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The Effects of Neurofeedback and Mindfulness-Based Cognitive Therapy on Cognitive Flexibility and Working Memory Performance in Older Adults with Alzheimer's Disease

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A B S T R A C T

The present study aimed to determine the effectiveness of neurofeedback and mindfulness-based cognitive therapy (MBCT) in improving cognitive flexibility and working memory performance among older adults with Alzheimer's disease. In terms of purpose, this was an applied study, and methodologically, it employed a quasi-experimental design with pretest, posttest, and three-month follow-up assessments and a control group. The statistical population consisted of older adults with Alzheimer's disease residing at the Kahrizak Nursing Home and Rehabilitation Center for Older Adults and Persons with Disabilities in Tehran during 2021–2022. Among eligible individuals, 45 older adults were selected through convenience sampling and, after being matched for age, were randomly assigned to three groups: neurofeedback, mindfulness-based cognitive therapy, and control. Data were collected using the Working Memory Test developed by Daneman and Carpenter (1980) and the Cognitive Flexibility Inventory developed by Dennis and Vander Wal (2010). The neurofeedback intervention was administered in 10 sessions of 45 minutes each, while mindfulness-based cognitive therapy was delivered in 10 one-hour sessions based on the protocol developed by Crane (2017); the control group received no intervention during this period. Data were analyzed using repeated-measures analysis of variance. The results indicated that, compared with the control group, both neurofeedback and mindfulness-based cognitive therapy significantly increased cognitive flexibility in older adults with Alzheimer's disease. In addition, both interventions improved the working memory components of storage and processing compared with the control group. The posttest and follow-up findings also demonstrated the effectiveness of the interventions on the variables under investigation. The findings suggest that neurofeedback and mindfulness-based cognitive therapy can be used as nonpharmacological, adjunctive interventions to improve cognitive flexibility and working memory performance in older adults with Alzheimer's disease. Incorporating these interventions alongside conventional care and treatment may contribute to the maintenance and enhancement of cognitive functioning in these patients.

Keywords: *Alzheimer's disease; cognitive flexibility; working memory; older adults; neurofeedback; mindfulness-based cognitive therapy.*

1. Introduction

Population aging has become one of the most significant demographic and public health transformations of recent decades, accompanied by a growing prevalence of age-related cognitive disorders and an increasing need for interventions capable of maintaining cognitive functioning and quality of life in later adulthood. Cognitive health in old age is influenced by multiple biological, psychological, neurological, and environmental factors, and its deterioration can substantially undermine independence, adaptive functioning, decision-making, and participation in daily life (1). Among neurodegenerative disorders, Alzheimer's disease is the most prominent and clinically consequential cause of progressive cognitive decline in older adults. It is characterized by gradual impairment in memory, executive functioning, attention, language, orientation, and other higher-order cognitive processes, with symptoms becoming increasingly disruptive as the disease progresses. Contemporary research has also emphasized the complex neuropathological nature of Alzheimer's disease, including the spatial progression of tau pathology across neural systems and the relationship between pathological processes and the emergence of cognitive and behavioral manifestations (2). Beyond cognitive deterioration, Alzheimer's disease may also be associated with substantial psychological distress, reduced autonomy, caregiver burden, and increased vulnerability to adverse mental health outcomes, reinforcing the importance of multidimensional approaches to prevention, rehabilitation, and supportive treatment (3).

Despite considerable advances in the understanding of Alzheimer's disease, available pharmacological treatments remain limited in their capacity to restore lost cognitive functioning or comprehensively halt disease progression. Consequently, growing attention has been directed toward complementary and nonpharmacological interventions that may enhance residual cognitive capacities, strengthen compensatory mechanisms, and preserve daily functioning. Research in Alzheimer's disease has increasingly explored a wide range of therapeutic approaches, including neuromodulation, behavioral interventions, cognitive rehabilitation, lifestyle modification, and even plant-derived bioactive compounds with potential neuroprotective effects (4). Within this broader therapeutic landscape, interventions that directly target cognitive flexibility and working memory are particularly relevant because these functions contribute substantially to adaptive behavior, problem-solving, learning, emotional regulation, and the ability to respond effectively to changing environmental demands. Accordingly, identifying interventions that can strengthen these cognitive processes may have meaningful clinical implications for older adults living with Alzheimer's disease.

Cognitive flexibility refers to the capacity to modify thoughts, strategies, perspectives, or behavioral responses in accordance with changing situational demands. It is considered a core component of executive functioning and allows individuals to shift between cognitive sets, generate alternative interpretations, revise ineffective response patterns, and adapt to new or unexpected conditions. The construct has traditionally been examined in relation to adaptive reasoning, coping, cultural adjustment, and higher-order cognitive control (5). In older adults, reduced cognitive flexibility may manifest as difficulty changing routines, shifting attention, considering alternative solutions, or disengaging from ineffective strategies. Such impairments can become especially pronounced in neurodegenerative conditions, where structural and functional changes in frontal and frontoparietal networks disrupt the neural systems responsible for executive control. Recent evidence from noninvasive neuromodulation research suggests that cognitive flexibility is not entirely fixed and may be enhanced by interventions capable of modulating neural activity in networks involved in executive functioning (6). This has important implications for Alzheimer's rehabilitation, where preserving adaptive cognitive control may contribute to better everyday functioning and greater psychological adjustment.

Working memory is another fundamental cognitive system that is frequently compromised with advancing age and neurodegenerative disease. It refers to the limited-capacity system responsible for temporarily maintaining and manipulating information while an individual engages in complex cognitive activities such as comprehension, reasoning, decision-making, and problem-solving. Working memory involves both the storage and active processing of information and is therefore essential for successful performance across a wide range of everyday tasks. Its

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functional importance has been demonstrated across different populations, with research showing that working memory capacity is closely associated with attentional control and broader cognitive functioning (7). In Alzheimer's disease, working memory impairment can interfere with the ability to follow instructions, retain recently presented information, perform multistep activities, and integrate new information with previously stored knowledge. Such deficits can significantly reduce independence and may contribute to increased reliance on caregivers. Therefore, interventions capable of improving or stabilizing working memory are of substantial interest in cognitive aging and neurorehabilitation.

One approach that has attracted increasing attention in this context is neurofeedback. Neurofeedback is a form of biofeedback in which individuals receive real-time information about their own brain activity, typically measured through electroencephalography, and learn to modify specific patterns of neural activation through repeated training. The theoretical premise is that brain activity can be shaped through operant conditioning, allowing participants to increase neural patterns associated with desirable cognitive states while suppressing patterns associated with less efficient functioning (8). In cognitive rehabilitation, neurofeedback has been applied to the modulation of attention, executive functioning, memory, and self-regulation. Earlier studies have reported beneficial effects of neurofeedback on executive functions in clinical populations such as individuals with attention-deficit/hyperactivity disorder and epilepsy, suggesting that repeated regulation of targeted neural frequencies may contribute to improvements in cognitive control (9). More recent systematic evidence has similarly demonstrated that neurofeedback can improve executive functioning in populations characterized by attentional and inhibitory control deficits (10).

The potential value of neurofeedback for older adults is particularly noteworthy because age-related cognitive decline is associated with altered oscillatory activity, reduced neural efficiency, and diminished functional connectivity in networks involved in executive control and memory. Neurofeedback may help older individuals develop greater regulation over these neural processes and thereby strengthen cognitive performance. Frontal-midline theta neurofeedback, for example, has been investigated as a means of enhancing working memory in older adults, with evidence indicating that training-related changes in neural oscillatory activity may be accompanied by improvements in working memory performance (11). Similarly, frontal neurofeedback has been associated with improved working memory in individuals with mild cognitive impairment, a condition frequently considered a transitional state between normal aging and dementia (12). Meta-analytic evidence further suggests that electroencephalography-based neurofeedback can produce beneficial effects on both working memory and episodic memory in elderly populations, although outcomes may vary according to protocol characteristics and participant profiles (13).

Recent studies have extended this line of research by conceptualizing neurofeedback as a broader cognitive enhancement tool for aging populations. Evidence indicates that neurofeedback may improve working memory by strengthening self-regulation of neural activity and promoting more efficient recruitment of cognitive-control networks (14). At the same time, the literature on Alzheimer's rehabilitation suggests that neurofeedback is increasingly being considered as a promising nonpharmacological modality, although the evidence base remains heterogeneous and further controlled studies are required to establish optimal protocols and clarify the magnitude and durability of treatment effects (15). This research gap is particularly relevant for patients with Alzheimer's disease, as many neurofeedback studies have focused on healthy older adults, mild cognitive impairment, or other neurological and psychiatric populations rather than individuals with established Alzheimer's disease.

Mindfulness-based cognitive therapy represents a different but potentially complementary approach to cognitive rehabilitation. MBCT integrates principles of cognitive therapy with mindfulness practices that cultivate nonjudgmental awareness of present-moment experiences. Through repeated attention to thoughts, emotions, bodily sensations, and internal experiences, individuals are trained to observe cognitive events without automatically reacting to them. This process may reduce habitual rumination, improve attentional regulation, increase metacognitive awareness, and promote more flexible responses to distressing internal states. Studies in older adults suggest that

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mindfulness-based interventions may support psychological well-being and modify maladaptive cognitive and emotional patterns. For example, mindfulness-based cognitive therapy has been associated with reductions in irrational beliefs and increases in happiness among older adults (16). Mindfulness-based approaches have also been shown to improve psychological flexibility and emotion regulation, highlighting their relevance to adaptive cognitive processing beyond symptom reduction alone (17).

The effects of mindfulness are increasingly understood to extend beyond emotional well-being to executive and cognitive functioning. Mindfulness training requires sustained attention, monitoring of internal experiences, disengagement from distracting thoughts, and intentional redirection of attention, all of which recruit processes closely related to executive control. Accordingly, MBCT has been examined as a potential method for strengthening cognitive flexibility and executive functioning in older adults. Experimental findings suggest that mindfulness-based interventions can enhance cognitive flexibility in later life by improving attentional switching, reducing cognitive rigidity, and facilitating more adaptive responses to changing demands (18). Randomized controlled evidence has also indicated that mindfulness interventions can produce improvements in cognitive flexibility among elderly participants, supporting the possibility that repeated mindfulness practice may enhance cognitive adaptability in aging populations (19). Furthermore, research focused specifically on executive functions has demonstrated that MBCT may positively influence higher-order cognitive processes such as inhibitory control, attentional regulation, and flexible cognitive responding in older adults (20).

MBCT may also affect cognitive functioning indirectly through improvements in sleep, emotional regulation, and psychological distress. Sleep disturbances are common among older adults and may exacerbate cognitive inefficiency, attentional problems, and memory difficulties. A systematic review and meta-analysis examining MBCT among older adults with sleep disorders reported beneficial effects on sleep-related outcomes, suggesting that mindfulness-based interventions may support cognitive health partly through improvements in restorative sleep and reductions in cognitive arousal (21). Moreover, age-adapted MBCT has demonstrated beneficial effects on mental health outcomes among older adults with depressive symptoms, indicating that the intervention can be modified successfully to accommodate the needs and limitations of older populations (22). A more recent systematic review and meta-analysis has likewise shown that MBCT is effective in reducing depression and anxiety in older adults, strengthening the evidence for its psychological benefits in aging populations (23). These effects may be particularly important for individuals with cognitive impairment, because emotional distress and cognitive decline can interact in ways that further diminish everyday functioning.

Although neurofeedback and MBCT arise from different theoretical traditions, both may influence cognitive functioning through mechanisms related to self-regulation. Neurofeedback targets the self-regulation of neural activity directly, whereas MBCT trains the self-regulation of attention, cognition, and emotional responses. This conceptual convergence raises the possibility that both approaches may improve cognitive flexibility and working memory, albeit through different pathways. Neurofeedback may promote neural efficiency by reinforcing adaptive electrophysiological patterns, while MBCT may reduce automatic cognitive processing and strengthen top-down attentional control. The comparison of these interventions is therefore clinically meaningful, particularly in Alzheimer's disease, where multimodal cognitive deficits require approaches that are both tolerable and capable of addressing different aspects of cognitive dysfunction.

Current evidence, however, remains fragmented. Some studies have examined neurofeedback in healthy elderly individuals, mild cognitive impairment, or other clinical groups, while mindfulness-based research has frequently focused on emotional outcomes, sleep, depression, or general executive functioning rather than working memory and cognitive flexibility specifically. In addition, relatively few studies have directly compared neurofeedback and MBCT within the same experimental design among older adults with Alzheimer's disease. The absence of such comparative evidence limits the ability of clinicians and researchers to determine whether one intervention is more effective than the other or whether both produce comparable benefits. Given the progressive nature of Alzheimer's disease and the importance of preserving cognitive functioning for as long as possible, comparative evaluation

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of nonpharmacological interventions is necessary to inform evidence-based rehabilitation strategies.

Accordingly, the aim of the present study was to compare the effects of neurofeedback and mindfulness-based cognitive therapy on cognitive flexibility and working memory performance in older adults with Alzheimer's disease.

2. Methods and Materials

2.1. Study Design and Participants

The present study was applied in terms of purpose and employed a quasi-experimental design with pretest, posttest, and three-month follow-up assessments and a control group. The statistical population consisted of older adults with Alzheimer's disease residing at the Kahrizak Nursing Home and Rehabilitation Center for Older Adults and Persons with Disabilities in Tehran, Iran, during 2021–2022. The required sample size was estimated using GPower software based on a repeated-measures analysis of variance design. Considering three study groups, including the first experimental group receiving neurofeedback, the second experimental group receiving mindfulness-based cognitive therapy (MBCT), and a control group, as well as three measurement occasions comprising pretest, posttest, and three-month follow-up, the sample size calculation was performed using a significance level of .05, statistical power of .80, and an anticipated effect size of .40. The GPower analysis indicated that a minimum of 12 participants was required in each group. To compensate for possible attrition during the intervention and follow-up phases, the sample size was increased to 15 participants per group, resulting in a final sample of 45 older adults. Participants were recruited using convenience sampling from eligible residents of the center. After recruitment, participants were matched as closely as possible with respect to age and were then randomly assigned to the neurofeedback group, MBCT group, or control group, with 15 participants in each group. The inclusion criteria were a diagnosis of Alzheimer's disease, age between 65 and 85 years, and no reported history of other psychological disorders. Participants were excluded from the study if they were absent from more than two intervention sessions. Ethical principles applicable to interventional research involving human participants were observed throughout the study. Before enrollment, the aims, procedures, and general requirements of the study were explained to the participants, and informed consent was obtained. Participation was voluntary, participants' information was kept confidential and used exclusively for research purposes, and participation imposed no financial costs on the participants. Following completion of the study, the control group was provided with the opportunity to receive the intervention. The potential benefits and risks associated with the interventions were considered throughout the study, and participants were monitored during the intervention and follow-up phases. The study was conducted after approval by the relevant Research Ethics Committee and was registered in the Iranian National Committee for Ethics in Biomedical Research under the ethics code IR.IAU.TJ.REC.1400.004.

2.2. Data Collection Tools

The Daneman and Carpenter Working Memory Capacity Test was developed by Daneman and Carpenter (1980) to assess working memory capacity through the simultaneous evaluation of information processing and storage. The instrument consists of 27 sentences organized into six progressively demanding sets ranging from two-sentence to seven-sentence sequences. Its principal feature is that it requires participants to engage concurrently in the processing and storage components of working memory while performing a cognitive task. All sentences are assigned equal weight, with one point awarded for each correct response and no points awarded for incorrect or omitted responses. Accordingly, two scores are obtained for each participant: a processing score, reflecting the accurate evaluation or identification of the presented sentences, and a storage score, reflecting the accurate recall and recording of the final word presented in each sentence. Because the test contains 27 sentences of equal value, scores for both the processing and storage components range from 0 to 27. The overall working memory score is calculated from the mean of the combined processing and storage scores and can be expressed as a percentage. Daneman and Carpenter (1980) reported a reliability coefficient of .89 for the original version of the instrument. In an Iranian preliminary validation study involving 84 students from the Faculty of Psychology and Educational Sciences at Allameh Tabataba'i

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University, Asadzadeh (2004) reported a validity coefficient of .88. In addition, Mojtabazadeh (2006) reported a Kuder–Richardson reliability coefficient of .87 among third-year secondary-school students in Zanjan, while Asadzadeh (2004) reported a split-half reliability coefficient of .85, indicating satisfactory internal consistency and reliability of the measure.

The Cognitive Flexibility Inventory (CFI) was developed by Dennis and Vander Wal (2010) and consists of 20 items designed to assess individuals' capacity for flexible cognitive responding. The instrument was developed for assessing changes in cognitive flexibility in both clinical and nonclinical populations and has also been used to evaluate the development of flexible thinking within cognitive-behavioral interventions for depression and other psychological disorders. In the Iranian validation of the instrument, Shareh et al. (2013) identified three dimensions, including Alternatives, Control, and Alternatives for Human Behaviors. The Alternatives dimension includes items 3, 5, 6, 12, 13, 14, 16, 18, and 19; the Control dimension includes items 1, 2, 4, 7, 9, 11, 15, and 17; and the Alternatives for Human Behaviors dimension was reported to include items 10 and 18. Responses are scored on a seven-point Likert scale ranging from 1 (strongly disagree) to 7 (strongly agree), with items 2, 4, 7, 9, 11, and 17 reverse-scored. Subscale scores are calculated by summing the scores of the corresponding items, and the total cognitive flexibility score is calculated by summing all item scores, with higher scores indicating greater cognitive flexibility. Dennis and Vander Wal (2010) reported a concurrent validity coefficient of −.39 between the CFI and the Beck Depression Inventory and a convergent validity coefficient of .75 with the Cognitive Flexibility Scale developed by Martin and Rubin. In the Iranian population, Shareh et al. (2013) reported a Cronbach's alpha coefficient of .71 for the total scale, supporting its acceptable internal consistency.

The Wisconsin Card Sorting Test (WCST) is a neuropsychological measure of executive functioning originally developed to assess several aspects of higher-order cognitive performance and is particularly sensitive to frontal-lobe functioning. The version used in the present study was based on the procedure described by Grant and Berg (1984). The WCST provides information regarding problem-solving ability, cognitive set shifting, response inhibition, attention, and planning. Two principal indices were considered particularly relevant: the number of perseverative errors, which reflects difficulty inhibiting previously reinforced but no longer appropriate response patterns, and the number of categories completed, which provides an indicator of conceptual organization, sustained attention, cognitive flexibility, and planning ability. Higher perseverative-error scores represent poorer executive control, whereas a greater number of successfully completed categories indicates better executive functioning. Anderson et al. (1991) reported criterion-related validity coefficients exceeding .86 for the test, while Spreen and Strauss (1991) reported a reliability coefficient of .83. In an Iranian sample, Ghadiri et al. (2006) reported a test–retest reliability coefficient of .85, supporting the reliability of the WCST for the assessment of executive functioning in Iranian populations.

2.3. Interventions

The mindfulness-based cognitive therapy intervention was administered in 10 weekly sessions, each lasting approximately 60 minutes, based on the protocol described by Crane (2017). The first session focused on introducing participants to the intervention, establishing familiarity with the therapeutic setting, administering the pretest, explaining the aims and structure of the sessions, and introducing the basic concept of mindfulness-based cognitive therapy. The second session provided a more comprehensive introduction to mindfulness and included discussion of participants' experiences, abilities, treatment histories, and illness-related experiences, followed by further explanation of the principles of MBCT. The third session focused on the relationship between thoughts and emotional states and introduced the cognitive model of mindfulness, the effects of maladaptive thoughts and rumination on mood, and the three-minute breathing exercise as an initial strategy for achieving relaxation and present-moment awareness. The fourth session addressed the importance of sleep quality for physical and psychological health and introduced meditation exercises and psychomotor relaxation techniques. The fifth session focused on increasing awareness of bodily sensations and emotional experiences, using mindfulness to interrupt automatic cognitive and behavioral processes, and teaching the body-scan exercise. In the sixth session,

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previously learned exercises were reviewed, participants were encouraged to identify and verbalize negative thoughts and emotions, and strategies were introduced for replacing maladaptive negative thought patterns with more adaptive and positive emotional and cognitive responses; the session also included body scanning and selection of an attentional focus. The seventh session emphasized the use of initial relaxation techniques to facilitate concentration and incorporated the three-minute breathing exercise, mindful attention, muscular relaxation, awareness of bodily sensations, review of internal dialogue, coping strategies, and mental imagery of adaptive actions. The eighth session focused on identifying emotions and understanding the consequences of difficulties in emotional awareness and expression; breathing exercises for emotional relaxation, body scanning for recognizing stress and negative emotions, sleep-related issues, and therapeutic metaphors emphasizing the importance of supportive interpersonal networks were also addressed. The ninth session concentrated on disrupting cycles of negative thinking and rumination, practicing replacement of negative cognitions, strengthening positive internal dialogue, and assigning home practice involving relaxation and breathing exercises. The tenth and final session involved consolidation of the material covered throughout the intervention, review of previously learned skills, collection of participant feedback regarding satisfaction with the exercises and sessions, and administration of the posttest.

The neurofeedback intervention consisted of 10 sessions of approximately 45 minutes each and was delivered using an SA7990A Ver. 0.5 neurofeedback device. All sessions were conducted under the instruction and supervision of a specialist trained in psychology and neurofeedback. At the beginning of each session, the participant was seated comfortably in the designated treatment chair, after which the O1 and O2 electrode sites were identified on the scalp according to the International 10–20 System of Electrode Placement. Active and reference electrodes were then positioned at the designated sites using TEN20 conductive paste, and the ground electrode was attached to the left ear. Each neurofeedback training session lasted 45 minutes and was based on suppression of activity within the 4–7 Hz frequency band, corresponding primarily to theta activity, and reinforcement of activity within the 15–18 Hz frequency band, corresponding to the upper sensorimotor rhythm/low-beta range. Training programs intended to enhance cognitive functioning were implemented using the same frequency parameters. The level of training difficulty and reinforcement thresholds were automatically adjusted using BioGraph software according to the 20–80 rule and were optimized for the cognitive and functional characteristics of the older participants. According to the protocol applied in this study, approximately 20% of activity within the 4–7 Hz band was targeted for suppression, whereas approximately 80% of activity within the 15–18 Hz band was targeted for reinforcement. To reduce fatigue and maintain engagement during the 45-minute sessions, the neurofeedback training incorporated three different visual feedback animations: puzzle completion, a boat-racing task, and animated visual stimuli, each presented for approximately 15 minutes. The control group did not receive neurofeedback, MBCT, or any other study-specific psychological intervention during the corresponding treatment period and continued to receive routine care available at the residential center.

2.4. Data Analysis

Data were analyzed at both descriptive and inferential levels using IBM SPSS Statistics version 23. Descriptive statistics, including means and standard deviations, were calculated to summarize the study variables across the neurofeedback, MBCT, and control groups at the pretest, posttest, and three-month follow-up assessments. One-way analysis of variance was used, where appropriate, to examine baseline differences among the three groups in demographic and continuous background characteristics. Before conducting the primary inferential analyses, the statistical assumptions underlying repeated-measures analysis were evaluated. The normality of the distributions was examined using the Shapiro–Wilk test, homogeneity of variances was assessed using Levene's test, equality of covariance matrices across groups was examined using Box's M test, and the assumption of sphericity for within-subject effects was evaluated using Mauchly's test of sphericity. Changes in cognitive flexibility and working memory performance, including the processing and storage components of working memory, across the pretest, posttest, and three-month follow-up assessments were examined using repeated-measures analysis of variance. This analysis was used to

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evaluate the main effect of time, the between-group effect, and the group-by-time interaction in order to determine whether the pattern of change over time differed among the neurofeedback, MBCT, and control groups. F statistics were used to evaluate the significance of the corresponding effects. When significant differences were identified, Bonferroni-adjusted pairwise comparisons were conducted to determine the specific differences between groups and/or measurement occasions while controlling for inflation of the Type I error rate associated with multiple comparisons. All statistical tests were conducted using a two-tailed significance level of .05.

3. Findings and Results

In the present study, 45 older adults with Alzheimer's disease were examined in three groups: neurofeedback, mindfulness-based cognitive therapy (MBCT), and control, with 15 participants in each group. In each of the three groups, 10 participants (66.67%) were women and 5 (33.33%) were men. The mean age and standard deviation of participants were 67.93 ± 5.75 years in the neurofeedback group, 68.33 ± 5.63 years in the MBCT group, and 69.00 ± 6.96 years in the control group. The results of one-way analysis of variance indicated that there was no statistically significant difference among the three groups in mean age.

Table 1

Mean and Standard Deviation of Cognitive Flexibility and Working Memory Components Across the Three Groups and Three Measurement Stages

Variable	Group	Pretest	Posttest	Follow-up
Cognitive flexibility	Neurofeedback	35.66 ± 4.70	43.33 ± 4.22	43.46 ± 4.53
Cognitive flexibility	Mindfulness-based cognitive therapy	35.53 ± 4.82	42.93 ± 4.65	43.00 ± 4.82
Cognitive flexibility	Control	34.93 ± 4.99	34.60 ± 4.33	34.40 ± 3.77
Storage	Neurofeedback	4.00 ± 1.51	7.20 ± 1.26	7.00 ± 1.36
Storage	Mindfulness-based cognitive therapy	3.66 ± 1.04	6.80 ± 1.37	6.40 ± 1.54
Storage	Control	4.20 ± 1.26	4.20 ± 0.94	4.33 ± 1.04
Processing	Neurofeedback	4.66 ± 1.39	7.06 ± 1.27	7.06 ± 1.16
Processing	Mindfulness-based cognitive therapy	4.73 ± 1.16	7.13 ± 1.30	7.20 ± 1.37
Processing	Control	5.06 ± 1.22	5.33 ± 1.11	5.60 ± 0.83

As shown in Table 1, the mean cognitive flexibility score increased from pretest to posttest in both intervention groups, and this increase was maintained at the follow-up assessment, whereas no substantial change was observed in the control group. A similar pattern was observed for the storage and processing components of working memory, such that the mean scores for both components increased at posttest and follow-up relative to pretest in the neurofeedback and MBCT groups.

Before conducting the repeated-measures analysis of variance, the relevant statistical assumptions were examined. The results of Levene's test indicated that the assumption of homogeneity of error variances was satisfied for the study variables ($p > .05$). Box's M test was significant for cognitive flexibility ($p = .011$) and working memory ($p = .009$); therefore, given the sensitivity of this test, Pillai's trace was used for the multivariate analyses. In addition, the assumption of sphericity was violated for cognitive flexibility ($p = .009$) and the storage component of working memory ($p = .007$). Accordingly, based on the epsilon values, the Huynh–Feldt correction was applied in the analyses of these variables.

The multivariate test results indicated that the overall effect of the interventions on cognitive flexibility was statistically significant. Pillai's trace was .871, with $F(4, 84) = 16.20$, $p = .001$, and an effect size of .435. Likewise, the overall effect of the interventions on working memory was statistically significant, with Pillai's trace = .617, $F(8, 168) = 9.37$, $p = .001$, and an effect size of .309.

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Table 2

Results of Repeated-Measures Analysis of Variance for Cognitive Flexibility and Working Memory Components

Variable	Source of Effect	*F*	*p*	η^2
Cognitive flexibility	Group	9.03	.001	.301
Cognitive flexibility	Time	343.77	.001	.891
Cognitive flexibility	Time × Group	101.99	.001	.829
Storage	Group	11.39	.001	.352
Storage	Time	—	.001	—
Storage	Time × Group	—	.001	.513
Processing	Group	4.71	.014	.183
Processing	Time	66.66	.001	.613
Processing	Time × Group	9.97	.001	.322

The repeated-measures analysis of variance showed that the main effect of group on cognitive flexibility was statistically significant, F = 9.03, p = .001, η^2 = .301. The main effect of time and the time × group interaction were also statistically significant at the .001 level. Therefore, changes in cognitive flexibility across the pretest, posttest, and follow-up assessments were not equivalent among the three study groups. With respect to working memory, the main effect of group on the storage component was statistically significant, F = 11.39, p = .001, η^2 = .352. The main effect of group on the processing component was also statistically significant, F = 4.71, p = .014, η^2 = .183. In addition, the main effect of time and the time × group interaction were statistically significant at the .001 level for both working memory components. Overall, these findings indicated that both interventions improved cognitive flexibility and the storage and processing components of working memory compared with the control condition.

Table 3

Results of Bonferroni Post Hoc Comparisons Between Groups

Variable	Group Comparison	Mean Difference	*p*
Cognitive flexibility	Neurofeedback – Mindfulness-based cognitive therapy	0.333	1.000
Cognitive flexibility	Neurofeedback – Control	6.17	.001
Cognitive flexibility	Mindfulness-based cognitive therapy – Control	5.84	.003
Storage	Neurofeedback – Mindfulness-based cognitive therapy	0.444	.811
Storage	Neurofeedback – Control	1.82	.001
Storage	Mindfulness-based cognitive therapy – Control	1.37	.004
Processing	Neurofeedback – Mindfulness-based cognitive therapy	−0.089	1.000
Processing	Neurofeedback – Control	0.933	.046
Processing	Mindfulness-based cognitive therapy – Control	1.02	.025

The Bonferroni post hoc test results showed that, for cognitive flexibility, the difference between the neurofeedback group and the control group was statistically significant (p = .001), as was the difference between the MBCT group and the control group (p = .003). However, no statistically significant difference was observed between the neurofeedback and MBCT groups (p = 1.000). Comparisons across measurement occasions further showed significant differences between pretest and posttest and between pretest and follow-up at the .001 level, whereas the difference between posttest and follow-up was not statistically significant. This pattern indicates that the beneficial effects of the interventions on cognitive flexibility were maintained at the follow-up assessment.

For the storage component of working memory, the difference between the neurofeedback group and the control group was statistically significant (p = .001), as was the difference between the MBCT group and the control group (p = .004). In contrast, the difference between the two intervention groups was not statistically significant (p = .811). For the processing component of working memory, the difference between the neurofeedback group and the control group was statistically significant (p = .046), and the difference between the MBCT group and the control group

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was also statistically significant (p = .025). However, no statistically significant difference was found between the neurofeedback and MBCT groups (p = 1.000). Comparisons across the working memory measurement occasions also revealed statistically significant differences between pretest and posttest and between pretest and follow-up at the .001 level, whereas no statistically significant difference was observed between posttest and follow-up. Accordingly, the beneficial effects of both interventions on working memory were maintained during the follow-up period.

Overall, the findings demonstrated that both neurofeedback and mindfulness-based cognitive therapy significantly improved cognitive flexibility and working memory performance in older adults with Alzheimer's disease, and these effects persisted through the follow-up assessment. However, no statistically significant differences were observed between neurofeedback and mindfulness-based cognitive therapy in their effectiveness on the study variables.

4. Discussion and Conclusion

The present study investigated the effects of neurofeedback and mindfulness-based cognitive therapy (MBCT) on cognitive flexibility and working memory performance in older adults with Alzheimer's disease. The findings showed that both neurofeedback and MBCT significantly improved cognitive flexibility compared with the control group. Significant effects of time and the time × group interaction further indicated that improvements observed after the interventions were maintained at the three-month follow-up. Bonferroni comparisons showed that both the neurofeedback and MBCT groups differed significantly from the control group, whereas no significant difference emerged between the two active interventions. A similar pattern was observed for working memory. Both neurofeedback and MBCT significantly improved the storage and processing components of working memory relative to the control condition, and the gains persisted through follow-up. Again, no statistically significant difference was found between the two interventions. Taken together, these results suggest that both neurofeedback and MBCT can produce meaningful and relatively sustained improvements in important cognitive functions among older adults with Alzheimer's disease.

The significant improvement in cognitive flexibility following neurofeedback is consistent with the growing literature on the modifiability of executive functions through noninvasive neuromodulatory approaches. Cognitive flexibility is a central component of executive functioning that enables individuals to shift between mental sets, alter strategies when environmental demands change, and disengage from ineffective patterns of thought or behavior. Evidence from neuromodulation research suggests that cognitive flexibility can be strengthened through interventions that influence activity within neural networks supporting executive control (6). In the present study, neurofeedback involved suppression of 4–7 Hz activity and reinforcement of 15–18 Hz activity, a protocol intended to reduce excessive slow-wave activity while enhancing faster frequencies associated with attention and cognitive activation. Through repeated feedback and reinforcement, participants may have gradually acquired greater regulation over neural activity related to attentional control and executive processing, thereby facilitating more flexible cognitive responding. This interpretation is compatible with the theoretical basis of neurofeedback as a learning-based method through which individuals develop voluntary regulation of specific electrophysiological patterns (8).

The improvement in cognitive flexibility is also broadly consistent with previous neurofeedback research demonstrating enhancement of executive functions in clinical populations. Khaksarian et al. reported beneficial effects of neurofeedback on executive functioning among individuals with attention-deficit/hyperactivity disorder and epilepsy, suggesting that neurofeedback can influence cognitive processes involving inhibition, attentional control, and behavioral regulation (9). More recent systematic evidence has similarly indicated that neurofeedback can improve executive functions in populations with impaired cognitive control (10). Although Alzheimer's disease differs substantially from these disorders in etiology and neuropathology, executive dysfunction is a shared functional concern, and the capacity of neurofeedback to reinforce more adaptive neural activity may therefore have relevance across diagnostic groups. This may be especially important in Alzheimer's disease, in which progressive neural degeneration affects networks involved in cognitive control and adaptive behavior.

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The findings concerning working memory also support the proposed cognitive benefits of neurofeedback. Participants receiving neurofeedback showed significant improvements in both storage and processing, indicating that the intervention influenced not only temporary retention of information but also the ability to manipulate information during ongoing cognitive activity. This result is consistent with evidence demonstrating that frontal-midline theta neurofeedback can enhance working memory in older adults (11). Neurofeedback may improve working memory by increasing functional efficiency in neural circuits responsible for maintaining task-relevant information, allocating attentional resources, and coordinating executive operations. Although the protocol used in the present study emphasized suppression of theta-range activity and reinforcement of 15–18 Hz activity rather than enhancement of frontal-midline theta, both approaches reflect attempts to optimize electrophysiological states associated with efficient cognitive functioning.

The current results are also consistent with findings reported in individuals with mild cognitive impairment. Frontal neurofeedback training has been shown to improve working memory in people experiencing early cognitive decline (12). This is particularly relevant because mild cognitive impairment may precede the development of Alzheimer's disease in some individuals, and cognitive mechanisms targeted during earlier stages may remain partially responsive to intervention after dementia symptoms emerge. Meta-analytic findings further suggest that electroencephalography-based neurofeedback can improve both working memory and episodic memory in elderly populations (13). Similarly, neurofeedback has increasingly been conceptualized as a cognitive enhancement strategy capable of improving working memory in older individuals through repeated modulation of neural activity and reinforcement of adaptive brain states (14). The findings of the present study extend this body of evidence by suggesting that comparable benefits may also be observed among older adults already diagnosed with Alzheimer's disease.

The relevance of neurofeedback to Alzheimer's rehabilitation is further supported by emerging reviews of the field. Research examining neurofeedback applications in Alzheimer's disease has suggested that the technique may have potential as a nonpharmacological rehabilitation strategy, although the literature remains heterogeneous with respect to neurofeedback protocols, cognitive outcomes, and methodological quality (15). The present findings contribute to this developing evidence base by demonstrating improvements in both cognitive flexibility and working memory across repeated assessments. Given that Alzheimer's disease is characterized by complex neuropathological changes, including progressive spread of tau pathology across neural systems (2), complete reversal of cognitive impairment through behavioral or neuromodulatory intervention is unlikely. Nevertheless, interventions capable of improving efficiency within preserved neural networks or strengthening compensatory processes may help maintain functional abilities despite ongoing pathology.

MBCT also produced significant improvements in cognitive flexibility, and these effects were maintained at follow-up. This result is consistent with previous studies showing that mindfulness-based interventions enhance flexible cognitive responding in older adults. Mindfulness practice requires individuals to observe ongoing thoughts, feelings, and bodily sensations without immediately reacting to them, and to redirect attention deliberately when distraction occurs. These repeated processes may reduce cognitive rigidity and strengthen the ability to disengage from habitual patterns of thought. Zeidan et al. reported that mindfulness-based cognitive therapy enhanced cognitive flexibility in older adults, providing direct support for the present findings (18). Likewise, randomized evidence has shown that mindfulness interventions can significantly improve cognitive flexibility among elderly individuals (19). Such findings suggest that mindfulness practice may promote adaptive cognitive shifting by increasing awareness of automatic mental processes and facilitating more intentional allocation of attention.

The improvement in cognitive flexibility following MBCT may also be interpreted in terms of enhanced executive control and psychological flexibility. Mindfulness-based cognitive therapy combines attentional training with cognitive decentering, encouraging individuals to view thoughts as transient mental events rather than fixed representations that require immediate behavioral responses. This process can facilitate consideration of alternative interpretations and reduce perseverative thinking. Research

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has shown that mindfulness-based therapy can improve psychological flexibility and emotion regulation in clinical populations (17), while other evidence suggests that MBCT can improve broader executive functions in older adults (20). These mechanisms may be particularly valuable for individuals with Alzheimer's disease, in whom cognitive rigidity and difficulty shifting between mental sets can impair adaptation to changing tasks and daily demands.

The beneficial effects of MBCT on working memory may similarly be explained through improvement in attentional control and reduction of cognitive interference. Working memory performance depends heavily on the ability to maintain task-relevant information while resisting distraction. Mindfulness exercises repeatedly train sustained attention, monitoring, and deliberate redirection of attention, all of which may increase the efficiency with which limited working memory resources are used. In addition, reduced rumination and emotional reactivity may decrease competition for cognitive resources, thereby allowing greater capacity for information storage and processing. The observed improvement in both working memory components is therefore theoretically compatible with the attentional and executive mechanisms cultivated through MBCT.

Additional support for these findings comes from studies examining the broader effects of mindfulness interventions in older adults. MBCT has been associated with reductions in irrational beliefs and increased happiness in elderly individuals, suggesting improvements in cognitive-emotional regulation that may support adaptive functioning (16). Mindfulness interventions have also demonstrated beneficial effects on sleep among older adults (21). Because sleep quality is closely related to attention, memory consolidation, and executive performance, improvements in sleep may indirectly contribute to better cognitive functioning. The relationship between working memory, attention, and sleep-related functioning has also been demonstrated in other populations, emphasizing the interconnected nature of these cognitive processes (7). Thus, MBCT may influence cognitive performance through both direct attentional mechanisms and indirect improvements in psychological and physiological regulation.

The effectiveness of MBCT among older populations is further supported by recent evidence concerning emotional and psychological outcomes. Age-modified MBCT has been found to improve mental health among older adults with depressive symptoms (22), and systematic review and meta-analytic evidence indicates that MBCT can reduce depression and anxiety in older populations (23). Although the present study focused on cognitive rather than affective outcomes, these psychological benefits may be relevant because depression, anxiety, stress, and repetitive negative thinking can interfere with cognitive performance. Reduction of psychological distress may free attentional resources and reduce cognitive load, thereby facilitating improved performance on tasks involving memory and executive functioning. In individuals with Alzheimer's disease, who may experience substantial emotional distress in response to cognitive decline and loss of independence, such mechanisms may have particular clinical importance. The broader psychological consequences associated with Alzheimer's disease, including vulnerability to severe distress, further reinforce the value of interventions capable of addressing both cognitive and emotional self-regulation (3).

An important finding of the present study was the absence of a significant difference between neurofeedback and MBCT. Both interventions produced comparable improvements in cognitive flexibility and working memory. This result may indicate that different therapeutic mechanisms can ultimately influence overlapping cognitive systems. Neurofeedback operates primarily through direct reinforcement of desired patterns of brain activity, while MBCT relies on attentional training, metacognitive awareness, cognitive decentering, and regulation of automatic responses. Despite these differences, both approaches may strengthen top-down cognitive control and improve the allocation of attentional resources. Cognitive flexibility itself is a multidimensional capacity that supports adaptation across changing contexts (5), and it is therefore plausible that interventions acting through different neurocognitive pathways can yield similar behavioral outcomes.

The maintenance of intervention effects at the three-month follow-up represents another important result. Neither cognitive flexibility nor working memory showed a significant decline from posttest to follow-up in the intervention groups. In the neurofeedback condition,

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repeated practice may have produced learned patterns of neural self-regulation that persisted after training ended. In the MBCT condition, participants may have continued using breathing exercises, body awareness, attentional refocusing, or other mindfulness strategies after completion of formal sessions. Maintenance of gains is particularly important in Alzheimer's disease because cognitive health in older age is affected by ongoing biological and environmental pressures (1). Although nonpharmacological interventions cannot eliminate the underlying neurodegenerative process, sustained improvements or temporary stabilization of cognitive functioning may still have meaningful implications for independence, participation in everyday activities, and quality of life.

The findings should also be understood within the broader movement toward multimodal and nonpharmacological approaches to Alzheimer's disease. Current research encompasses a wide range of potential therapeutic strategies, including cognitive rehabilitation, neuromodulation, psychological interventions, and investigation of biologically active compounds with possible neuroprotective effects (4). The present findings support the inclusion of both neurofeedback and MBCT within this broader therapeutic framework. Rather than viewing these approaches as alternatives to conventional medical care, they may be considered adjunctive strategies aimed at maximizing preserved cognitive capacities and supporting functional adaptation. Their apparent comparability in the present study also suggests that treatment selection could potentially be informed by patient preference, accessibility, cognitive status, treatment tolerance, and availability of trained professionals.

The present study had several limitations that should be considered when interpreting the findings. First, the sample consisted of only 45 older adults recruited from a single residential care setting in Tehran, which limits the generalizability of the results to broader populations of individuals with Alzheimer's disease living in the community or receiving care in different clinical and cultural settings. Second, convenience sampling was used before random allocation to the study groups, which may have introduced selection bias. Third, although participants were diagnosed with Alzheimer's disease, the study did not stratify individuals according to disease severity, duration of diagnosis, medication regimen, neurological comorbidities, or baseline level of cognitive impairment, all of which may influence responsiveness to neurofeedback or MBCT. Fourth, the intervention period was relatively short, consisting of 10 sessions, and the follow-up period was limited to three months. Therefore, the long-term durability of treatment effects remains uncertain. Fifth, the study relied primarily on neuropsychological and questionnaire-based measures and did not incorporate objective neurophysiological or neuroimaging measures to clarify the mechanisms underlying improvement. Finally, the absence of an active placebo or attention-control condition means that nonspecific factors such as therapist contact, expectation of benefit, social engagement, and participation in structured activities cannot be completely excluded as contributors to the observed effects.

Future studies should replicate these findings using larger and more heterogeneous samples recruited from multiple clinical centers and community settings. Stratification according to Alzheimer's disease severity, age, educational level, medication use, and baseline cognitive functioning would help identify subgroups most likely to benefit from each intervention. Randomized controlled trials with active comparison conditions are recommended to distinguish intervention-specific effects from nonspecific therapeutic factors. Longer follow-up periods, such as six months or one year, would provide a clearer understanding of the persistence of cognitive gains. Future research should also incorporate electroencephalographic, neuroimaging, or other physiological indicators to determine whether behavioral improvements correspond to measurable changes in neural activity or connectivity. Comparative studies examining different neurofeedback frequency protocols and different intensities or formats of MBCT may help establish optimal treatment parameters. In addition, combined interventions integrating neurofeedback with mindfulness training could be investigated to determine whether simultaneous neural and cognitive self-regulation produces additive or synergistic effects. Future studies may also examine outcomes such as activities of daily living, quality of life, emotional symptoms, sleep quality, caregiver burden, and functional independence to determine whether cognitive improvements translate into meaningful everyday benefits.

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The findings suggest that neurofeedback and mindfulness-based cognitive therapy may be considered as complementary nonpharmacological interventions within comprehensive care programs for older adults with Alzheimer's disease. Clinicians and rehabilitation professionals may use these approaches alongside routine medical and psychosocial care when patients have sufficient cognitive and functional capacity to participate. Neurofeedback may be particularly appropriate in settings with access to trained personnel and electrophysiological equipment, whereas MBCT may offer a comparatively accessible intervention that can be adapted to older adults through simplified instructions, shorter exercises, repetition, and caregiver support. Treatment planning should take into account the individual's stage of cognitive decline, fatigue tolerance, sensory limitations, emotional state, and ability to engage with structured training. Because the two interventions showed comparable effectiveness in the present study, treatment choice may reasonably be guided by patient preference, clinical feasibility, available resources, and therapist expertise. Incorporating structured cognitive monitoring before, during, and after intervention may also help clinicians evaluate individual response and adjust treatment intensity accordingly.

Authors' Contributions

All authors contributed substantially to the study and to manuscript development, and all approved the final version.

Declaration

The authors declare that artificial intelligence tools were used only to assist with language editing, translation, and improvement of the manuscript's readability. All conceptualization, study design, data collection, data analysis, interpretation of findings, and final approval of the manuscript were performed by the authors. The authors take full responsibility for the accuracy, integrity, and originality of the content.

Transparency Statement

Data are available for research purposes upon reasonable request to the corresponding author.

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Declaration of Interest

The authors report no conflict of interest.

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Ethics Considerations

The study placed a high emphasis on ethical considerations. Informed consent obtained from all participants, ensuring they are fully aware of the nature of the study and their role in it. Confidentiality strictly maintained, with data anonymized to protect individual privacy. The study adhered to the ethical guidelines for research with human subjects as outlined in the Declaration of Helsinki.

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