disorder Clinic of Ewha Womans University Mokdong Hospital in Seoul, Republic of Korea. A CONSORT flow diagram of the present study is shown in Figure 1. No patients or members of the public were involved in the design, conduct, reporting, or dissemination of this research.

Sample size calculation

We assumed a moderate group difference in EEG-derived measures of neural activity following the 10-week cognitive training intervention, with a mean difference of 0.13 and a standard deviation of 0.13. Based on a two-sided significance level of 0.05 and 80% power, a minimum of 17 participants per group was required. Accounting for an anticipated 15% dropout rate, a total of 40 participants (20 per group) were recruited.

Participants

A total of 42 CU older adults were recruited from Ewha Womans University Mokdong Hospital in Seoul. All participants underwent a comprehensive neuropsychological evaluation administered by trained clinical neuropsychologists using the Seoul Neuropsychological Screening Battery-II (SNSB-II).[22] The SNSB-II assesses five major cognitive domains: attention, visuospatial function, memory, language, and frontal executive function. Attention was measured using the Digit Span Forward and Backward tests. Visuospatial function was evaluated using the copy score of the Rey–Osterrieth Complex Figure Test (RCFT). Verbal memory was assessed via the delayed recall score of the Seoul Verbal Learning Test (SVLT), and visual memory was assessed using the delayed recall score of the RCFT. Language ability was evaluated with the Korean version of the Boston Naming Test (K-BNT), and frontal executive function was assessed using the Trail Making Test (TMT) Parts A and B.

CU status was defined as individuals aged 60 years or older who scored above -1 standard deviation from the mean of age- and education-matched norms in assessments of attention, visuospatial function, memory, language, and frontal executive function.

Exclusion criteria included the presence of any of the following: 1) suspected or diagnosed mild cognitive impairment or dementia; 2) suspected or diagnosed major neurological

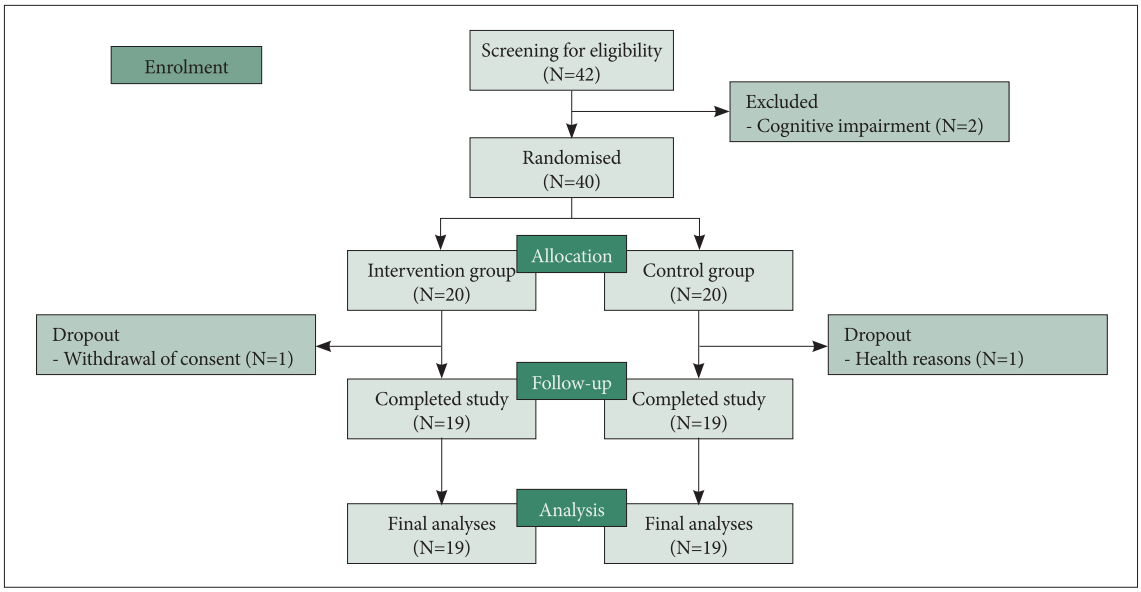

Figure 1. CONSORT flow diagram of the study.

or psychiatric disorders, including major depressive disorder; 3) severe visual or hearing impairments that could interfere with questionnaire responses; 4) use of medications affecting cognitive or emotional function within the past 3 months; and 5) other major medical conditions.

Of the 42 participants initially recruited, two were excluded due to screening results indicating mild cognitive impairment. Therefore, a total of 40 participants were included in this study. Written informed consent was obtained from all participants. The research protocol was approved by the institutional review board (IRB) of Ewha Womans University Mokdong Hospital (IRB No. 2024-07-004-004) and conducted in accordance with relevant guidelines and regulations, including the Declaration of Helsinki. Written informed consent was obtained from all participants. The study protocol was also registered at the Clinical Research Information Service as KCT0009867. No changes were made to the protocol after trial initiation.

Randomization

After the baseline assessment, 40 participants were randomly allocated in a 1:1 ratio to two groups: the intervention group (n=20) and the control group (n=20) (Figure 1). Simple randomization was performed by a statistician who did not participate in the study and had no contact with study participants.

Blindness

This study was conducted as a single-blind RCT. Outcome evaluators were blinded to the group assignment of participants and were not involved in the delivery of the intervention. Randomization was performed using a computer-generated allocation sequence by an independent third party who had no contact with participants. Participants were not informed of their group allocation during the trial period. While the intervention (tablet-based cognitive training) was distinguishable from the passive control condition, evaluators remained blinded throughout the study to minimize assessment bias.

Intervention

Participants in the intervention group underwent a structured 10-week tablet-based cognitive training program called FunXingQ (Creple). This program was designed to enhance eight cognitive domains: abstract thinking, reasoning, analytical skills, judgment, spatial cognition, perceptual speed, constructive ability, and visual-perceptual insight. Participants were instructed to complete training sessions for at least 60 minutes per day, 5 days per week.

The program comprised a total of 31 gamified training tasks categorized into the following eight cognitive domains: 1) Abstract thinking: designed to develop the ability to classify and synthesize diverse information and concepts to understand the properties and attributes of objects. For example, identifying patterns with the same motif despite different shapes. 2) Reasoning: focused on enhancing logical inference and problem-solving skills by deducing new information from existing facts. For instance, identifying missing numbers in a numerical sequence. 3) Analytical skills: aimed at strengthening the ability to deconstruct complex situations and uncover hidden meanings, such as performing arithmetic operations (e.g., subtraction) by observing a game of jackstones and determining how many stones remain on the hand ver-

sus those dropped. 4) Judgment: intended to improve decision-making abilities by evaluating the correctness or relevance of information. For example, identifying the side view or shadow of an animal based on its rear view. 5) Spatial cognition: enhances the capacity to perceive spatial relationships, distances, and positions, and manipulate this information. For instance, reconstructing original shapes from fragmented pieces. 6) Constructive ability: develops the skill to integrate individual components into a cohesive structure and understand its overall organization. For example, finding matching composite shapes and their constituent parts. 7) Perceptual speed: trains participants to rapidly recognize and process visual stimuli. For example, identifying the color of a flag held by a driver and inferring the color of the driver's clothing. 8) Visual-perceptual insight: aims to foster multi-perspective interpretation and visual problem-solving. For instance, inferring the season by observing the state of trees and identifying hidden animals behind them. Examples of each training component are illustrated in Figure 2.

Each daily session comprised two training blocks, each containing eight tasks, for a total of 16 tasks per day. The difficulty of tasks was adaptively adjusted throughout the program to match participants' evolving abilities and to maintain engagement. For instance, early sessions emphasized simpler tasks such as basic pattern recognition or arithmetic, while later sessions introduced more complex exercises involving multi-step problem solving and abstract reasoning.

To promote adherence, participants' activity logs were automatically generated and reviewed weekly by study personnel. If a participant failed to complete their assigned training, research staff contacted them to provide support and encouragement. Adherence was operationally defined as the proportion of completed training sessions out of the total number of prescribed sessions for each participant.

Outcome measures

Primary outcome: brain function measured by quantitative EEG

Resting-state brain activity was assessed using an FDA 510(k)-cleared wireless dry EEG system (iSyncWave®; iMediSync Inc.; K220056), equipped with 19 Ag/AgCl-coated conductive polymer dry electrodes placed according to the international 10–20 system (Fp1, Fp2, F7, F3, Fz, F4, F8, T3, C3, Cz, C4, T4, T5, P3, Pz, P4, T6, O1, O2).[23-25] EEG data were recorded for 3 minutes each under eyes-open and eyes-closed conditions. Raw signals were bandpass-filtered between 0.5–70 Hz with a 60 Hz notch filter to eliminate line noise.

Resting-state EEG artifact removal was conducted in two steps. Initially, epochs with excessive transient noise or unstable signals were automatically flagged using amplitude threshold criteria (e.g., ±100 μV) and confirmed by visual inspection to exclude contaminated segments.[26-28] Subsequently, stationary artifacts related to eye movement, electrocardiographic, and electromyographic activity were removed using Adaptive Mixture Independent Component Analysis (AMICA), an advanced ICA technique that models EEG as mixtures of source distributions.[29] This procedure was augmented by the iSyncBrain® cloud-based platform, which employs a patented automated denoising system combining AMICA with convolutional neural network-based deep learning and machine learning algorithms to further detect and eliminate artifact-contaminated channels and epochs.[30,31]

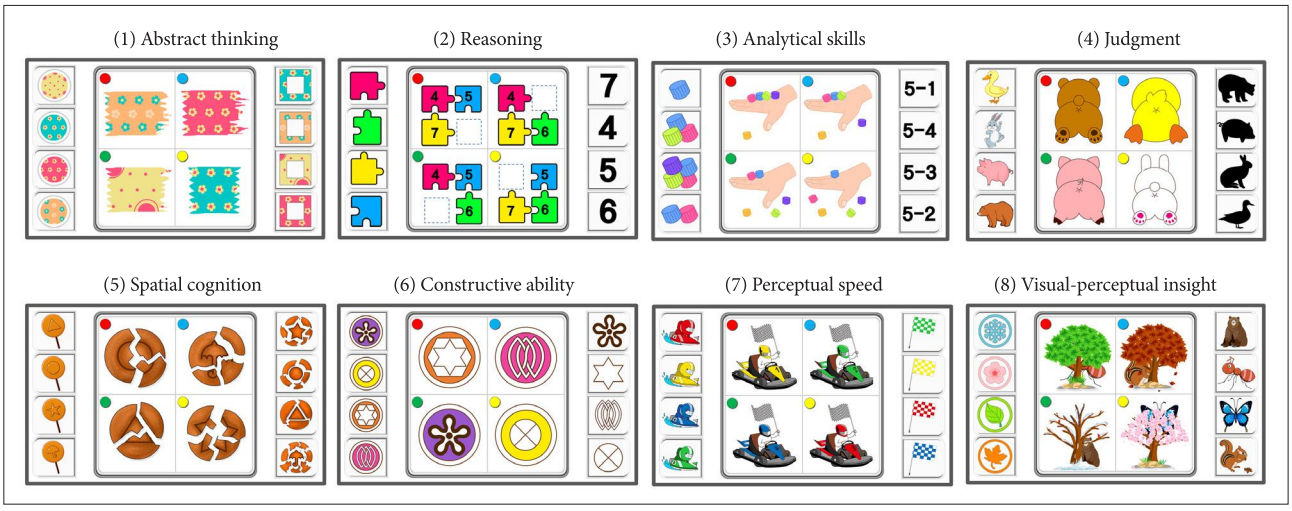

Figure 2. Example tasks from the eight cognitive domains targeted by the FunXingQ cognitive training program. Task examples are provided for (1) abstract thinking, (2) reasoning, (3) analytical skills, (4) judgment, (5) spatial cognition, (6) constructive ability, (7) perceptual speed, and (8) visual-perceptual insight. Detailed descriptions of each domain are provided in the methods section.

At the sensor level, absolute power ($\mu V^2/Hz$) was computed using fast Fourier transform across the following EEG frequency bands: delta (1–4 Hz), theta (4–8 Hz), alpha1 (8–10 Hz), alpha2 (10–12 Hz), beta1 (12–15 Hz), beta2 (15–20 Hz), beta3 (20–30 Hz), and gamma (30–45 Hz). For analytical purposes, these frequency bands were grouped into lower (delta, theta), middle (alpha1, alpha2, beta1, beta2, beta3), and higher (gamma) frequency ranges, following established classifications.[32,33] Relative power for each band was derived by dividing its absolute power by the total power. Artifact-free spectral values were averaged across five scalp regions: frontal, central, parietal, temporal, and occipital.

Topographic maps of absolute power were generated using the cloud-based quantitative EEG analysis platform, iSyncBrain®.[34] FC was evaluated via the imaginary part of coherence (iCoh), which quantifies phase synchronization while minimizing volume conduction influences. Source-level signals were reconstructed using standardized low-resolution brain electromagnetic tomography (sLORETA), projecting EEG data onto 68 cortical regions as defined by the Desikan–Killiany atlas.[35,36] Finally, graph theoretical methods applied to sLORETA-derived connectivity matrices were used to assess the topological organization of functional networks. All EEG analyses were performed through the iSyncBrain® cloud-based platform.

Secondary outcome: cognitive performance

Secondary outcome variables included changes in mean scores in the seven tests based on the CANTAB, a computerized cognitive assessment tool designed to evaluate various cognitive domains including memory, attention, and executive function.[37,38] Each task targeted a specific cognitive domain, and a corresponding outcome variable was selected for analysis as follows:

Memory

Delayed matching to sample

This task assesses short-term visual recognition memory. The outcome variable was delayed matching to sample percent correct at 0-second delay (DMS PC0), which reflects the percentage of trials with no delay in which the participant correctly identified the matching stimulus on their first attempt.

Paired associates learning

This task measures episodic memory by requiring participants to recall the locations of visual patterns. The outcome variable was paired associates learning total errors (PAL TE), defined as the total number of incorrect responses made across all assessed trials.

Pattern recognition memory

This task evaluates recognition memory for previously presented visual patterns. The outcome variable was pattern recognition memory correct latency standard deviation (PRM CLSDD), representing the variability in reaction times (RTI in ms) for correct responses during delayed recognition trials.

Attention

Rapid visual information processing

This task assesses sustained attention and the ability to detect target sequences in a continuous stream of digits. The outcome variable was rapid visual information processing mean response latency (RVP ML), representing the average response time (in ms) for correct detections.

RTI

This task evaluates psychomotor speed and attentional response by measuring RTI to visual stimuli. The outcome variable was RTI median five-choice reaction time (RTI FMDRT), defined as the median time (in ms) taken to release the response button after the appearance of a target in one of five possible locations.

Executive function

One touch stockings of cambridge

This task tests spatial planning and executive reasoning by requiring participants to match arrangements of colored balls. The outcome variable was one touch stockings of cambridge median latency to first choice (OTS MDLFC), which represents the median time (in ms) taken to make the first correct response after the stimulus presentation.

Spatial working memory

This task assesses the ability to retain and manipulate spatial information, as well as strategic efficiency. The outcome variable was spatial working memory strategy score (SWM S), which indicates the number of times a participant initiated a search from a different starting box in multi-token trials. Higher scores reflect less consistent strategic behavior.

For all tasks, raw performance scores were converted into standardized Z-scores using the baseline mean and standard deviation of the control group. Z-scores were reverse-coded so that higher values represented better performance. No adverse events were expected or systematically monitored due to the non-invasive nature of the intervention.

Statistical analyses

Statistical analyses were conducted using STATA software version 18 (StataCorp). Baseline demographic and clinical characteristics of the intervention and control groups were compared using the chi-square test for categorical variables, independent-sample t-tests for continuous variables, and the Mann-Whitney U test for non-normally distributed variables. To examine baseline differences in neuropsychological test scores, analysis of covariance (ANCOVA) was performed, adjusting for age, sex, and years of education as covariates. A generalized linear mixed-effects model was employed to evaluate group differences in CANTAB score changes from baseline to post-intervention, incorporating visit and visit-by-group interaction as fixed effects, while treating the within-subject factor as a random effect. The model included age, sex, years of education, and baseline CANTAB scores as covariates. To assess significant between-group differences over time, each outcome variable was analyzed using ANCOVA, with baseline values included as covariates.[32] EEG data were analyzed using the cloud-based QEEG analysis platform iSyncBrain®. For sensor-level analyses, independent-sample t-tests were conducted to compare absolute power values across frequency bands at each electrode between the intervention and control groups. In addition, group-level comparisons of topographic EEG power distributions were used to assess regional scalp-level differences. For topographic analyses of absolute power across cortical regions, Mann–Whitney U tests were employed to compare group differences in regions exhibiting significant effects. For source-level analyses, FC, as measured by imaginary coherence (iCoh), was compared between the two groups across 68 cortical regions of interest using independent-sample t-tests based on sLORETA. All available outcome data were analyzed; no imputation was performed for missing values. No interim analyses or early stopping guidelines were specified.

RESULTS

Baseline characteristics

The baseline demographic and clinical characteristics of participants in the intervention (n=20) and control (n=20) groups are summarized in Table 1. All 40 participants who completed the intervention as assigned were included in the analysis of both the primary (EEG) and secondary (CANTAB) outcomes. The mean age was 74.7±4.9 years in the intervention group and 76.0±7.1 years in the control group (p=0.52). The proportion of female participants was 80% in the intervention group and 70% in the control group (p=0.47). Years of education were similar between groups (11.7±4.1 vs. 11.9±3.7, p=0.87). Baseline anxiety and depression scores, as measured by the Geriatric Anxiety Inventory (GAI) and Geriatric Depression Scale (GDS), were also comparable between groups (GAI: 2.30±4.16 vs. 3.00±1.14, p=0.92; GDS: 1.45±2.96 vs. 2.10±3.92, p=0.66). Family history of dementia did not differ significantly (35% vs. 30%, p=0.74). Cognitive function, as measured by the Korean Mini-Mental State Examination (K-MMSE-2), also showed no significant difference between the two groups.

There were no significant differences in comorbidities including diabetes mellitus, hypertension, hyperlipidemia, and heart disease between the two groups. Baseline neuropsychological performance including attention (digit span), memory (SVLT and RCFT delayed recall), language (K-BNT), and executive function (TMT-A/B) did not differ significantly between the two groups (p>0.05 for all comparisons). The average training adherence rate in the intervention group was 82.9%.

Changes in FC across EEG frequency bands in intervention and control groups

Sensor level analysis

A sensor-level analysis of EEG absolute power ($\mu V^2/Hz$) revealed significant group differences across multiple frequency bands when comparing the intervention groups to the control group. Specifically, frontal (e.g., Fp2, F3, F7, Fz), central (Cz, C4), and occipital (O1) electrode sites showed notable changes in gamma, delta, theta, alpha1/2, and beta1/2/3 bands. For instance, both gamma and delta band power significantly differed at frontal, central, and occipital sensors, whereas theta band changes were prominent in these regions as well as in the parietal area. Both alpha1 and alpha2 bands showed significant effects mainly in the central region, whereas the beta bands demonstrated changes predominantly in frontal, central, and occipital areas. All detailed statistical results (including p-values) for each sensor and frequency band are provided in Supplementary Material. While significant group differences were found in absolute power at various electrode sites and frequency bands, no statistically significant differences were observed in relative power measures.

Topographic analysis

The topographic EEG analysis demonstrated significant differences in absolute power between the intervention and control groups across specific frequency bands. In the theta band, absolute power significantly increased in the frontal region for the intervention group compared to the control group (p=0.025) (Figure 3A). In the beta bands, consistent and significant increases in absolute power were observed in the frontal and central regions. Specifically, in the beta1 band, ab-

Table 1. Baseline characteristics of the participants

	Intervention (N=20)	Control (N=20)	p
Demographic			
Sex, female†	16 (80)	14 (70)	0.47
Age (yr)	74.70±4.88	75.95±7.05	0.52
Education (yr)	11.65±4.08	11.85±3.67	0.87
Geriatric Anxiety Inventory†	2.30±4.16	3.00±1.14	0.92
Geriatric Depression Scale†	1.45±2.96	2.10±3.92	0.66
Family history of dementia	7 (35)	6 (30)	0.74
K-MMSE	28.45±0.33	28.45±0.41	0.65
Co-morbidities			
Diabetes mellitus	3 (15)	6 (30)	0.26
Hypertension	10 (50)	9 (45)	0.75
Hyperlipidemia	12 (60)	12 (60)	0.52
Heart disease	0 (0)	4 (20)	0.32
Baseline cognitive performance (Z-scores)‡			
Attention			
Digit span (forward)	0.24±0.95	0.04±0.83	0.58
Digit span (backward)	0.43±1.16	0.49±1.22	0.38
Visuospatial function			
RCFT	-0.21±0.82	-0.25±0.69	0.06
Memory			
SVLT delayed recall	0.92±0.98	0.67±0.79	0.37
RCFT delayed recall	1.11±0.90	0.95±0.88	0.96
Language			
K-BNT	0.83±0.78	0.63±0.66	0.41
Frontal executive			
TMT-A	0.92±0.37	0.83±0.39	0.11
TMT-B	0.65±0.65	0.63±0.49	0.88

Data are presented as mean±standard deviation or number (%) for dichotomous variables. †variables that failed the Shapiro–Wilk test for normality were compared between groups using the Mann–Whitney U (rank-sum) test; all others were compared by Student's t-test; ‡adjusted for age, sex, and years of education. K-MMSE, Korean version of the Mini-Mental State Examination; K-BNT, Korean version of the Boston Naming Test; RCFT, Rey–Osterrieth Complex Figure Test; SVLT, Seoul Verbal Learning Test; TMT-A, Trail Making Test Part A; TMT-B, Trail Making Test Part B.

solute power was significantly higher in the frontal (p=0.003) and central (p=0.021) regions (Figure 3B). The beta2 band similarly showed significant increases in the frontal (p=0.009) and central (p=0.025) regions (Figure 3C), while the beta3 band demonstrated elevated power in the frontal (p=0.021) and central (p=0.023) regions (Figure 3D). Additionally, in the gamma band, absolute power significantly increased in the central region for the intervention group (p=0.033) (Figure 3E). All numerical data corresponding to Figure 3 are summarized in Table 2. No significant group differences were observed in the delta, alpha1, and alpha2 bands. Topographic maps for these non-significant frequency bands are provided in Supplementary Figure 1.

FC analysis (iCoh)

FC analysis revealed significant group differences across all EEG frequency bands (Figure 4). In the lower frequency bands (delta and theta), the intervention group exhibited widespread hyper-connectivity, particularly across fronto–temporal and fronto–occipital networks, while the control group showed hypo-connectivity primarily in occipital–temporal areas (Figure 4A and B). In the alpha bands (alpha1 and alpha2), more localized changes were observed. Minimal alterations were found in the alpha1 band (Figure 4C), whereas significant increases in connectivity, especially frontal pole-rh and lingual-lh regions (rh, right hemisphere; lh, left hemisphere), were detected in the alpha2 band (Figure 4D). In the

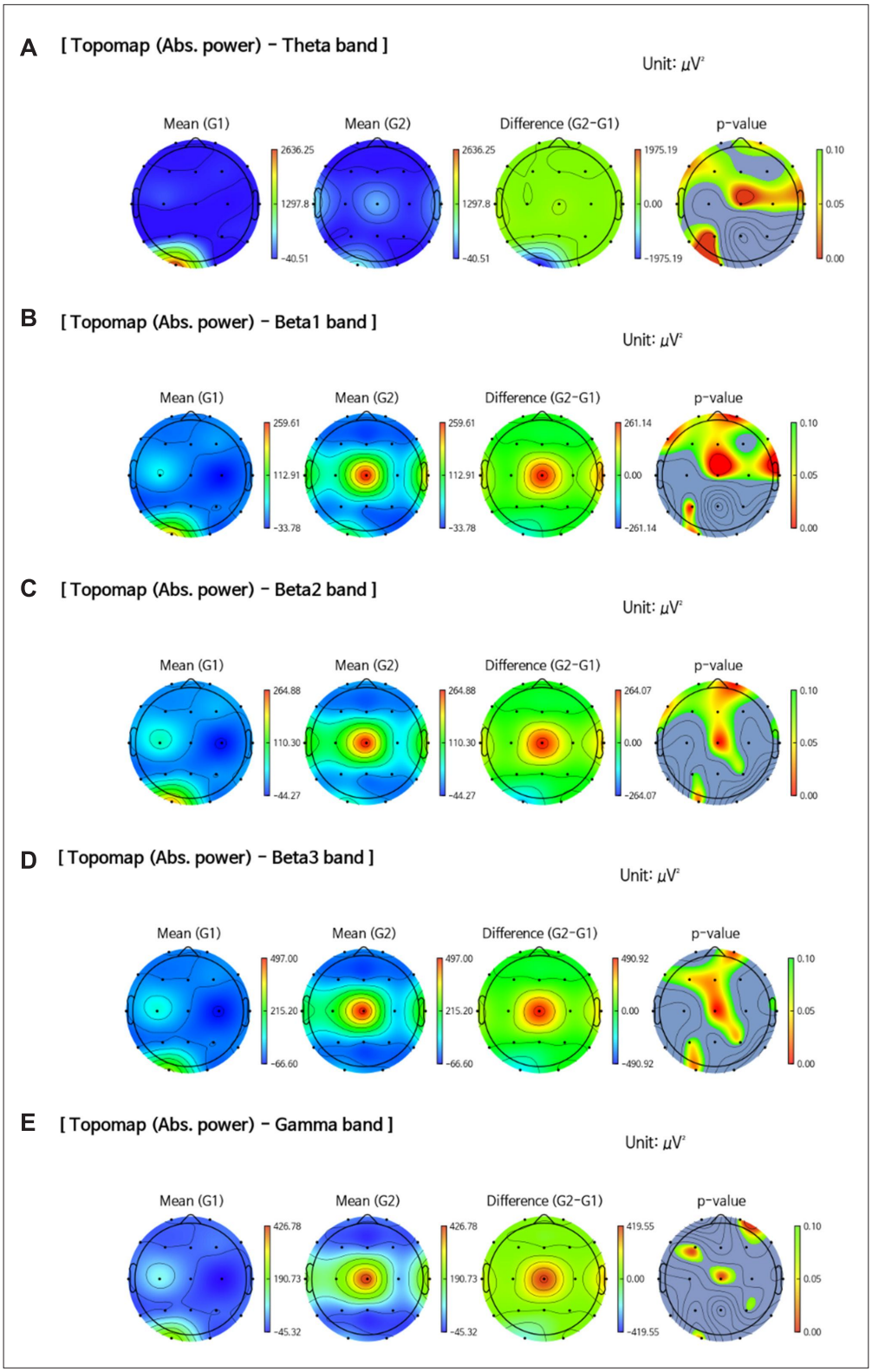

Figure 3. Topographic electroencephalography band power changes across cortical regions between intervention and control groups. A: In the theta band (4–8 Hz), absolute power significantly increased in the frontal region (p=0.025) for the intervention group. B: For the beta1 band (12–15 Hz), significant increases were observed in the frontal (p=0.003) and central regions (p=0.021) for the intervention group. C: The beta2 band (15–20 Hz) exhibited significant power increases in the frontal (p=0.009) and central regions (p=0.025). D: The beta3 band (20–30 Hz) showed elevated absolute power in the frontal (p=0.021) and central regions (p=0.023). E: Gamma band (30–45 Hz), the intervention group demonstrated a significant increase in the central region (p=0.033).

Table 2. Topographic differences in absolute electroencephalography power across frequency bands and cortical regions between intervention and control groups

Frequency band	Region	Intervention	Control	p
Theta (4–8 Hz)	Frontal	15.57±36.78	15.05±46.33	0.025*
Beta1 (12–15 Hz)	Frontal	7.04±22.82	2.67±9.30	0.003*
	Central	117.90±381.77	1.76±117.57	0.021*
Beta2 (15–20 Hz)	Frontal	6.13±18.15	2.57±8.97	0.009**
	Central	132.41±386.92	3.71±153.21	0.025*
Beta3 (20–30 Hz)	Frontal	11.66±40.04	3.34±12.53	0.021*
	Central	248.31±750.53	11.79±222.66	0.023*
Gamma (30–45 Hz)	Central	213.39±659.17	4.47±159.70	0.033*

Data are presented as mean±standard deviation. *p<0.05; **p<0.01.

higher frequency bands (beta1, beta2, beta3, gamma), the intervention group consistently demonstrated extensive hyperconnectivity involving frontal, temporal, and occipital regions (Figure 4E-H). Compared to lower frequency bands, beta band enhancements were broader, indicating greater network engagement (Figure 4E-G). In the gamma band, the intervention group exhibited elevated connectivity across fronto–temporal and occipital networks, while the control group displayed corresponding hypo-connectivity (Figure 4H).

Changes in cognitive performance on CANTAB measures in intervention and control groups

Based on the CANTAB results, significant differences between the intervention and control groups were observed in memory-related tasks. Specifically, the intervention group showed significantly greater improvement in DMS (mean change, 0.43) compared to the control group (mean change, -0.37; p=0.001). Similarly, the intervention group demonstrated a significant improvement in PAL (mean change, -0.34) relative to the control group (mean change, 0.36; p=0.004). PRM also showed a significantly greater improvement in the intervention group (mean change, -0.68) compared to the control group (mean change, 0.90; p=0.001) (Figure 5). To enhance clarity, Figure 5 visualizes only the outcomes with significant improvements (DMS, PAL, and PRM). In contrast, measures of attention and executive function did not significantly differ between the two groups. Specifically, there were no significant differences observed for RVP (intervention: -0.16, control: 0.06; p=0.320), RTI (intervention: -0.15, control: 0.28; p=0.289), SWM (intervention: -0.08, control: -0.09; p=0.712), or OTS (intervention: -0.51, control: -0.19; p=0.256) (Table 3). No adverse events or unintended effects were reported in either group during the intervention period.

DISCUSSION

This study investigated the effects of a 10-week, tablet-based cognitive training intervention on brain function and cognitive performance in CU older adults using quantitative EEG measures and standardized neuropsychological assessments. The average training adherence rate in the intervention group was 82.9%, reflecting overall satisfactory compliance.[39]

One of our major findings is that tablet-based cognitive training is associated with measurable neurophysiological changes, increased frontal theta, central gamma, and frontal/central beta1–3 power, with frequency-specific FC changes across key cortical regions. Theta activity is associated with sustained attention and encoding, gamma with memory consolidation and information integration, and beta oscillations with top–down attentional modulation, inter-regional communication, and working-memory operations.[12,40-42] The concurrent enhancement across these bands suggests strengthened integration between attentional and memory networks, which may support cognitive flexibility, memory encoding, and retrieval essential for successful aging. Topographic analysis further supported these effects, showing significant regional increases in beta1–3 and gamma power in the frontal and central lobes, suggesting enhanced activation in regions that are particularly vulnerable to age-related decline.[40,43]

FC analysis (iCoh) further demonstrated substantial improvements in inter-regional coherence, especially along fronto–temporal and fronto–occipital links, whereas the control group showed widespread posterior hypo-connectivity. This pattern accords with prior work showing training-related gains in neural synchrony and network integration in older adults.[20,44] From a neuroplasticity perspective, these changes suggest training-induced reorganization that may bolster cognitive resilience[45,46] and are consistent with cognitive reserve, whereby strengthened frontal/temporal power and connectivity support compensatory capacity.[5,7] Such adaptations align with

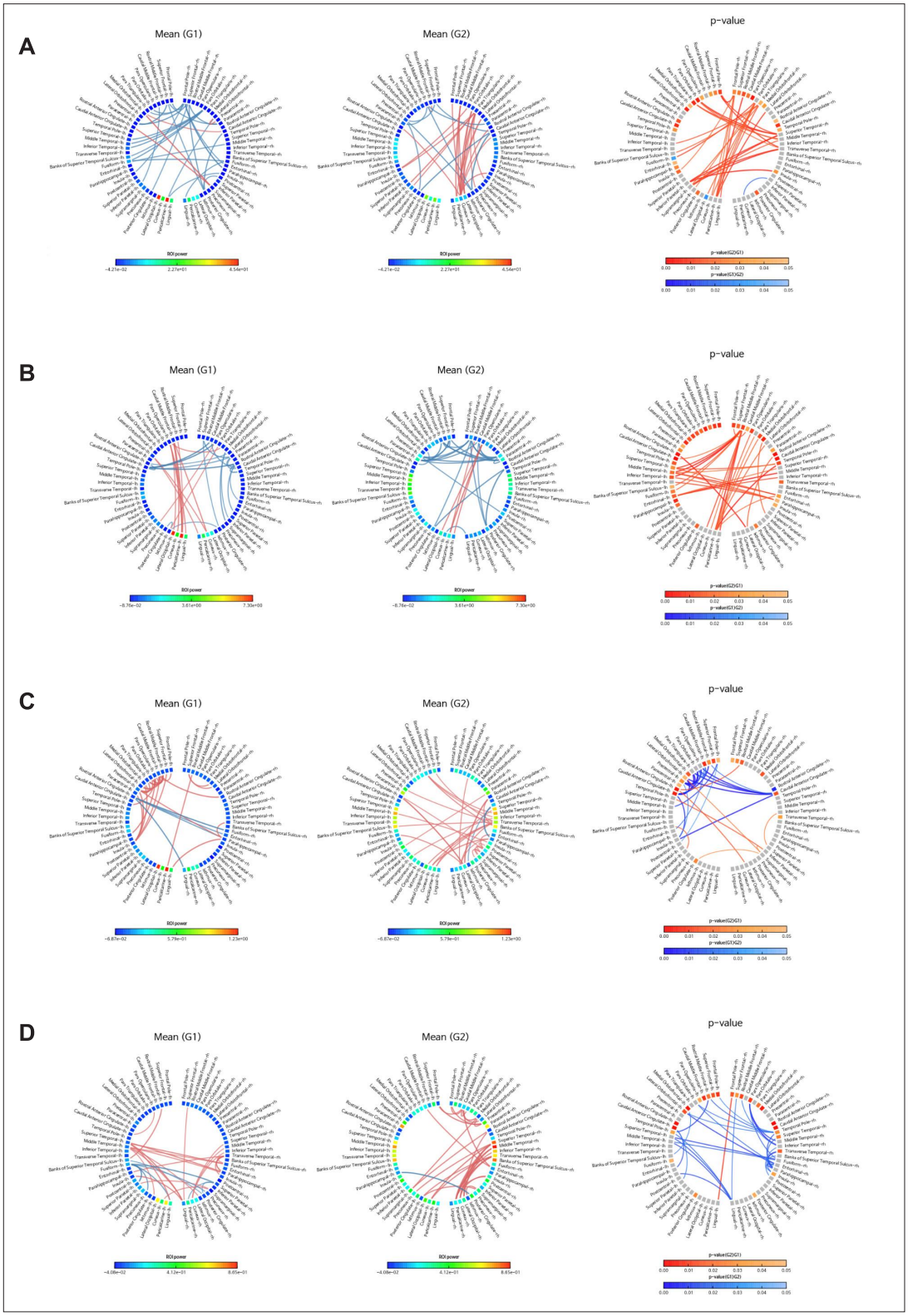

Figure 4A-D. Lower frequency EEG bands: FC differences between intervention and control groups. Circular connectivity plots illustrate FC patterns across 68 cortical ROIs based on the Desikan–Killiany atlas. Left panels represent the mean FC of the control group (G1); middle panels represent the mean FC of the intervention group (G2); right panels display statistical significance maps (p-value maps), where hyper-connectivity (G2>G1) is shown in red and hypo-connectivity (G2<G1) in blue. Significant connections ($p<0.05$) are highlighted. A: Delta band (1–4 Hz). B: Theta band (4–8 Hz). C: Alpha1 band (8–10 Hz). D: Alpha2 band (10–12 Hz). EEG, electroencephalography; FC, functional connectivity; ROI, regions of interest; LH, left hemisphere; RH, right hemisphere.

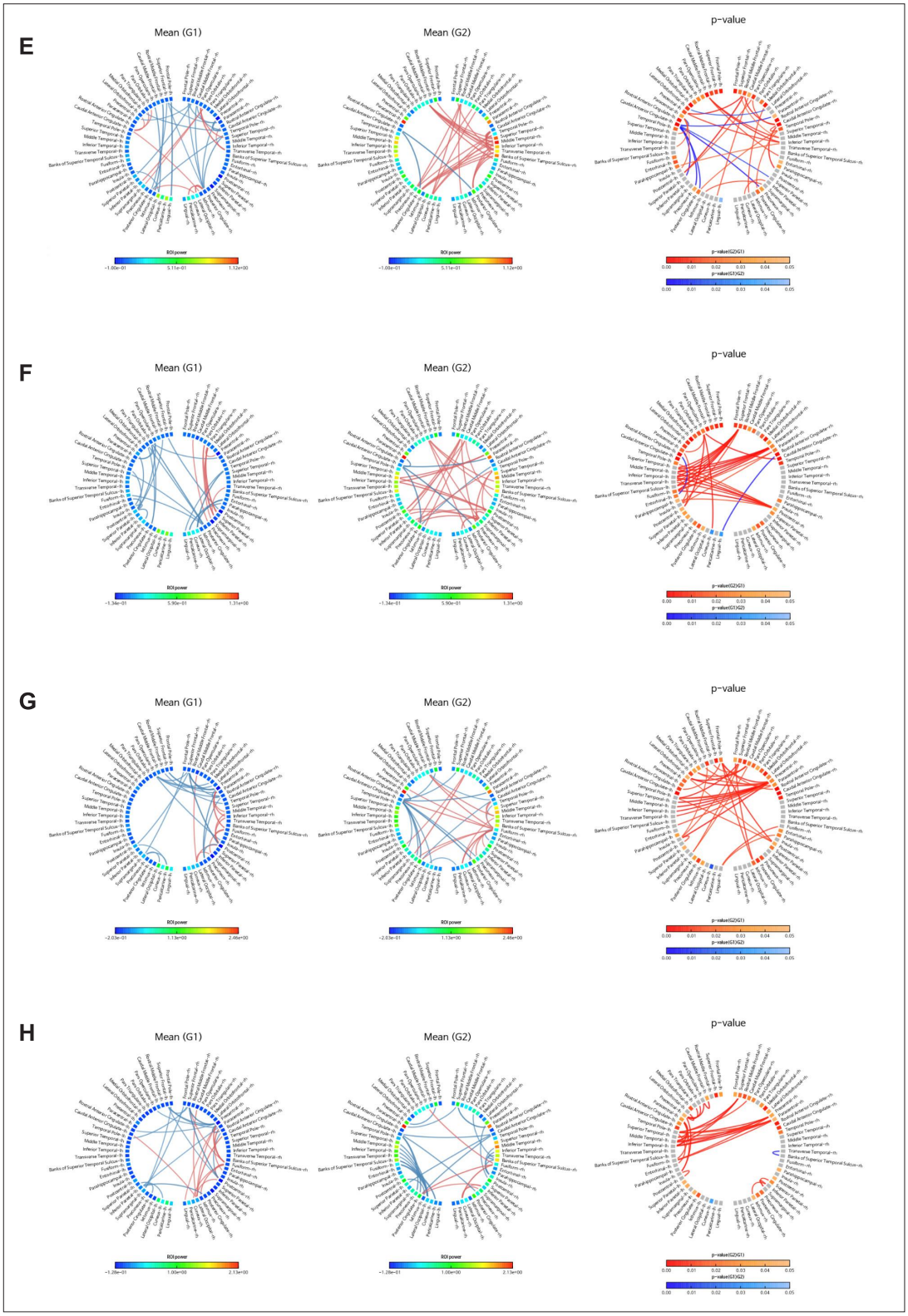

Figure 4E-H. Higher frequency EEG bands: FC differences between intervention and control groups. Circular connectivity plots show FC across 68 cortical ROIs (Desikan–Killiany atlas). Left panels display mean FC for the control group (G1); middle panels display mean FC for the intervention group (G2); right panels show statistical significance maps, with hyper-connectivity (G2>G1) indicated in red and hypo-connectivity (G2<G1) in blue. Significant group differences ($p<0.05$) are emphasized. E: Beta1 band (12–15 Hz). F: Beta2 band (15–20 Hz). G: Beta3 band (20–30 Hz). H: Gamma band (30–45 Hz). EEG, electroencephalography; FC, functional connectivity; ROI, regions of interest; LH, left hemisphere; RH, right hemisphere.

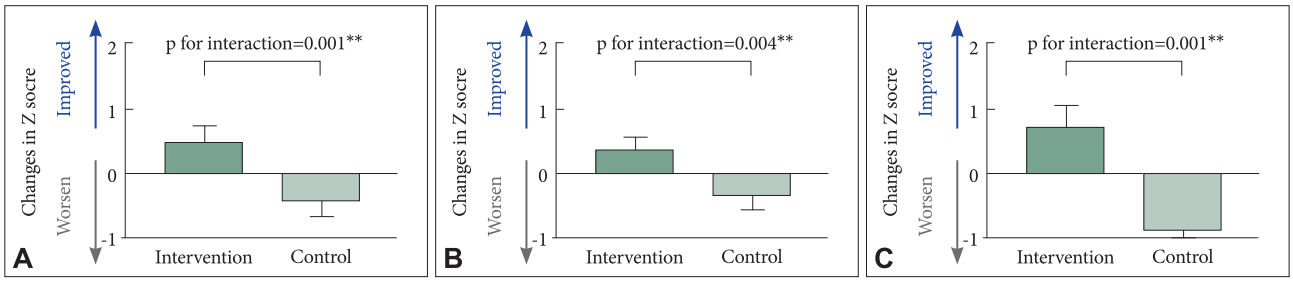

Figure 5. Effects of the cognitive intervention on memory function. The effects of cognitive intervention on cognitive function. A: Delayed matching to sample scores were significantly better in the intervention group than in the control group after the 10-week cognitive intervention (groupxtime interaction, p=0.001). B: Paired associates learning scores were significantly better in the intervention group than in the control group after the 10-week cognitive intervention (groupxtime interaction, p=0.004). C: Pattern recognition memory scores were significantly better in the intervention group than in the control group after the 10-week cognitive intervention (groupxtime interaction, p=0.001). **p<0.01.

Table 3. Changes in cognitive function after 10-week intervention

	Intervention		Mean change (Week12-baseline)	Control		Mean change (Week12-baseline)	p (group×time interaction)
	Baseline (N=20)	Week 12 (N=19)		Baseline (N=20)	Week 12 (N=19)		
Memory							
DMS	0.04±0.87	0.47±0.67	0.43	0.00±1.00	-0.37±1.08	-0.37	0.001**
PAL†	-0.02±0.83	-0.36±0.70	-0.34	0.00±1.00	0.36±1.15	0.36	0.004**
PRM†	0.65±1.29	-0.02±0.67	-0.68	0.00±1.00	0.90±1.98	0.90	0.001**
Attention							
RVP†	-0.04±0.52	-0.20±0.70	-0.16	0.00±1.00	0.06±1.21	0.06	0.320
RTI†	0.15±1.19	0.00±1.19	-0.15	0.00±1.00	0.28±0.97	0.28	0.289
Executive function							
SWM†	0.14±1.22	0.06±1.17	-0.08	0.00±1.00	-0.09±1.16	-0.09	0.712
OTS†	0.13±1.25	-0.37±0.65	-0.51	0.00±1.00	-0.19±0.71	-0.19	0.256

Adjusted for age, sex, years of education, and the baseline score of each task from CANTAB. Data are presented as mean±standard deviation. **p<0.01; †lower scores represent better performance. DMS, delayed matching to sample; OTS, one touch stockings of cambridge; PAL, paired associates learning; PRM, pattern recognition memory; RTI, reaction time; RVP, rapid visual information processing; SWM, spatial working memory; CANTAB, Cambridge Neuropsychological Test Automated Battery.

the Compensation-Related Utilization of Neural Circuits Hypothesis[47] and the Scaffolding Theory of Aging and Cognition frameworks, which propose that older adults recruit additional neural resources or alternative pathways to maintain function despite neural aging.[6,47,48]

Notably, the intervention group showed significant improvements in memory-related tasks (DMS, PAL, and PRM), despite the fact that the training program did not include explicit memory exercises. Instead, it primarily targeted reasoning, spatial cognition, perceptual speed, and other non-memory domains. Therefore, the observed gains in memory performance are likely to reflect far transfer effects,[49,50] whereby cognitive processes trained in non-memory domains such as working memory, information integration, and problem-solving indirectly enhance memory function. Many of these gamified tasks required sustained attention, manipulation of complex information, and strategic reasoning, all of which engage fronto–hippocampal networks critical for encoding and retrieval. This interpretation is consistent with our EEG findings, in which increased frontal theta and gamma activity has been closely linked to memory-related neural dynamics in previous studies.[51,52]

In contrast, we did not detect significant improvements in attention or executive function measures, nor did we observe robust resting-state EEG changes specific to frontal executive networks. Several factors may account for this discrepancy. First, the proportion and difficulty level of executive-type tasks in the 10-week program may have been insufficient to provide the level of stimulation needed to drive measurable neuroplastic changes in these domains. Second, executive control networks may inherently require more prolonged and complex, multidomain stimulation to exhibit measurable adaptation, as evidenced by long-term trials such as the Finnish Geriatric Intervention Study to Prevent Cognitive Impairment and Disability and the Advanced Cognitive Training for Independent and Vital Elderly studies.[53]

Taken together, these findings suggest that while the intervention may have preferentially engaged neural processes supporting memory through far transfer mechanisms, the duration and structure of the program may need to be modified—for example, by increasing executive function task load and by extending the training period—to produce more widespread cognitive and neural benefits.

Several limitations warrant consideration in interpreting the results of our study. First, although our sample size of 40 participants (20 per group) was sufficient to detect significant effects, larger samples may yield more robust and generalizable findings. Second, the 10-week training period may not fully capture long-term neurophysiological adaptations or broader cognitive improvements. Rebok et al.[54] demonstrated that reasoning and speed-of-processing training effects persisted for up to 10 years, highlighting the importance of extended intervention periods and long-term follow-up assessments. Moreover, booster sessions conducted at intervals post-training further enhanced the durability of these effects, underscoring the need for periodic reinforcement to sustain long-term gains. Third, we did not assess participants' habitual physical activity levels or prior experience with digital devices, both of which can influence engagement with tablet-based training and cognitive outcomes. Fourth, our study did not examine underlying neurobiological or genetic biomarkers, such as amyloid-beta deposition or genetic predispositions, which could modulate responsiveness to cognitive interventions. Incorporating such markers could help identify predictors of training efficacy and support the development of personalized intervention strategies. Fifth, although we reported significant changes in EEG metrics and cognitive scores following training, we did not directly analyze associations at the individual participant level between EEG changes and improvements in CANTAB memory scores. Lastly, the use of Z-scores to report CANTAB performance may limit clinical interpretability, as such scores are less intuitive for assessing real-world significance.

These limitations point to several promising directions for future research. Future work should include larger samples and extended training durations to evaluate long-term efficacy and generalizability. In addition, integrating multimodal neuroimaging approaches, such as combining EEG with fMRI or PET, can help clarify underlying neural mechanisms. Additionally, incorporating genetic and biological markers could enable the identification of individual differences in responsiveness, ultimately guiding the development of personalized cognitive intervention strategies.

Supplementary Materials

The Supplement is available with this article at https://doi.org/10.30773/pi.2025.0160.

Availability of Data and Material

The datasets generated or analyzed during the study are available from the corresponding author on reasonable request.

Conflicts of Interest

This study was conducted using a program developed by Creple Inc., with research funding provided by the Goyang Industry Promotion Agency. However, neither the funder nor the company had any role in the study design, data collection, data analysis, interpretation, or manuscript preparation.

Author Contributions

Conceptualization: all authors. Data curation: Sooin Moon, Seungwon Chung, Bori R. Kim. Formal analysis: Bori R. Kim. Funding acquisition: Geon Ha Kim. Investigation: Sooin Moon, Seungwon Chung, Bori R. Kim. Validation: Jee Hyang Jeong. Writing—original draft: Bori R. Kim. Writing—review & editing: Geon Ha Kim.

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