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# Transcranial Direct Current Stimulation Neuromodulation in Elderly Individuals and Its Impact on Anxiety and Depression Symptoms

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## ABSTRACT

**Objectives:** To evaluate the effects of anodal transcranial direct current stimulation (tDCS) over the left prefrontal cortex, combined with computerized cognitive training, on cognitive performance, anxiety, depression, motor reaction time, and neurophysiological markers in elderly women with subjective cognitive decline or preserved cognition.

**Methods:** This was a randomized double-blind clinical trial involving 30 elderly women allocated to three groups: active tDCS, sham tDCS, and controls. The intervention consisted of nine sessions of tDCS combined with cognitive training. Cognitive aspects (Addenbrooke's Cognitive Examination-Revised), depressive symptoms (CES-D), anxiety symptoms (GAI), motor reaction times, and neurophysiological aspects (EEG) were assessed. Statistical analyses included ANOVA and paired *t*-tests for between-group comparisons.

**Results:** The tDCS group exhibited significant improvements in global cognition, episodic memory, verbal fluency, and language. Additionally, there was a significant reduction in anxiety and depression scores compared to those in the sham and control groups. The motor reaction time was reduced in the tDCS group, indicating improved sensorimotor integration. The EEG data demonstrated increased cortical excitation and improved emotional valence in the tDCS group.

**Conclusion:** Anodal tDCS associated with computerized cognitive training has proven to be an effective strategy for optimizing performance in memory tasks, verbal fluency, and decision-making as well as for reducing anxiety and depression symptoms in elderly individuals with or without subjective cognitive decline. Based on these findings, tDCS is a promising and safe tool for developing cognitive interventions for the elderly. Future studies should explore the long-term effects and impact of different stimulation protocols.

**Trial Registration:** This clinical trial is registered in the Brazilian Clinical Trials Registry (ReBEC) under the identification number RBR-16768

## 1 | Introduction

Cognitive interventions are essential for promoting neural plasticity and mitigating age-related cognitive decline. Strategies such as computerized cognitive training (CCT) have shown efficacy in maintaining functions like memory, processing speed, and executive skills [1]. Adaptive multi-domain CCT has also been associated with white matter neuroplasticity and improved performance on tasks like the Stroop Test [2]. However, neuropathological factors such as amyloid deposition may limit benefits, highlighting the need for personalized approaches that consider individual cognitive reserves.

Transcranial direct current stimulation (tDCS) has emerged as a promising tool to enhance cognitive interventions. By modulating cortical excitability, tDCS reinforces neural networks involved in cognition. When combined with CCT, tDCS may amplify gains in executive function and verbal memory [3]. It has also been linked to prefrontal white matter microstructure modulation and increased functional connectivity [4], suggesting synergistic effects when paired with cognitive training in aging populations.

Subjective cognitive decline (SCD), defined by self-perceived cognitive worsening without objective deficits, is a common concern among older adults. It is recognized as a potential early marker of future cognitive impairment [5]. Tools like the Everyday Cognition Scale (ECoG) help identify individuals at risk, as self-reported cognitive changes often predict objective decline [6]. SCD is frequently accompanied by anxiety and depression, especially when individuals express concern over their symptoms [7].

The COVID-19 pandemic has intensified cognitive complaints, including SCD, across diverse populations. Evidence suggests that SARS-CoV-2 can trigger both subjective and objective deficits, with severity influenced by age, infection intensity, and comorbidities [8]. These symptoms often persist as part of post-acute sequelae (PASC or long COVID), even in mild cases, with common complaints including forgetfulness and concentration difficulties [9].

Physiopathological mechanisms such as neuroinflammation and microvascular injury likely underlie these deficits and may increase the risk for neurodegenerative diseases [10]. Additionally, pandemic-related stress has been shown to exacerbate SCD and its affective comorbidities. Stress perception directly influences the relationship between SCD, anxiety, and depression, suggesting that stress modulation could help mitigate these effects [11].

In this context, tDCS stands out as a promising strategy to reduce SCD impact, particularly when combined with structured cognitive training. Stimulation of the dorsolateral prefrontal cortex has consistently yielded improvements in cognition and quality of life, with prolonged effects when integrated into interleaved or complementary protocols [12]. However, individual variability in response and psychosocial barriers to adherence remain key challenges [13].

This study investigates the efficacy of anodal tDCS targeting the left prefrontal cortex, combined with cognitive games, in healthy older adults and those with SCD. Beyond assessing cognitive outcomes, it explores predictors of better response, such as baseline brain connectivity and cognitive status. These findings aim to inform personalized tDCS protocols and optimize cognitive preservation strategies in aging.

## 2 | Materials and Methods

### 2.1 | Study Design

This randomized, double-blind clinical trial was approved by the Ethics Committee of Centro Universitário Euro-Americano (Approval no. 6.929.974) and followed the Declaration of Helsinki. The protocol was registered in ReBEC (#16768), based on prior studies [14], and conducted between July 2023 and November 2024, following CONSORT guidelines.

This study was designed as an exploratory clinical trial with a neurophysiological approach, aiming to evaluate the effects of transcranial direct current stimulation (tDCS) on cortical excitation and emotional valence as measured by EEG in Brazilian elderly women. The sample size was determined a priori using G*Power 3.1.9.2 based on a one-way ANOVA for three independent groups (active tDCS, sham tDCS, and control), with the $\beta/\alpha$ ratio (arousal index) as the primary outcome variable.

Assuming a large effect size ($f = 0.50$)—in line with prior findings involving EEG modulation in aging populations and adopting $\alpha = 0.05$ and power $(1–\beta) = 0.80$, the estimated required sample size was 30 participants ($n = 10$ per group) to detect statistically and clinically meaningful between-group differences.

Initially, 36 participants were recruited and equally allocated across the three study groups ($n = 12$ per group). However, six participants were excluded throughout the trial due to voluntary withdrawal ($n = 4$) and minor clinical intercurrences that prevented participation ($n = 2$). Thus, the final protocol was completed with 30 participants ($n = 10$ per group), fully meeting the minimum statistical requirement as calculated.

### 2.2 | Participants

Volunteers were recruited via community centers, social media, and health presentations. After being informed about the study objectives and procedures, interested individuals underwent initial screening. Eligible participants were guided and signed a Free and Informed Consent Form before the study began.

Inclusion criteria: (i) women ≥ 60 years; (ii) BMI < 28 kg/m$^2$; (iii) no diagnosis of neuromuscular/neurodegenerative diseases or diabetes; (iv) no visual impairment; (v) alcohol abstinence 24 h before sessions; (vi) no prior neuromodulation; (vii) documented COVID-19 infection; (viii) self-reported post-COVID cognitive complaints (e.g., memory, attention, and reasoning).

Self-reported cognitive decline was assessed with the question: "After COVID-19 infection, have you noticed changes in memory, task performance, attention, or organization?" Exclusion criteria included: (1) significant cognitive impairment, defined

as a score below 24 on the Mini-Mental State Examination (MMSE), adjusted for educational level following Brazilian norms [15]; and (2) clinical or functional limitations incompatible with participation in the study protocol.

The Mini-Mental State Examination (MMSE) is a widely used cognitive screening instrument designed to assess general cognitive functioning across six core domains: orientation (time and place), immediate memory (registration), attention and concentration, delayed recall, language skills, and visuospatial abilities. The test has been culturally adapted and validated for use in the Brazilian population, including education-adjusted cutoff scores to increase diagnostic sensitivity in older adults with low literacy [15].

### 2.3 | Procedures

The participants underwent a comprehensive initial assessment, including a semi-structured questionnaire to collect sociodemographic and health information, depressive and anxiety symptoms, subjective cognitive complaints associated with COVID-19, and cognitive assessment tests. Data on age, sex, education level, social class, marital status, occupational status, predominant profession, household arrangements, and perception of income sufficiency were collected to characterize the sample.

Depressive symptoms were assessed using the Center for Epidemiological Studies Depression Scale (CES-D), which is composed of 20 items with scores ranging from 0 to 3, and measures the frequency of depressive symptoms in the past week [16]. Anxiety was assessed using the Geriatric Anxiety Inventory (GAI), which was developed specifically for older adults and validated in Brazil [17].

Cognitive assessment was conducted using Addenbrooke's Cognitive Examination—Revised (ACE-R), which is composed of five domains (attention, memory, fluency, language, and visuospatial skills), with a maximum score of 100. Scores below 82 indicated cognitive impairment [18].

Before the intervention, anthropometric measurements were taken, followed by the administration of the CES-D, GAI, and ACE-R questionnaires and an electroencephalogram (EEG) using the EMOTIV EPOC+ device. The EEG recordings followed the international 10–20 system [19], covering the frontal, prefrontal, temporal, parietal, and occipital lobes. Participants performed 15-s recordings with their eyes open and closed to establish a baseline.

### 2.4 | Motor Reaction Time Test (MRT)

Two conditions were used:

- *Simple*: press "space" upon red square appearance (5 practices, 28 trials);
- *Fatigue*: hold "space" during a red bar's movement and release at the end (5 practices, 14 trials).

TRT_S2012 software recorded reaction times [20].

### 2.5 | Electroencephalography During MRT

During the MRT, EEG recorded cortical activity using the following protocol:

I. 3 s of preparation with countdown;
II. 15 s of recording with eyes open;
III. 3 s of preparation with countdown;
IV. 15 s of recording with eyes closed.

EEG analysis was conducted to evaluate changes in brain activity during the tasks (Figure 1).

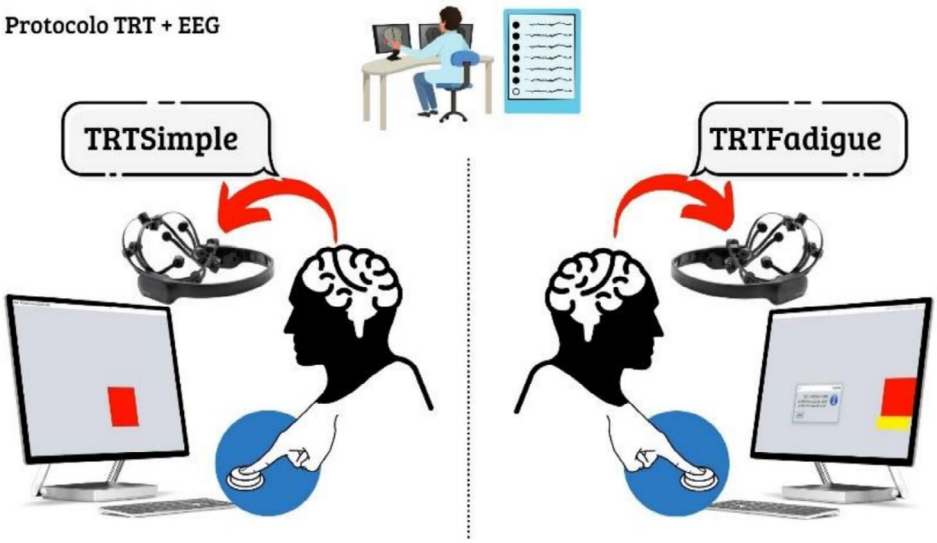


**FIGURE 1** | Motor reaction time (MRT) task with electroencephalography (EEG).

## 2.6 | Randomization and Groups

Participants were randomized into three study groups using a simple method: a bag containing balls of different colors (white, blue, and green). At the end of the initial screening, each participant drew a ball and was allocated to one of the following groups:

- tDCS group (white ball): received active neuromodulation during the cognitive training sessions.
- Sham tDCS group (blue ball): received placebo neuromodulation with the device attached but without electrical current emission, in addition to cognitive training.
- Control group (green ball): underwent only cognitive training without neuromodulation.

All participants reported subjective cognitive impairment during the initial screening. Therefore, all participants were included in the study and received some type of cognitive intervention, either through active tDCS or cognitive training alone, to ensure a focus on the comparative analysis of neuromodulation efficacy.

## 2.7 | Neuromodulation Protocol

The tDCS protocol consisted of nine non-consecutive sessions conducted over 3 weeks, with three sessions per week (Monday/Wednesday/Friday or Tuesday/Thursday/Saturday). tDCS was administered using the MicroEstim Genius stimulator (NKL) with the following parameters:

### 2.7.1 | Current Intensity: +2.0 mA

This current level was chosen based on its well-established capacity to modulate synaptic plasticity through mechanisms such as long-term potentiation and neurotransmitter system modulation, both of which are crucial for cognitive enhancement in older adults [21]. Anodal tDCS at 2.0 mA has been shown to increase cortical excitability, particularly in the left dorsolateral prefrontal cortex (lDLPFC), leading to improvements in executive functions and memory [22]. Additionally, this intensity aligns with standardized protocols widely adopted in neuromodulation studies, ensuring cross-study consistency and comparability of results.

### 2.7.2 | Ramp-Up and Ramp-Down: 20 s

Gradual ramping of 20 s at the beginning and end of stimulation was applied to reduce discomfort and minimize the risk of adverse effects such as tingling or burning sensations, especially common during abrupt current shifts [23]. This approach is particularly relevant in older adults, who may exhibit increased sensitivity to electrical stimulation.

### 2.7.3 | Stimulation Duration: 20 min for the Active tDCS Group and 30 s for the Sham Group

A 20-min stimulation period is commonly adopted in studies involving cognitive enhancement and affective symptom reduction in older adults. Evidence suggests this duration is sufficient to induce lasting neuroplastic changes without compromising participant safety or comfort [24, 25]. The 30-s stimulation in the sham condition follows validated protocols to ensure effective blinding while minimizing neural modulation.

### 2.7.4 | Maximum Impedance: 40 kΩ

Limiting impedance to 40 kΩ ensures that the current remains within safe and effective ranges, preventing excessive current delivery that could cause discomfort or skin irritation—especially relevant in elderly populations with variable scalp and skin characteristics. Maintaining impedance within this threshold also contributes to consistent current delivery, which is essential for achieving the desired neuromodulatory effects. High impedance variability can compromise the reproducibility and effectiveness of cognitive interventions [22, 26].

## 2.8 | Electrode Placement

- The anode was positioned over the left dorsolateral prefrontal cortex (DLPFC), corresponding to position F3 of the 10–20 EEG system [19].
- The return electrode was placed in the F7 area.
- Both electrodes were fixed in 35 $cm^2$ conductive sponges soaked in saline solution (NaCl 154 mM, 12 mL per sponge).

The neuromodulation protocol was developed based on previous studies that have demonstrated promising results in patients with post-COVID-19 cognitive impairment [27].

## 2.9 | Cognitive Training

All groups used the BrainHQ platform (Posit Science, 2025), which adapts task difficulty in real time. The tasks were based on a protocol [27] adapted to maximize benefits in patients with post-COVID-19 cognitive impairment. The following games were used:

- Hanoi: develops planning and executive function via Tower of Hanoi puzzle.
- Corsi: strengthens memory and attention through block sequence reproduction.
- People skills: trains emotion recognition and facial memory.
- Target tracker: enhances visual attention and spatial tracking.

## 2.10 | Data Processing and Statistical Methods

To extract the relevant characteristics from the EEG data, a preprocessing pipeline was used to eliminate noise and trivial information using the EEGLAB [28] tool in Matlab R2019b (The

MathWorks, Natick, MA, USA). Signals were resampled to 250 Hz and filtered (Butterworth, 0.01–45 Hz). Artifacts (e.g., blinks and eye movements) were removed via Independent Component Analysis (ICA), following established procedures [29, 30].

The resulting EEG signals were then filtered into traditional frequency bands: Delta ($\delta$), 0.5–4 Hz; Theta ($\theta$), 4–8 Hz; Alpha ($\alpha$), 8–13 Hz; Beta ($\beta$), 13–30 Hz; and Gamma ($\gamma$), 30–45 Hz, according to [31].

Cortical excitation was evaluated based on the ratio of beta (12–28 Hz) and alpha (812 Hz) waves, which are indicators of alertness and relaxation, respectively [32]. EEG signals were measured at four sites in the prefrontal cortex: AF3, AF4, F3, and F4. Excitation (arousal) was calculated using the following formula:

$$\text{Arousal} = (\beta F3 + \beta F4 + \beta AF3 + \beta AF4) / (\alpha F3 + \alpha F4 + \alpha AF3 + \alpha AF4)$$

To determine emotional valence, activation levels between the left and right hemispheres were compared, considering that the left frontal lobe is associated with positive emotions and the right frontal lobe is associated with negative emotions [33–35]. The valence was calculated based on the ratio of the alpha and beta waves in the F3 and F4 electrodes:

$$\text{Valence} = (\alpha F4 / \beta F4) - (\alpha F3 / \beta F3)$$

All statistical analyses were performed using SPSS Statistics (version 23.0; IBM, Chicago, IL, USA). Shapiro–Wilk tested normality. Descriptive data were reported as mean ± SD and CI. Between-group comparisons used one-way ANOVA with Tukey post hoc; omega squared ($\omega$) and $r$ indicated effect sizes. Within-group effects were tested with paired $t$-tests ($\alpha = 0.05$).

## 3 | Results

The sample comprised 30 elderly women (mean age: 71.1 ± 6.45 years; weight: 62.96 ± 10.79 kg; height: 1.56 ± 0.07 m; BMI: 25.89 ± 4.09). No significant differences were observed among the tDCS, sham, and control groups in age ($p = 0.149$), weight ($p = 0.339$), height ($p = 0.384$), or BMI ($p = 0.678$), confirming sample homogeneity.

Baseline and post-intervention MMSE scores showed no significant differences between or within groups ($p = 0.385$; $p = 0.306$). Similarly, education levels did not differ across groups ($p = 0.629$), ensuring comparable cognitive reserve among participants (Table 1; Figure 1; Tables S2 and S3).

Post-intervention analysis of the ACE-R total score revealed significant differences between groups ($p = 0.002$), indicating notable cognitive changes. Within-group analysis showed score increases in all groups: +10.5 (tDCS), +5.9 (sham), and +6.4 (control) (Table 2; Figure 2; Supporting Information).

For the memory domain, the intergroup $p$-value dropped from 0.153 to 0.003 post-intervention, suggesting a specific effect of tDCS. All groups improved, with the tDCS group showing the greatest gain, reinforcing its impact on episodic memory.

In domain-specific analysis, the tDCS group improved in total score, attention/orientation, memory, fluency, and language. The sham group improved in total score, attention/orientation, and memory, while the control group improved only in total score, attention/orientation, and memory (Table 2; Figure 2; Supporting Information).

In the assessment of mood and anxiety symptoms, a significant intergroup difference was found for depressive symptoms (CES-D; $p = 0.021$) and anxiety (GAI) in the somatic, cognitive, and social domains and the total score. In the within-group analysis, the tDCS group showed improvement in all scores, whereas the sham tDCS group did not show significant improvement in CES-D, GAI social, and GAI total scores. The control group showed improvement only in the total GAI score (Table 3; Tables S4–S6).

In the assessment of motor reaction time, a significant difference was found between the groups post-intervention in terms of simple

**TABLE 1** | Sample characterization by MMSE and education level.

| | | | | | 95% confidence interval for mean | | | Pairwise comparison | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | *n* | Mean | SD | Lower bound | Upper bound | *p* ANOVA | *A*/*B* | *A*/*C* | *B*/*C* |
| General MMSE score (30)—Pre | tDCS | 10 | 25.60 | 3.27 | 23,263 | 27,946 | 0.385 | — | — | — |
| | tDCS—Sham | 10 | 26.60 | 2.27 | 24,985 | 28,225 | | | | |
| | Control | 10 | 24.50 | 4.20 | 21,501 | 27,503 | | | | |
| | Total | 30 | 25.57 | 3.34 | 24,324 | 26,812 | | | | |
| Education level (years of study) | tDCS | 10 | 4.14 | 1.85 | 2953 | 5247 | 0.629 | — | — | — |
| | tDCS—Sham | 10 | 4.85 | 1.81 | 3672 | 5922 | | | | |
| | Control | 10 | 4.21 | 1.54 | 3234 | 5165 | | | | |
| | Total | 30 | 4.36 | 1.71 | 3756 | 4977 | | | | |

*Note:* Comparative analysis between intervention groups was performed using the one-way ANOVA test for parametric variables, with Tukey's post hoc test for pairwise comparison, adopting a significance value of $p \leq 0.05$.

**TABLE 2** | Comparison of cognitive scores (ACE-R) before and after the intervention in the tDCS, Sham tDCS, and control groups.

| | | | | | 95% confidence interval for mean | | | Pairwise comparison | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | *n* | Mean | SD | Lower bound | Upper bound | *p* ANOVA | *A/B* | *A/C* | *B/C* |
| General MMSE score (30)—post | tDCS | 10 | 26.90 | 2.33 | 25,234 | 28,572 | 0.306 | — | — | — |
| | tDCS—Sham | 10 | 27.00 | 1.83 | 25,695 | 28,313 | | | | |
| | Control | 10 | 25.50 | 2.88 | 23,447 | 27,563 | | | | |
| | Total | 30 | 26.47 | 2.40 | 25,579 | 27,365 | | | | |
| General ACE-R score (100)—pre | tDCS | 10 | 71.70 | 2.31 | 70,050 | 73,352 | 0.211 | — | — | — |
| | tDCS—Sham | 10 | 69.60 | 3.34 | 67,212 | 71,996 | | | | |
| | Control | 10 | 71.10 | 2.18 | 69,543 | 72,663 | | | | |
| | Total | 30 | 70.80 | 2.72 | 69,782 | 71,826 | | | | |
| General ACE-R score (100)—post | tDCS | 10 | 82.20 | 3.99 | 79,344 | 85,069 | 0.002 | 0.010 | 0.033 | 0.475 |
| | tDCS—Sham | 10 | 75.50 | 3.31 | 73,136 | 77,870 | | | | |
| | Control | 10 | 77.50 | 4.01 | 74,634 | 80,374 | | | | |
| | Total | 30 | 78.40 | 4.64 | 76,676 | 80,133 | | | | |
| ACE-R subtotals—attention and orientation (18)—pre | tDCS | 10 | 13.00 | 1.49 | 11,935 | 14,072 | 0.599 | — | — | — |
| | tDCS—Sham | 10 | 13.30 | 1.49 | 12,239 | 14,373 | | | | |
| | Control | 10 | 13.60 | 0.84 | 13,001 | 14,204 | | | | |
| | Total | 30 | 13.30 | 1.29 | 12,821 | 13,786 | | | | |
| ACE-R subtotals—attention and orientation (18)—post | tDCS | 10 | 15.60 | 1.58 | 14,473 | 16,733 | 0.289 | — | — | — |
| | tDCS—Sham | 10 | 14.70 | 1.49 | 13,634 | 15,779 | | | | |
| | Control | 10 | 14.60 | 1.51 | 13,522 | 15,682 | | | | |
| | Total | 30 | 14.97 | 1.54 | 14,391 | 15,541 | | | | |
| ACE-R subtotals—memory (26)—pre | tDCS | 10 | 9.70 | 1.16 | 8870 | 10,532 | 0.153 | — | — | — |
| | tDCS—Sham | 10 | 8.90 | 1.66 | 7715 | 10,093 | | | | |
| | Control | 10 | 8.60 | 0.84 | 8000 | 9202 | | | | |
| | Total | 30 | 9.07 | 1.31 | 8583 | 9561 | | | | |
| ACE-R subtotals—memory (26)—post | tDCS | 10 | 15.70 | 2.58 | 13,854 | 17,552 | 0.003 | 0.015 | 0.015 | 0.989 |
| | tDCS—Sham | 10 | 12.30 | 2.26 | 10,684 | 13,924 | | | | |
| | Control | 10 | 12.30 | 1.95 | 10,911 | 13,698 | | | | |
| | Total | 30 | 13.43 | 2.74 | 12,416 | 14,469 | | | | |
| ACE-R subtotals—fluency (14)—pre | tDCS | 10 | 9.20 | 1.40 | 8204 | 10,202 | 0.654 | — | — | — |
| | tDCS—Sham | 10 | 9.10 | 1.45 | 8067 | 10,147 | | | | |
| | Control | 10 | 9.70 | 1.77 | 8448 | 10,963 | | | | |
| | Total | 30 | 9.33 | 1.52 | 8774 | 9903 | | | | |
| ACE-R subtotals—fluency (14)—post | tDCS | 10 | 10.50 | 0.97 | 9805 | 11,204 | 0.111 | — | — | — |
| | tDCS—Sham | 10 | 9.80 | 1.03 | 9062 | 10,545 | | | | |
| | Control | 10 | 10.90 | 1.37 | 9924 | 11,888 | | | | |
| | Total | 30 | 10.40 | 1.19 | 9951 | 10,858 | | | | |
| ACE-R subtotals—language (26)—pre | tDCS | 10 | 24.70 | 0.95 | 24,023 | 25,383 | 0.136 | — | — | — |
| | tDCS—Sham | 10 | 23.60 | 1.51 | 22,523 | 24,683 | | | | |
| | Control | 10 | 24.20 | 1.03 | 23,466 | 24,945 | | | | |
| | Total | 30 | 24.17 | 1.23 | 23,716 | 24,635 | | | | |

(Continues)

**TABLE 2** | (Continued)

| | | | | | 95% confidence interval for mean | | | Pairwise comparison | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | *n* | Mean | SD | Lower bound | Upper bound | *p* ANOVA | *A/B* | *A/C* | *B/C* |
| ACE-R subtotals—language (26)—post | tDCS | 10 | 25.40 | 0.52 | 25,032 | 25,775 | 0.004 | 0.012 | 0.046 | 0.102 |
| | tDCS—Sham | 10 | 23.70 | 1.42 | 22,692 | 24,715 | | | | |
| | Control | 10 | 24.40 | 0.97 | 23,711 | 25,099 | | | | |
| | Total | 30 | 24.50 | 1.22 | 24,048 | 24,961 | | | | |
| ACE-R subtotals—visuospatial (16)—pre | tDCS | 10 | 13.40 | 1.07 | 12,634 | 14,173 | 0.987 | — | — | — |
| | tDCS—Sham | 10 | 13.30 | 1.57 | 12,186 | 14,422 | | | | |
| | Control | 10 | 13.40 | 1.96 | 12,000 | 14,801 | | | | |
| | Total | 30 | 13.37 | 1.52 | 12,801 | 13,933 | | | | |
| ACE-R subtotals—visuospatial (16)—post | tDCS | 10 | 13.80 | 1.32 | 12,863 | 14,743 | 0.963 | — | — | — |
| | tDCS—Sham | 10 | 13.60 | 1.35 | 12,633 | 14,572 | | | | |
| | Control | 10 | 13.70 | 2.11 | 12,192 | 15,218 | | | | |
| | Total | 30 | 13.70 | 1.58 | 13,111 | 14,295 | | | | |

*Note:* Comparative analysis between intervention groups was performed using the one-way ANOVA test for parametric variables, with Tukey's post hoc test for pairwise comparison, adopting a significance value of $p \leq 0.05$.

reaction time, initial fatigue, and final fatigue, with the tDCS group presenting shorter times. Within-group analysis showed a significant reduction in time in all domains in the tDCS group, whereas the sham tDCS and control groups also showed a reduction, but of a lesser magnitude (Figure 3; Tables S7–S10).

In the EEG data analysis, the tDCS group showed significantly better post-intervention values for cortical excitation and valence, whereas there was no significant difference between the sham and control groups. Within-group analysis revealed significant modifications in the tDCS group for both variables, whereas the sham group showed changes only in cortical excitation, and the control group did not demonstrate significant changes (Figure 4; Tables S11–S14).

## 4 | Discussion

This study reinforces the potential of anodal tDCS over the left prefrontal cortex combined with cognitive training to enhance cognition and mental health in the elderly. The intervention significantly improved cognition, anxiety, depression, and motor reaction time, with notable gains across assessed domains.

The substantial improvement in ACE-R scores, particularly in the memory, fluency, and language domains, highlights the impact of the intervention on cortical plasticity, facilitating the activation and strengthening of neural networks related to learning and recall. Previous studies have indicated that tDCS can enhance short-term memory and executive function, boosting learning and information retention capacity [36].

Furthermore, anodal stimulation of the left dorsolateral prefrontal cortex was particularly effective in improving general cognitive function, immediate and delayed memory, and decision-making [37]. This suggests that selective activation of these cortical networks not only enhances memory encoding and retrieval but also strengthens the neural circuits responsible for cognitive control and mental flexibility, as reflected in the improved verbal fluency and linguistic organization observed in the study participants.

The combination of tDCS and cognitive training has shown promise in enhancing cognitive functions, particularly short-term memory and executive function [36]. Moreover, adaptive multitasking cognitive training based on processes (p-BM-tact) has shown both direct and transfer effects on executive function and other cognitive domains with sustained benefits over time [38]. These findings reinforce the idea that interventions combining neural stimulation and structured cognitive exercises can amplify the observed gains in cortical plasticity and cognitive functionality.

The relationship between cognitive and emotional health measures was also evident in these findings. The reduction in anxiety and depression scores in the tDCS group suggests that stimulation may promote greater functional connectivity between the prefrontal cortex and limbic structures such as the amygdala, facilitating more efficient control of emotional responses.

Akabari et al. [39] demonstrated that tDCS applied to frontal regions significantly improves emotional processing, especially when associated with higher current intensities and prolonged stimulation durations. This relationship is corroborated by the findings of [40], which indicate that transcranial stimulation can correct hypofrontality patterns frequently observed in depressive and anxious states. Thus, the positive impact of the intervention on emotional regulation can be attributed to tDCS's ability to rebalance excitatory and inhibitory activity in the neural networks involved in emotional processing and decision-making. Studies involving cognitive training without cortical

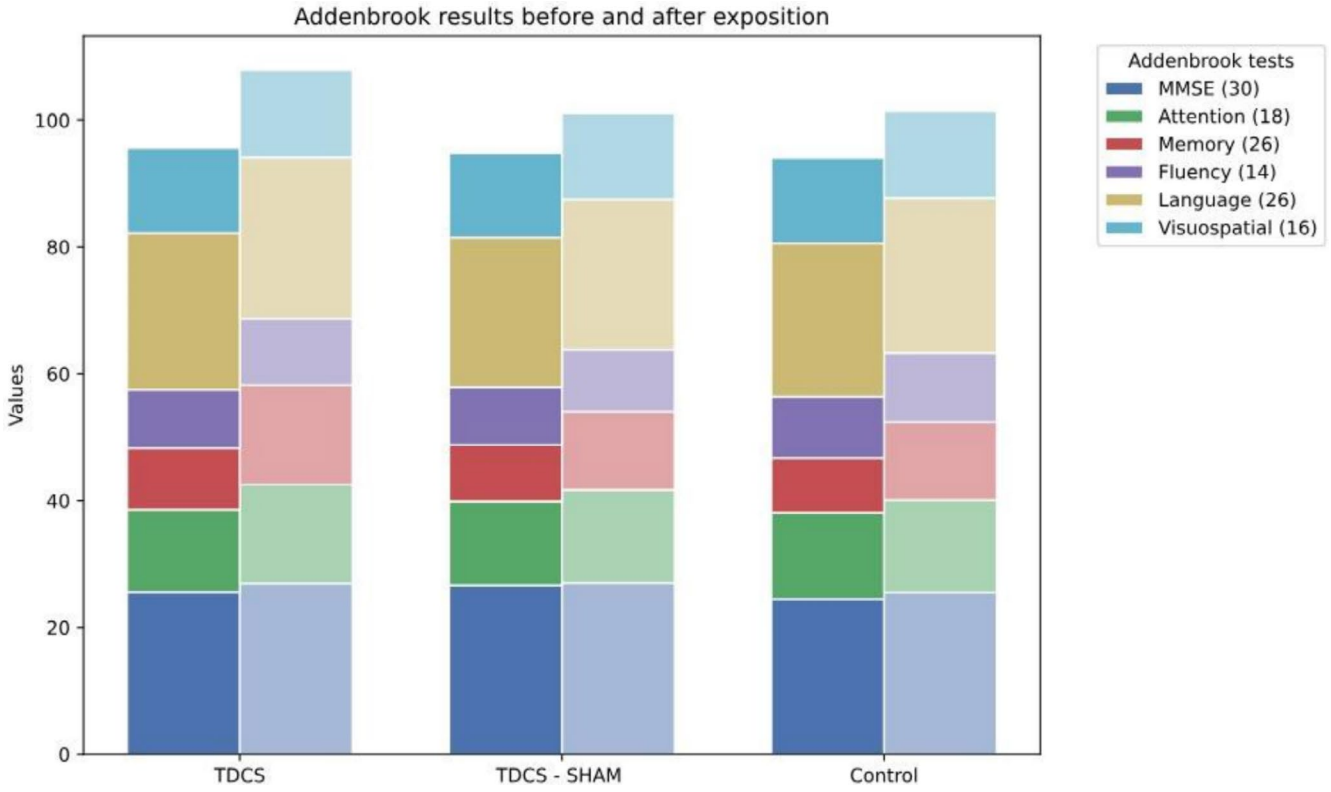


**FIGURE 2** | Intergroup and intragroup comparison of the evolution of ACE-R cognitive scores by domain before and after the intervention.

stimulation have shown that one of the associated outcomes is reduced depressive and anxiety symptoms [41]. This finding may be related to both subjective performance perception and secondary benefits of the intervention, such as increased socialization, well-being, and quality of life [42].

The link between cognition and motor reaction time is relevant, as reduced reaction time reflects improved sensorimotor integration and motor control. While specific studies on tDCS and reaction time are limited, evidence suggests that cognitive gains from stimulation can indirectly enhance motor efficiency via prefrontal cortex modulation [43]. The findings of Reis et al. indicate that tDCS facilitates communication between the cortical regions responsible for motor execution and the prefrontal cortex, promoting greater efficiency in motor control processes. Considering the relevance of this improvement in the elderly population, the reduction in the motor reaction time observed in this study may be associated with a lower risk of falls and better daily functionality, reinforcing the importance of tDCS as an intervention strategy for promoting functional autonomy.

In summary, the results of this study indicate that computerized cognitive training (CCT) can effectively improve episodic memory, modulate brain connectivity, and suggest potential neural plasticity [1]. Additionally, transcranial direct current stimulation (tDCS) is associated with episodic memory benefits, especially in individuals with subjective cognitive decline (SCD), through stimulation of the left dorsolateral prefrontal cortex (l-DLPFC) [44]. This effect contributes to improved memory reconsolidation, resulting in more stable performance over time. Thus, combining CCT with tDCS may represent a promising strategy for enhancing cognition and promoting overall well-being in older adults at risk of cognitive decline.

While tDCS combined with cognitive training shows promise, individual variability highlights the need for personalized protocols. Methodological heterogeneity and inconsistent results emphasize the importance of further studies to standardize procedures and evaluate long-term effects. Additional research should also explore outcomes in elderly individuals without post-COVID cognitive complaints and include larger samples for greater statistical power. Investigating diverse cognitive tasks and comparing their efficacy may help optimize neuromodulation strategies, enhancing cognitive and emotional outcomes and guiding more effective, individualized interventions for the aging population.

## 5 | Conclusion

This study shows that anodal tDCS combined with cognitive training effectively enhances cognition, emotional well-being, and motor integration in elderly individuals. Improvements in memory, verbal fluency, decision-making, and reaction time suggest strengthened cortical plasticity and neural connectivity. Reductions in anxiety and depression further highlight tDCS's potential in emotional regulation—key to healthy aging. Its noninvasive, safe application makes it a low-risk, accessible intervention. Personalized cognitive training amplifies these benefits. The results support tDCS as a promising strategy for preventing and managing subjective cognitive decline and promoting autonomy and quality of life. Further research should refine protocols and assess long-term effects.

**TABLE 3** | Intergroup comparison of depression (CES-D) and anxiety (GAI) scores before and after the intervention.

| | | | | | 95% confidence interval for mean | | | Pairwise comparison | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | *n* | Mean | SD | Lower bound | Upper bound | *p* ANOVA | *A*/*B* | *A*/*C* | *B*/*C* |
| CES-D depression scale—total score—Pre | tDCS | 10 | 20.30 | 5.66 | 16,254 | 24,353 | 0.224 | — | — | — |
| | tDCS—Sham | 10 | 25.20 | 7.58 | 19,785 | 30,626 | | | | |
| | Control | 10 | 24.60 | 6.77 | 19,767 | 29,443 | | | | |
| | Total | 30 | 23.37 | 6.85 | 20,812 | 25,920 | | | | |
| CES—D depression scale—total score—post | tDCS | 10 | 17.50 | 2.72 | 14,122 | 18,881 | 0.021 | 0.048 | 0.025 | 0.334 |
| | tDCS—Sham | 10 | 20.10 | 3.00 | 17,964 | 22,244 | | | | |
| | Control | 10 | 22.80 | 4.16 | 19,831 | 25,776 | | | | |
| | Total | 30 | 20.13 | 4.46 | 18,471 | 21,803 | | | | |
| GAI—somatic anxiety—pre | tDCS | 10 | 7.60 | 1.07 | 6836 | 8370 | 0.815 | — | — | — |
| | tDCS—Sham | 10 | 7.50 | 1.08 | 6739 | 8270 | | | | |
| | Control | 10 | 7.80 | 1.03 | 7064 | 8541 | | | | |
| | Total | 30 | 7.63 | 1.03 | 7256 | 8022 | | | | |
| GAI—somatic anxiety—post | tDCS | 10 | 3.00 | 0.82 | 2424 | 3583 | < 0.001 | 0.009 | 0.009 | 0.009 |
| | tDCS—Sham | 10 | 5.30 | 0.67 | 4820 | 5785 | | | | |
| | Control | 10 | 8.10 | 0.88 | 7471 | 8736 | | | | |
| | Total | 30 | 5.47 | 2.26 | 4622 | 6314 | | | | |
| GAI—cognitive anxiety—pre | tDCS | 10 | 6.40 | 1.07 | 5633 | 7173 | 0.970 | — | — | — |
| | tDCS—Sham | 10 | 6.40 | 0.97 | 5713 | 7092 | | | | |
| | Control | 10 | 6.50 | 1.08 | 5734 | 7273 | | | | |
| | Total | 30 | 6.43 | 1.01 | 6066 | 6813 | | | | |
| GAI—cognitive anxiety—post | tDCS | 10 | 2.60 | 0.52 | 2237 | 2976 | < 0.001 | 0.009 | 0.009 | 0.009 |
| | tDCS—Sham | 10 | 4.40 | 0.70 | 3908 | 4907 | | | | |
| | Control | 10 | 6.90 | 0.74 | 6377 | 7436 | | | | |
| | Total | 30 | 4.63 | 1.90 | 3922 | 5344 | | | | |
| GAI—social anxiety—pre | tDCS | 10 | 4.10 | 0.74 | 3577 | 4632 | 0.807 | — | — | — |
| | tDCS—Sham | 10 | 4.00 | 0.67 | 3524 | 4488 | | | | |
| | Control | 10 | 4.20 | 0.63 | 3759 | 4658 | | | | |
| | Total | 30 | 4.10 | 0.66 | 3850 | 4354 | | | | |
| GAI—social anxiety—post | tDCS | 10 | 2.00 | 0.67 | 1521 | 2485 | < 0.001 | 0.009 | 0.009 | 0.009 |
| | tDCS—Sham | 10 | 3.40 | 0.70 | 2900 | 3903 | | | | |
| | Control | 10 | 5.80 | 0.63 | 5352 | 6257 | | | | |
| | Total | 30 | 3.73 | 1.72 | 3093 | 4383 | | | | |
| GAI—total score—pre | tDCS | 10 | 18.10 | 1.52 | 17,010 | 19,193 | 0.468 | — | — | — |
| | tDCS—Sham | 10 | 17.90 | 0.74 | 17,372 | 18,439 | | | | |
| | Control | 10 | 18.50 | 0.85 | 17,896 | 19,116 | | | | |
| | Total | 30 | 18.17 | 1.09 | 17,763 | 18,578 | | | | |
| GAI—total score—post | tDCS | 10 | 7.60 | 1.51 | 6525 | 8686 | < 0.001 | 0.009 | 0.009 | 0.009 |
| | tDCS—Sham | 10 | 13.10 | 1.37 | 12,126 | 14,089 | | | | |
| | Control | 10 | 20.80 | 1.40 | 19,803 | 21,800 | | | | |
| | Total | 30 | 13.83 | 5.68 | 11,712 | 15,953 | | | | |

*Note:* Comparative analysis between intervention groups was performed using the one-way ANOVA test for parametric variables, with Tukey's post hoc test for pairwise comparison, adopting a significance value of $p \leq 0.05$.

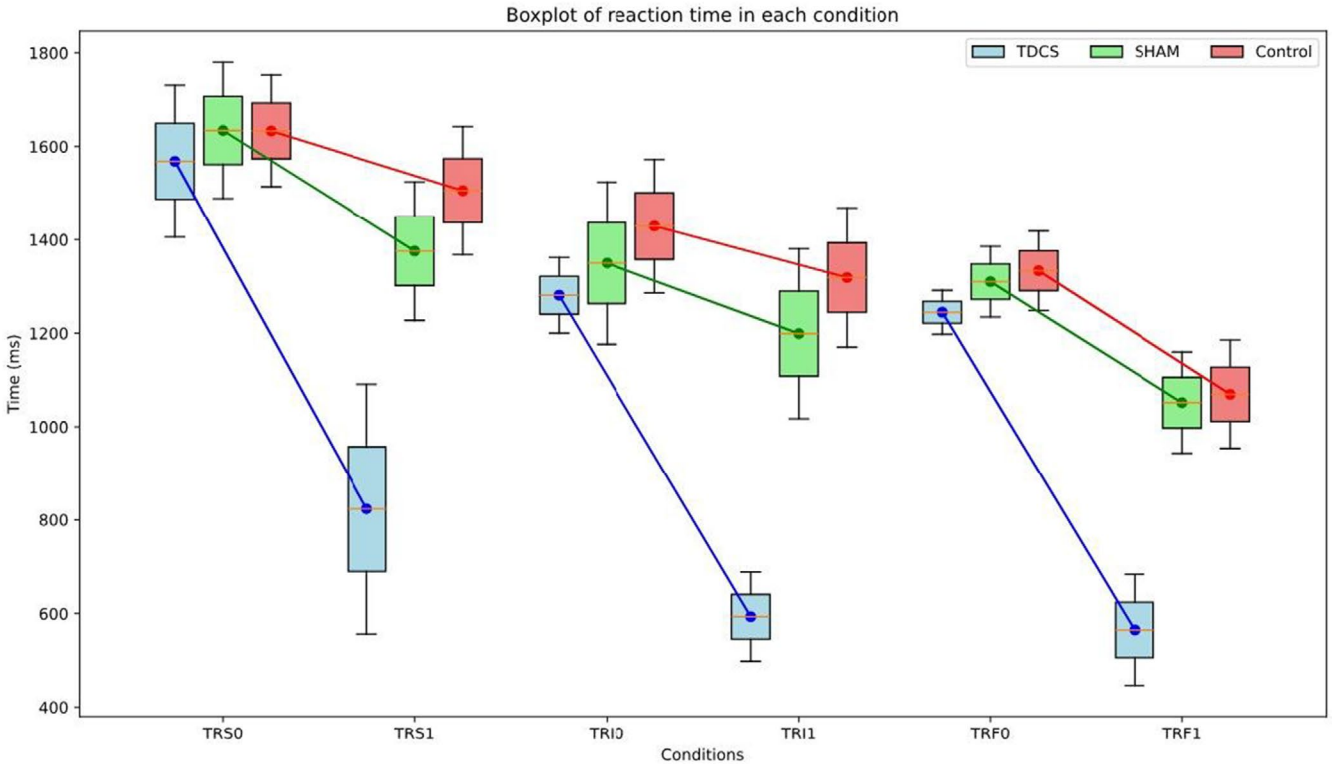


**FIGURE 3** | Intergroup and intragroup comparison of motor reaction times (Simple, Initial Fatigue, and Final Fatigue) before and after the intervention. 0 = pre-intervention; 1 = post-intervention.

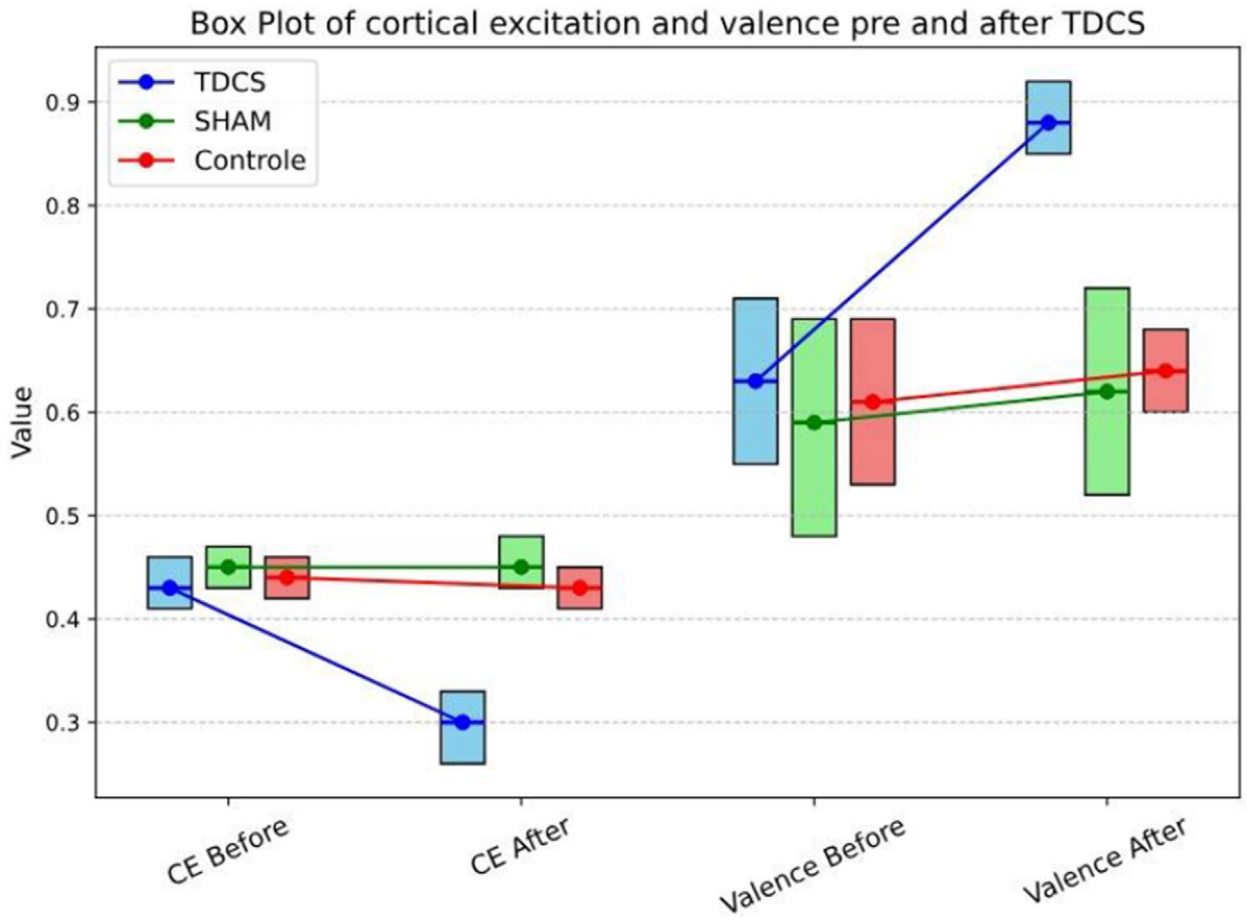


**FIGURE 4** | Intergroup and intragroup comparison of cortical excitation and emotional valence parameters before and after the intervention.

### Author Contributions

G.A.S.B.: conceptualized the study, analyzed and interpreted the data, and wrote the manuscript. AD.B, R.L.M, R.C.D.S., and E.B.C.J.: analyzed the data and critically revised the manuscript for important intellectual content. H.S.S.: contributed to the study's concept and design, supervised the research, and critically revised the manuscript for significant intellectual content.


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### Ethics Statement

This study was approved by the Research Ethics Committee of the Euro-American University Center (Approval number: 6.929.974).

### Consent

All participants provided written informed consent prior to enrollment in the study.

### Conflicts of Interest

The authors declare no conflicts of interest.

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## Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Tables S1–S14:** agm270059-sup-0001-TableS1-S14.docx.