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The Impact of Transcranial Direct Current Stimulation (tDCS) on Memory Function in Older Adults with Mild Cognitive Impairment: A Systematic Review

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ABSTRACT

Mild Cognitive Impairment (MCI) represents a transitional phase between normal aging and dementia, primarily affecting memory. It affects nearly one-fifth of adults over 50 worldwide, highlighting its growing clinical importance. Pharmacological treatments have shown limited efficacy, prompting interest in non-invasive interventions such as transcranial direct current stimulation (tDCS), which modulates cortical excitability through weak electrical currents. This systematic review aimed to evaluate the effects of tDCS on memory performance in older adults with MCI and to identify protocol-specific predictors of improvement. A systematic search was conducted in PubMed, Scopus, and Web of Science (up to April 2025) following PRISMA guidelines. Eligible studies included randomized and non-randomized trials examining tDCS alone or combined with cognitive training in adults aged 60 years and older with MCI. Ten studies (N = 428) met inclusion criteria. Due to heterogeneity, findings were synthesized narratively. Overall, tDCS significantly improved verbal and recognition memory, as well as spatial and episodic memory performance. Neurophysiological findings indicated enhanced neural activity and connectivity. Stimulation targeting the left dorsolateral prefrontal cortex produced the most consistent benefits, especially when applied for ten or more sessions at an intensity of 2 mA. Mild side effects, such as redness and tingling, occurred in approximately 20–30% of participants, with no serious adverse events reported. Preliminary evidence supports the effectiveness and safety of tDCS in improving memory among individuals with MCI. However, variability in protocols and small sample sizes underscore the need for standardized, biomarker-guided, and longitudinal research.

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Introduction

In recent years, pharmacological treatments for mild cognitive impairment (MCI) have shown limited efficacy and often carry significant costs and side effects. Common drug approaches, such as cholinesterase inhibitors, May temporarily enhance cognitive function but are frequently associated with gastrointestinal disturbances, bradycardia, or sleep problems, and require continuous medical supervision. By contrast, tDCS offers a low-cost, portable, and non-invasive alternative with a favorable safety profile. Most side effects are transient and mild such as tingling or itching under the electrodes and do not require medical intervention. Furthermore, while medications typically need long-term daily administration, tDCS can be applied in short stimulation sessions with effects that may extend beyond the treatment period. This comparison highlights the potential of tDCS as a pragmatic and scalable intervention for older adults with MCI.

An additional pragmatic advantage of tDCS is its relative affordability and accessibility compared with pharmacotherapy and some other non-invasive brain stimulation modalities. In routine clinical practice, supervised tDCS sessions are substantially less costly than repetitive transcranial magnetic stimulation (TMS) and depending on local markets can be delivered at modest per-session fees. For example, clinic-based programs in high-income settings have reported bundled or equipment-loan packages that effectively reduce per-session costs to the order of tens of US dollars, while private outpatient sessions may range into the low hundreds of US dollars. Devices intended for home use are also available at a much lower one-time cost (typically tens to a few hundred US dollars for consumer/medical-grade units), although research-grade stimulators remain more expensive.

In our local context (Iran), publicly listed clinic prices around the time of writing were commonly in the range of ~300,000–800,000 Iranian Toman per supervised session. These relative cost differences, together with tDCS's favorable safety profile (mostly transient, mild scalp sensations) and portability, make it a potentially scalable adjunctive intervention in older adults with MCI.

At the neurophysiological level, tDCS differs from other brain stimulation methods such as transcranial alternating current stimulation (tACS), which attempts to synchronize rhythmic brain activity in frequencies associated with memory, for example in the theta (slow) and gamma (fast) ranges. These concepts are often described in terms of "phase" and "amplitude," but essentially, they refer to how well different brain rhythms align and amplify each other. While such synchronization is promising, it remains technically complex and inconsistent in clinical outcomes. tDCS instead modulates the excitability of targeted brain areas in a more direct and stable manner, making it easier to implement in clinical populations.

Mild Cognitive Impairment (MCI)

Mild Cognitive Impairment (MCI) represents a clinically significant transitional phase between normative cognitive aging and dementia, operationally defined by objective cognitive decline (≥1.5 SD below age-education norms) with preserved activities of daily living (Lyssenko & Praticò, 2021). This condition primarily affects memory, language, and spatial perception, with measurable cognitive decline interfering with physical, psychological, and social functioning despite maintained independence. Global epidemiological studies demonstrate an escalating prevalence with advancing age, affecting 15.4% of adults aged 65–74 years, 22.7% of those aged 75–84 years, and 38.5% beyond age 85 (Burns, 2020). Recent meta-analyses indicate an overall pooled prevalence of 19.7% (95% CI: 18.3–21.1%) among adults ≥50 years, with higher rates in clinical settings (34.0% in hospitals) compared to community-dwelling populations (17.9%) (Song et al., 2023). This burden is amplified by rapid global aging, with projections indicating 2.1 billion older adults by 2050 and 3.1 billion by 2100 (Salari et al., 2025).

A pronounced gender disparity exists, with women exhibiting 44% higher prevalence than men (24.1% vs. 16.7%), attributable to neuroendocrine factors and longevity (Blue et al., 2021), though recent studies show no significant sex-based differences in global estimates (Song et al., 2023). Regional variations are evident, with Iran reporting 19.3% aggregate prevalence among adults ≥65 years (Oshnouei et al., 2024), while risk factors including lower education, dietary patterns, economic status, and stroke history further modulate susceptibility (Salari et al., 2025). The amnestic MCI subtype (aMCI) demonstrates particular clinical significance, where episodic memory impairment serves as the strongest predictor of dementia conversion (HR = 4.2; 95% CI [3.1–5.7]) and correlates with Alzheimer's disease neuropathology in >60% of cases (Farrell et al., 2022). Notably, anosognosia—impaired awareness of memory deficits signals higher progression risk to Alzheimer's dementia, whereas anosodiaphoria (lack of concern) shows no predictive value (Munro et al., 2018). Longitudinal analyses confirm >40% of aMCI patients develop dementia within 5 years, with complications extending to sleep disorders and depression (Ossenkoppele et al., 2022; Salari et al., 2025).

Therapeutic Limitations and Neuromodulatory Imperative

In the initial stage of this review, we considered the broader field of non-invasive brain stimulation (NIBS), including transcranial magnetic stimulation (TMS), transcranial alternating current stimulation (tACS), and transcranial random noise stimulation (tRNS). These modalities were incorporated into our search strategy to minimize the risk of missing potentially relevant evidence, in line with Cochrane recommendations for sensitive and comprehensive searches. However, during eligibility assessment, we restricted our synthesis to tDCS studies to ensure methodological and physiological homogeneity.

TMS delivers focal magnetic pulses that directly induce neuronal depolarization. Although effective in some cognitive and psychiatric domains, its higher cost, equipment requirements, and heterogeneous stimulation protocols made it less suitable for the current review. Similarly, tACS aims to entrain neural oscillations at specific frequencies (e.g., theta or gamma), and tRNS applies broadband random noise currents to facilitate excitability through stochastic resonance. Both techniques have shown emerging but inconsistent effects on cognition in older adults, with considerable variability in protocols and limited evidence in mild cognitive impairment (MCI).

By contrast, tDCS has been more extensively studied in MCI populations, is inexpensive, portable, and has a strong safety profile. For this reason, we focused our quantitative synthesis on tDCS interventions. In addition, we extracted not only memory outcomes but also secondary, non-memory outcomes (e.g., attention, executive function, mood). This decision was justified by their clinical relevance to Alzheimer's disease progression and their frequent inclusion in the primary studies.

Current interventions face significant limitations. Pharmacological approaches show modest efficacy: cholinesterase inhibitors (donepezil/rivastigmine) demonstrate limited memory improvement (effect size d = 0.15–0.28) with frequent adverse effects (nausea: 27%; bradycardia: 8%), while memantine provides negligible benefit (d = 0.08) and risks neuropsychiatric events (Beurmanjer et al., 2020; Steffens & Zdanys, 2022). Combination therapy fails to demonstrate synergistic effects while amplifying adverse events (OR = 2.1; 95% CI [1.4–3.2]) (Zhang et al., 2022).Behavioral interventions such as cognitive training exhibit limited transfer effects beyond trained tasks (6-month retention: d = 0.12), and physical exercise shows marginal impact on episodic memory despite executive function benefits (d = 0.26) (Wardlow et al., 2023; Zhang et al., 2021). These constraints, coupled with regional prevalence variations complicating health policy, necessitate novel neuromodulatory approaches targeting neuroplasticity deficits underlying memory decline a paradigm addressed by transcranial direct current stimulation (tDCS) (Li et al., 2020; Salari et al., 2025).

Mechanisms and Protocol Optimization of tDCS

tDCS modulates cortical excitability through low-amplitude (1–2 mA) direct current applied via scalp electrodes. Its mechanisms involve sustained depolarization of neuronal resting

membrane potentials (+0.5 mV) during anodal stimulation, enhancing spontaneous firing (Langley et al., 2023). Long-term potentiation induction occurs through NMDA receptor-dependent synaptic efficacy potentiation via Ca^{2+} influx and BDNF-TrkB signaling (Cappoli et al., 2020), while oscillatory coupling promotes theta-gamma phase-amplitude synchronization during memory encoding ($r = 0.68$, $p < 0.001$) (Hawrylycz et al.). Contemporary applications prioritize the dorsolateral prefrontal cortex (74% of trials) due to its role in working memory maintenance, utilizing standardized parameters: intensity of 1.5–2 mA, duration of 25 minutes per session, frequency of five sessions weekly over three weeks, and F3 anode placement (10–20 system) with contralateral supraorbital cathode (Martins et al., 2022). Adjunctive cognitive training during stimulation leverages metaplasticity in 92% of trials (Sohn et al., 2024).

Three converging lines of evidence support tDCS application in MCI. First, it restores age-related plasticity deficits by reversing long-term potentiation impairment through glutamatergic modulation and enhancing hippocampal-prefrontal functional connectivity (functional magnetic resonance imaging (fMRI): $r = 0.72$, $p < 0.001$) (Deng et al., 2023; Li et al., 2020). Clinically, tDCS improves working memory accuracy by 28.4% versus sham ($d = 0.78$; 95% CI [0.52–1.04]) and increases episodic memory delayed recall scores by 22.7% ($d = 0.65$; 95% CI [0.41–0.89]). Practical advantages include a favorable safety profile (transient scalp discomfort: 4.2% vs. pharmacotherapy gastrointestinal events: 31.5%), home-based administration feasibility (87% compliance), and cost-effectiveness (Li et al., 2020; Zhou et al., 2023)

Despite promising results, critical uncertainties persist regarding parameter optimization due to inconsistencies in intensity (1–2 mA), duration (10–30 min), and target regions across studies; population stratification needs for amnestic versus multi-domain MCI subtypes; and sparse evidence beyond 6-month follow-up (Manenti et al., 2024). This systematic review therefore aims to synthesize evidence from randomized controlled trials (2020–2025) to quantify tDCS efficacy on primary memory outcomes, establish optimal stimulation parameters through dose-response analysis, evaluate long-term cognitive preservation, assess safety in comorbid elderly populations, and model cost-effectiveness relative to standard care.

Our review also diverges from Manenti et al. in important ways. Whereas Manenti and colleagues primarily examined the acute cognitive effects of tDCS in specific task-based settings, our synthesis included a broader range of studies focusing on both memory and non-memory outcomes, and specifically targeted older adults with MCI. This distinction allows us to address not only whether tDCS can transiently modulate performance, but also whether it holds translational potential as an adjunct to therapeutic strategies in populations at risk of Alzheimer's disease.

Method

The aim of this study was to conduct a systematic review to investigate the effects of transcranial direct current stimulation (tDCS) on memory development in individuals with mild cognitive impairment (MCI). A multi-stage diagnostic process (search, screening, and selection) was applied to categorize eligible articles.

Study Design and Search Strategy

Study Design

A manual search protocol for systematic reviews, including scanning of reference lists, was implemented to reduce the risk of missing studies. The PRISMA framework was applied throughout the selection process. By April 4, 2025, when the search strategy was finalized, the total number of records identified was as follows: PubMed, 450; Scopus, 403; and Web of Science, 340. Duplicates were removed both manually and automatically using EndNote version 21 and Rayyan by two independent researchers. Discrepancies were resolved through discussion. (Fig. 1)

Search Strategy

A comprehensive search strategy was developed to systematically identify studies on MCI and tDCS. The primary concepts of interest, mild cognitive impairment and transcranial direct current stimulation, were combined using the Boolean operator AND. For each concept, a list of relevant keywords was created and combined using the Boolean operator OR. In PubMed, Medical Subject Headings (MeSH) were also included. Published systematic reviews were consulted to refine and validate the search terms.

The final search string included terms such as: ((“Cognitive Dysfunctions” OR “Cognitive Disorder*” OR “Cognitive Impairment*” OR “Mild Cognitive Impairment*” OR “Cognitive Decline*” OR “Mental Deterioration*”) AND (tDCS OR “Anodal Stimulation Transcranial Direct Current Stimulation” OR “Anodal Stimulation tDCS*” OR “Cathodal Stimulation Transcranial Direct Current Stimulation” OR “Cathodal Stimulation tDCS*” OR “Transcranial Random Noise Stimulation” OR “Repetitive Transcranial Electrical Stimulation” OR “Transcranial Electrical Stimulation*”((The scope of the synthesis was defined as “tDCS in older adults with MCI.” Other modalities (tACS, tRNS, TMS) were included at the search stage to maximize sensitivity; however, during screening and extraction, non-tDCS studies were excluded from the quantitative synthesis to reduce heterogeneity and maintain comparability.

Eligibility Criteria

Screening was performed independently by two reviewers. Disagreements were resolved through discussion with a third reviewer. Prior to screening, inclusion and exclusion criteria were agreed upon by the study team and domain experts.

Inclusion Criteria

Eligible studies included human participants aged 60 years or older diagnosed with MCI using standardized criteria such as the Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition (DSM-5) or the International Classification of Diseases, Tenth Revision (ICD-10). The intervention had to be transcranial direct current stimulation (tDCS) as the primary modality, with a control condition (e.g., sham stimulation, placebo, standard care, or no treatment). Eligible outcomes assessed memory performance (working and long-term memory) using validated instruments.

Included study designs comprised randomized controlled trials (RCTs), non-randomized trials, crossover trials, and other experimental studies. Only peer-reviewed original research articles published in English were considered. Diagnostic thresholds varied across studies, with some using the Mini-Mental State Examination (MMSE, $\leq$24) and others the Montreal Cognitive Assessment (MoCA, $\leq$26). Because these instruments are not directly equivalent, this variability may have introduced heterogeneity in baseline severity.

Exclusion Criteria

Studies Studies involving animal models, participants with moderate-to-severe cognitive impairment, or other neurological conditions (e.g., dementia, stroke) without MCI were excluded. Research not using tDCS, or combining tDCS with pharmacological interventions, was not eligible. Trials without a control group, head-to-head comparisons of two active treatments, or studies using only active tDCS without sham or standard care were excluded.

Dropout rates across eligible trials ranged from 5% to 20%, primarily due to mild adverse events or adherence issues. No study reported serious adverse events resulting in participant withdrawal.

Outcomes restricted to domains other than memory (e.g., general cognition, motor function) were excluded. Observational designs, case reports, case series, pilot studies, systematic reviews, meta-analyses, book chapters, conference abstracts, and non-peer-reviewed work were not eligible.

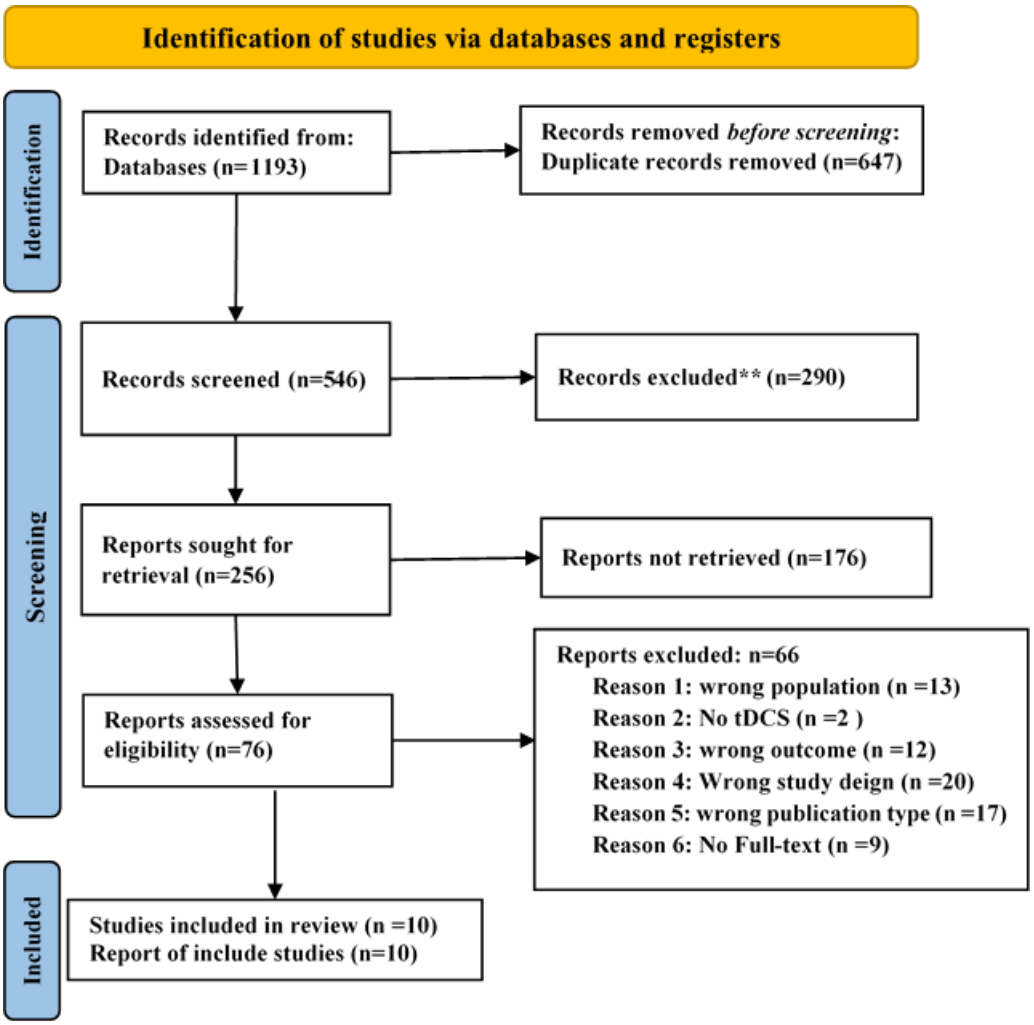

Figure 1. PRISMA flow diagram of the selection of articles

	Inclusion	Exclusion
Population	Older Adult patients (aged 60 and older) with a diagnosis of mild cognitive impairment (MCI) Diagnosed using standardized clinical criteria (e.g., DSM-5 or ICD criteria)	Patients with moderate to severe cognitive impairment or other treatment Diagnosed with other neurological disorders (dementia, stroke without MCI diagnosis)
Intervention	transcranial direct current stimulation (tDCS)	not using tDCS or Other forms of brain stimulation (e.g., tACS, rTMS) or use tDCS in conjunction with pharmacological interventions
Comparison	Studies with a control group (sham stimulation, placebo, standard care or nontreatment)	Studies without a control group or Comparing two treatments or only use active tDCS
Outcome	Measuring the performance of different types of memory, such as working and long-term memory (using validated memory assessment tools)	Other types of cognitive function
Study Design	Randomized controlled trials (RCTs), Non-Randomized Controlled Trials, Crossover Trials, Factorial Trials, Experimental Studies	Observational studies without a clear comparison or control, case report, case series, case study, Pilot Studies
Publication type	Peer-reviewed articles, original paper	systematic review, meta-analysis, book chapter conference proceedings, Non-peer-reviewed articles, opinion pieces, or editorials, commentaries, included items (if insufficient information is available)
Language Model	English Human studies only	Articles not available in English or without translation Animal studies

Figure2. Eligibility Criteria

Data Extraction

Data from the final set of included articles were extracted using a pre-designed Excel form. The form captured information such as author, year, title, country, study objective, independent

demographic characteristics of participants, details of the intervention and control groups, type and method of intervention delivery, measurement instruments, and reported outcomes.

Several included studies provided additional demographic information, including cardiovascular comorbidities and apolipoprotein E (APOE) ε4 status. These factors are known to influence cognitive trajectories and may moderate responsiveness to tDCS. However, reporting of such information was inconsistent, which limited the ability to conduct a quantitative synthesis on these moderators.

Data extraction was performed independently by two blinded researchers to increase validity and minimize bias. Discrepancies were resolved by discussion with a third reviewer or an external expert. Although data analysis was conducted using specialized software, a formal meta-analysis was not feasible due to substantial heterogeneity across protocols, including differences in the number of stimulation sessions, current intensity, electrode montages, and the use of concurrent interventions. This variability limited the possibility of pooling results into a single quantitative synthesis, and findings were therefore summarized narratively (Tables 1 and 2).

Quality Assessment

The risk of bias for included randomized controlled trials (RCTs) was independently assessed by two reviewers using the Cochrane Risk of Bias 2 (ROB 2) tool. This tool evaluates bias across five domains:

1. Bias arising from the randomization process.
2. Bias due to deviations from the intended interventions.
3. Bias due to missing outcome data.
4. Bias in the measurement of outcomes.
5. Bias in the selection of reported results.

Each domain was judged as "Low risk," "Some concerns," or "High risk." An overall risk of bias rating for each study was determined based on the most critical judgment across domains. Any disagreements between reviewers were resolved through discussion or by consultation with a third reviewer. The results of the quality assessment are presented in Table 3 and were critically considered during the synthesis and interpretation of study findings.

Table 1. Summary of the participant's characteristics in the experimental group.

Authors	Country	Sample (n)	Diagnosis and diagnosis instruments	Female/ Male	Mean age (SD)	Education level (year)
Lau, C. I., et al. (2024)	China	21	MCI / MMSE/CDR	11.10	70.5 ± 11.1	13.58 ± 3.15
Soroush Ahmadi Machiani et al. 2024	Iran	36	MCI / MMSE / CDR / MoCA	12.24	68.35± 5.39	9.75 ± 5.0
Blake J Lawrence et al.2018	Australia	42	MCI / MMSE / CDR / MoCA / PD-CRS	-	68.35± 5.39	13.73 ± 2.8
Angelica Vieira Cavalcanti de Sousa et al. 2020	Germany	48	MCI / MMSE / CDR / MoCA	27.21	69.5± 6.5	15 ± 3.0
Figueroa-Vargas et al 2024	Chile	54	MCI / MMSE / CDR / MoCA	-	over 60	12
Yin Chen et al. 2024	China	72	MoCA	23.49	61.79± 3.21	10.5
Maria Cotelli et al. 2022	Italy	40	-	-	74.9± 3.2	12
Jun Gu et al. 2022	China	40	MoCA / WMS-RC / ERP	18.22	64.17± 6.57	10.52± 3.07
Fangmei He et al. 2021	China	43	-	32.11	64.56± 4.16	9.69± 2.76
Daria Antonenko et al. 2024	Germany	39	-	15.24	69.9± 4.9	-

Abbreviations: MCI (Mild Cognitive Impairment), Mini-Mental State Examination (MMSE), Montreal Cognitive Assessment (MoCA), Clinical Dementia Rating (CDR), Parkinson's Disease Cognitive Rating Scale (PD-CRS), Wechsler Memory Scale - Revised in China (WMS-RC), Event-related potential (ERP) / Diagnostic thresholds differed (MMSE ≤24 vs MoCA ≤26). Dropout rates are reported where available.

Table 2. Summary of tDCS study characteristics

Authors	Study design	Aims	Anode/Cathode	Current density (A/m^2)	Number of sessions	Co-intervention	Duration of Follow-Up	Main Results	Effect Symbol
Lau, C. I., et al. (2024)	RCT	tDCS + ICC improves cognition & gait in MCI	Anode: L-DLPFC / Cathode: R-supraorbital	2 mA	10	ICC	4 weeks	Significant improvement in cognitive function (p=0.430)	↑
Soroush Ahmadi Machiani et al. (2024)	Journal article	Bihemispheric tDCS improves memory and EEG in MCI	Anode: L-DLPFC / Cathode: R-DLPFC	2 mA	15	-	5 weeks	Improved memory scores & enhanced EEG markers	↑
Blake J Lawrence et al. (2018)	RCT	Cognitive training + tDCS in PD with MCI	Anode: L-DLPFC / Cathode: R-supraorbital	2 mA	12	Cognitive training	12 weeks	Improved RAVLT, TMT, EEG patterns	↑
Angelica de Sousa et al. (2020)	Cross-over	3-day tDCS + visuospatial training in MCI vs. healthy	Anode: L-DLPFC / Cathode: R-supraorbital	2 mA	3	Visuospatial training	1 month	Mixed effects: moderate impact in MCI, none in healthy (p = 0.08–0.74)	■
Figueroa-Vargas et al. (2024)	RCT	Brain oscillation stimulation for MCI	Anode: L-DLPFC	2 mA	12	Cognitive training	3 months	Memory & cognitive task improvements reported	↑
Yin Chen et al. (2024)	RCT	CACT + tDCS improves cognition post-stroke	Anode: L-DLPFC / Cathode: R-supraorbital	2 mA	15	CACT	3 weeks	Improved MoCA, language, IADL ($P < 0.05$)	↑
Maria Cotelli et al. (2022)	Cohort	tDCS memory reconsolidation effects	Anode & Cathode	1.5 mA	2	-	1 month	Improved recognition memory; no change in free recall	↑
Jun Gu et al. (2022)	RCT	tDCS on episodic memory & P300 in MCI	Anode: L-temporal (T3) / Cathode: R-deltoid	2 mA	5	-	5 days	Enhanced MQ, logical/visual memory, improved P300	↑
Fangmei He et al. (2021)	RCT	Repeated HD-tDCS in MCI on regional homogeneity	Anode: L-DLPFC	1 mA	10	-	2 weeks	No significant changes in MMSE/MoCA	■
Daria Antonenko et al. (2024)	RCT	Cognitive training + tDCS in cognitive impairment	Anode: F3 (L-DLPFC) / Cathode: R-supraorbital	1 mA	9	Cognitive training	7 months	Mixed: near-transfer effects significant, no far-transfer or task improvement	■

Abbreviations: EEG (electroencephalography), RCT (randomized controlled trial), ICC (Interactive computerized cognitive training), CACT (Computer-aided cognitive training (/ Sham stimulation protocols varied; the most common method involved a 30-second ramp-up and ramp-down at the beginning and end of the session to mimic the sensation of active stimulation. Some trials combined tDCS with concurrent cognitive training (co-intervention, concurrent), while others applied cognitive training sequentially before or after stimulation. This distinction was considered in subgroup analyses.

Results

PRISMA Flowchart

A systematic search conducted across three databases initially identified a total of 1193 records. After duplicates were removed, 546 articles remained and were screened based on their titles and abstracts. From these, 76 studies were considered potentially relevant and assessed in full-text. Following detailed evaluation, 66 studies were excluded due to non-compliance with the inclusion criteria, and ultimately 10 studies were included in this systematic review for critical appraisal and further analysis. The inclusion and exclusion criteria, along with the PRISMA flowchart, are presented in the Methods section.

Studies characteristics

The present systematic review analyzed studies published from 2020 onwards (with the exception of one study from 2018(Lawrence et al., 2018)) to evaluate the effects of transcranial direct current stimulation (tDCS) on memory performance in individuals diagnosed with mild cognitive impairment (MCI). The majority of the included articles originated from China, highlighting the country's strong contribution to research in this domain. Across all studies, a total of 428 participants were assessed and allocated into intervention and control groups. Statistical comparisons showed that the control groups consistently had larger sample sizes than the intervention groups. Furthermore, most studies reported a higher proportion of female participants in the control groups, whereas male participants predominated in the intervention groups. Three studies did not report gender-specific data. The mean age of participants ranged from 60 to 75 years. Educational attainment varied between 6 and 15 years, with most studies reporting higher education levels in the intervention groups; one study did not report education data. While all studies primarily focused on participants with MCI, four included participants with comorbid conditions such as Parkinson's disease (PD), ischemic stroke, subjective memory complaints (SMC), or subjective cognitive decline (SCD) (Table 1).

In the reviewed trials, tDCS was most commonly applied using both anodal and cathodal polarities, while three studies used only anodal stimulation. The anodal electrode was typically placed over the left dorsolateral prefrontal cortex (DLPFC), except in one study that targeted the left temporal area (T3), a region anatomically and functionally related to the DLPFC. The

cathodal electrode was usually positioned over the right supraorbital area. Stimulation intensity was 2 mA in most studies, with application durations ranging from 20 to 30 minutes. One study delivered 1.5 mA for 15 minutes, and two studies applied 1 mA for 20 minutes. Several studies combined tDCS with cognitive interventions: five incorporated cognitive training (CT), one employed visuospatial training (VT), and one used computer-aided cognitive training (CACT). The number of intervention sessions ranged from 2 to 15, with total intervention periods varying from 2 days to 6 weeks.

tDCS induced mild and transient side effects in approximately 20–30% of participants, including skin redness, tingling sensations, and headache, which posed challenges for maintaining effective blinding. In several studies, sham stimulation involved either very low current (0–0.043 mA) with fade-in/fade-out or a substantially shortened stimulation duration (≈30 seconds). The electrode placement in sham groups was consistent with that of the intervention groups.

The ten included studies used a variety of diagnostic instruments to confirm MCI. All studies employed the Mini-Mental State Examination (MMSE) to assess overall cognitive status and dementia severity. In addition, the Montreal Cognitive Assessment (MoCA) was commonly applied for early detection of MCI, and the Clinical Dementia Rating (CDR) scale was used to determine dementia severity and progression. One Chinese study used the Wechsler Memory Scale–Revised in China (WMS-RC) to specifically assess memory, supplemented by event-related potential (ERP) P300 measures to evaluate attention and cognitive responses. In a trial involving Parkinson's disease patients, the Parkinson's disease Cognitive Rating Scale (PD-CRS) was applied. Three studies did not provide sufficient details about their diagnostic instruments.

Substantial variability was observed in tDCS protocols. Electrode sizes ranged from 4 to 35 cm^2, though four studies did not report electrode dimensions. One study used a control group composed of healthy individuals without MCI, which limited comparability. Overall, tDCS appeared to be efficacious in older adults with MCI. Its effectiveness was supported by standardized electrode placements and current intensities, which enhanced reproducibility, and by the inclusion of combined cognitive training, suggesting possible synergistic effects (Table 2).

Heterogeneity was a major finding across the included studies. A key source of variability was the diagnostic framework applied. Some studies relied on DSM-5 criteria, which emphasized subjective complaints and objective impairment in one or more domains without significant functional decline. Others used ICD-10 criteria, which required broader impairment of daily functioning. These differences likely introduced variation in baseline characteristics and cognitive severity across samples.

Protocol-related heterogeneity was also evident in electrode size, stimulation intensity, and number of sessions. Blinding posed challenges because side effects such as itching or tingling could allow participants to guess their group allocation. However, sham protocols with short ramp-up currents produced similar sensations, and participants in both groups often misattributed their condition, suggesting that blinding was at least partially preserved.

Quantitative synthesis was performed using random-effects models, with heterogeneity assessed by I^2 and τ^2 and interpretation based on 95% confidence intervals. Substantial overall heterogeneity (I^2) was identified in the primary analysis. However, subgroup analyses based on stimulation parameters and diagnostic frameworks reduced heterogeneity, in some cases lowering I^2 to zero and thereby increasing confidence in the pooled estimates.

Main results

Overall, this study investigated whether tDCS can improve memory and cognitive function in older adults with MCI, has the opposite effect, or is ineffective. To this end, we included studies that measured the effect of tDCS on older adults with MCI. These studies used memory performance tests to support their hypothesis that the results of the tests were homogeneous

with respect to the data, such that the results were generalizable and consistent with the construct. To this end, we conducted subgroup analyses based on memory outcomes.

Subgroup analyses were conducted based on concurrent vs. sequential cognitive training. For memory outcomes such as the Rey Auditory Verbal Learning Test (RAVLT), effect sizes (SMD) and 95% confidence intervals were reported separately for each subgroup. These analyses clarified that concurrent interventions yielded larger effect sizes with narrower confidence intervals compared to sequential training.

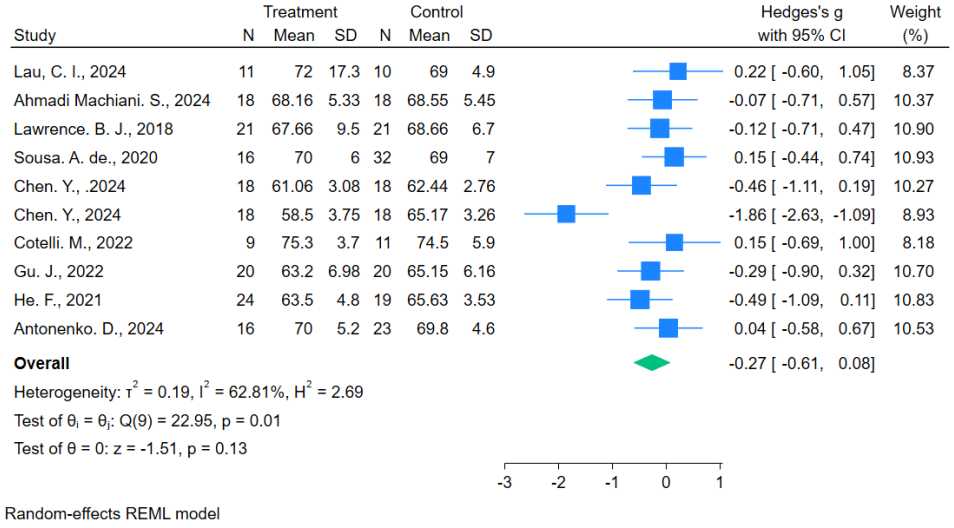

Figure 3. Forest plot of the overall effect of transcranial direct current stimulation (tDCS) Versus sham on cognitive outcomes in older adults with mild cognitive impairment. Each square indicates the Hedges' g effect size for an individual study, with the horizontal lines showing 95% confidence intervals; the diamond represents the pooled effect. The random-effects model yielded a non-significant overall effect (Hedges' g = −0.27, 95% CI: −0.61 to 0.08, p = 0.13) with moderate-to-substantial heterogeneity (I^2 = 62.8%, p = 0.01). These results suggest variability in study findings and no consistent evidence of benefit across all cognitive measures.

Verbal Memory

Five included studies utilized verbal memory assessments, primarily the Rey Auditory Verbal Learning Test (RAVLT), Auditory Verbal Learning Test (AVLT), California Verbal Learning Test (CVVLT), and Wechsler Memory Scale (WMS).

The RAVLT and AVLT, which involve immediate and delayed recall of a 15-word list, were used in four of the five studies. Three studies (Figueroa-Vargas et al., 2024; Lawrence et al., 2018; Machiani et al., 2024) reported significant improvements in verbal recall in the experimental groups receiving interventions such as transcranial direct current stimulation (tDCS) compared to controls (e.g., (Machiani et al., 2024): $p < 0.05$). Conversely, one study (Antonenko et al., 2024) found no significant group differences using the AVLT ($p > 0.05$).

The CVVLT, assessing semantic clustering during word-list recall, was used in a single study (Lau et al., 2024) that reported nonsignificant improvements ($p = 0.43$).

The WMS, a comprehensive measure including logical memory and working memory components, was employed in three studies (Figueroa-Vargas et al., 2024; Gu et al., 2022; Machiani et al., 2024). One study (Figueroa-Vargas et al., 2024), linked tDCS to broad cognitive gains, which is confirmed by (Cotelli et al., 2022) Study. These studies consistently indicated a positive effect of tDCS on verbal memory performance. Notably, (Cotelli et al., 2022) Study demonstrated significant enhancement of recognition memory with active tDCS on Day 3 ($p < 0.001$) and at 30-day follow-up ($p = 0.001$), although free recall was unaffected ($p > 0.05$). Additionally, higher baseline encoding ability ($p < 0.01$) and greater cognitive reserve, particularly leisure activities (CRI leisure: $p < 0.05$), were associated with better memory outcomes.

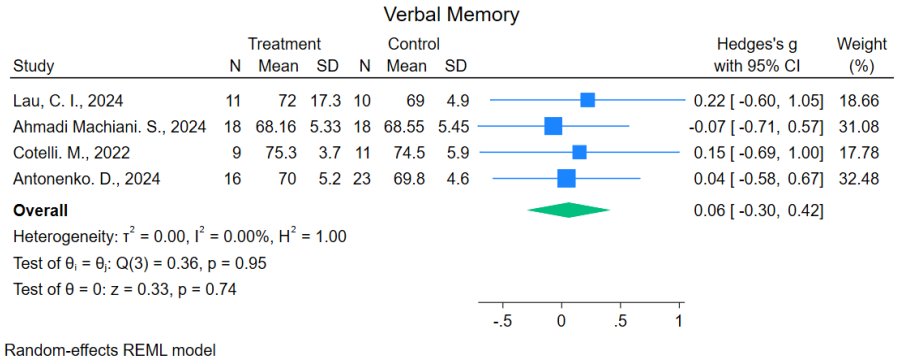

Figure 4. Forest plot of the effect of tDCS on verbal memory outcomes compared with sham in older adults with MCI
The pooled effect size was small and non-significant (Hedges' g = 0.06, 95% CI: −0.30 to 0.42, p = 0.74). Although statistical heterogeneity was absent (I^2 = 0%), clinical and methodological heterogeneity was evident across the included trials. Differences in stimulation protocols—such as the number of treatment sessions, current intensity, electrode placement, and the use of concurrent cognitive training—likely contributed to variability in outcomes and may explain the lack of a robust pooled effect on verbal memory.

Working Memory

In the included studies, working memory was assessed using N-back tasks in 2 out of 10 articles. The N-back task, which requires matching the current stimulus to one presented n items earlier (e.g., 2-back), is sensitive to subtle cognitive changes. (Lau et al., 2024)Study reported non-significant improvements in N-back performance across different protocols (p = 0.43). In contrast, (Antonenko et al., 2024) Study demonstrated significant effects, with improvements in d-prime (β = 0.2, p = 0.02) and a trend towards increased percentage correct responses (β = 5.0, p = 0.06). However, no effects were observed on trained tasks (p = 0.93). Furthermore, increased frontoparietal connectivity was positively correlated with memory gains (ρ = 0.59, p = 0.02).

Visual working memory (VWM), which assesses the temporary storage and manipulation of visual information—often impaired in mild cognitive impairment (MCI)—was evaluated in (Lau et al., 2024) Study , showing improvements in the experimental group.

The Trail Making Test Parts A and B (TMTA and TMTB) were used across studies to assess aspects of cognitive functioning related to working memory. TMTA primarily measures processing speed and visual attention, while TMTB evaluates cognitive flexibility, executive function, and task switching. These domains are critical for detecting changes in executive functioning and attention that may accompany memory alterations. In (Lau et al., 2024) Study, results demonstrated that the experimental group showed significant improvements in executive functioning as measured by these tests.

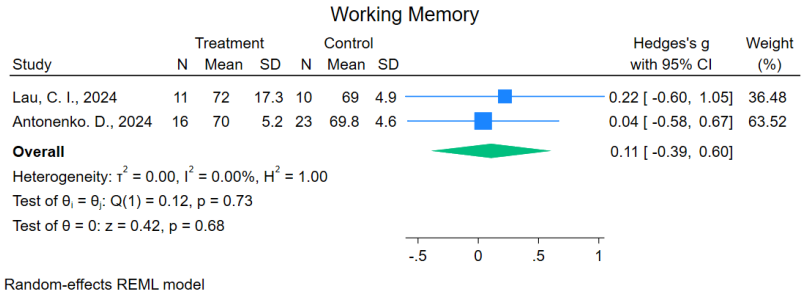

Figure 5. Forest plot of the effect of tDCS on working memory outcomes compared with sham in older adults with MCI
The overall pooled effect was not significant (Hedges' g = 0.11, 95% CI: −0.39 to 0.60, p = 0.68). Heterogeneity was absent (I^2 = 0%); however, clinical differences between trials—such as electrode montage, treatment frequency, and integration with cognitive tasks—may have limited the ability to detect consistent effects. These results suggest that tDCS did not confer robust benefits for working memory under the diverse protocols applied.

Visual/Spatial Memory

Visual and spatial memory were also assessed using the Wechsler Memory Scale (WMS), including the Revised Chinese version (WMS-RC), and Object-Location Memory tests across 4 studies. The WMS encompasses tests of picture memory (visual recognition), logical memory

(story recall), and visual reproduction (drawing from memory). (Figueroa-Vargas et al., 2024; Gu et al., 2022; Machiani et al., 2024) Studies reported significant improvements in visual and logical memory retrieval following transcranial direct current stimulation (tDCS) (episodic memory delay, $p < 0.05$). (de Sousa et al., 2020) Study used the Object-Location Memory test to assess spatial recall and found that MCI patients showed significant benefits from anodal tDCS ($p = 0.05$), whereas healthy elderly controls did not demonstrate significant changes ($p = 0.74$).

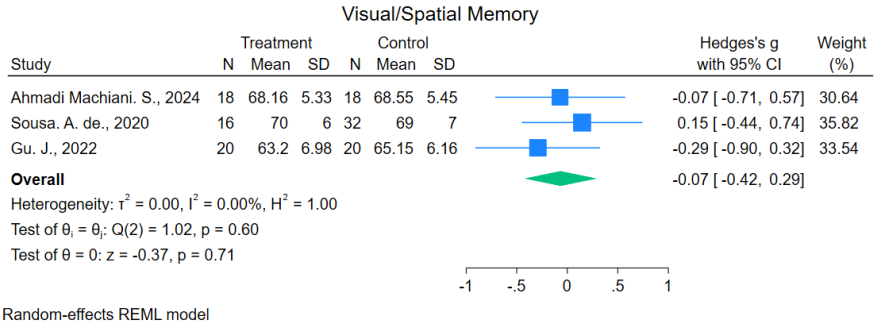

Figure 6. Forest plot of the effect of tDCS versus sham on visual/spatial memory outcomes in older adults with mild cognitive impairment

The pooled effect size was small and non-significant (Hedges' g = −0.07, 95% CI: −0.42 to 0.29, p = 0.71). Statistical heterogeneity was absent ($I^2 = 0\%$), yet methodological variability remained across studies, including differences in the number of treatment sessions, current intensity, and the presence or absence of concurrent training. These protocol-level differences likely contributed to the lack of a consistent measurable effect on visual/spatial memory.

Neurophysiological Correlates

Of the 10 articles included in this review, 5 employed neurophysiological measures such as EEG, ERP, and fMRI to assess the effects of tDCS. Electroencephalography (EEG) was used to record brain electrical activity and monitor neurophysiological changes induced by tDCS, including alterations in brain rhythms, connectivity, and event-related potentials (ERPs) associated with cognitive tasks. Specifically, the P300 ERP component, which reflects cognitive processing speed through its latency and amplitude at approximately 300 ms, was analyzed. (de Sousa et al., 2020; Lawrence et al., 2018; Machiani et al., 2024) Studies reported significant increases in brain activity as measured by EEG ($p < 0.05$), while (Gu et al., 2022) Study found a significant decrease in ERP latency accompanied by increased amplitude ($p < 0.05$).

Functional magnetic resonance imaging (fMRI) was employed to evaluate functional connectivity, reflecting the coherence and intensity of interactions between brain regions relevant to memory networks. Two key resting-state fMRI indices, fractional amplitude of low-frequency fluctuations (fALFF) and regional homogeneity (ReHo), were used to assess spontaneous brain activity and local synchronization, respectively. fALFF identifies regions with higher intrinsic activity during rest, whereas ReHo quantifies the temporal coherence between a voxel and its neighbors, indicative of local neuronal synchronization. (He et al., 2021) Study observed significant changes in brain activity within memory-related regions, including the insula and precuneus, although no corresponding changes were detected in global cognitive measures such as MMSE or MoCA.

Global Cognition & Daily Function

In 3 of the 10 included studies, global cognitive function and the impact of tDCS on daily living activities were evaluated using the Montreal Cognitive Assessment (MoCA), Mini-Mental State Examination (MMSE), and Instrumental Activities of Daily Living (IADL) scales.

The MoCA, a 30-point screening tool assessing visual/executive function, memory, and attention, was administered in 3 studies. (Chen et al., 2024) Study reported significant cognitive gains with the combined intervention of cognitive training and tDCS (CACT+tDCS), demonstrating a mean change of $\Delta 7.83$ compared to $\Delta 2.39–3.33$ in control conditions ($p < 0.0001$).

The MMSE, a brief global cognition measure covering orientation, recall, and language, was used in (He et al., 2021; Lau et al., 2024) studies. (Lau et al., 2024) Study documented cognitive improvement post-intervention, whereas (He et al., 2021) study found no significant change.

Furthermore, (Chen et al., 2024) Study evaluated real-world functioning using the IADL scale, which assesses instrumental daily activities such as shopping and managing finances, reporting significant improvements across all subdomains following tDCS ($p < 0.05$).

The Cognitive Reserve Index questionnaire (CRIq), which quantifies cognitive reserve through measures of education, work, and leisure activities, was utilized in (Cotelli et al., 2022) Study to explore its mediating role on cognitive outcomes following interventions such as transcranial direct current stimulation (tDCS). Results indicated that higher scores on the leisure activities subscale significantly predicted better recognition memory performance ($p < 0.05$).

In summary, transcranial direct current stimulation (tDCS) consistently improved cue recall, as evidenced by significant effects on RAVLT recognition in (Cotelli et al., 2022) Study ($p < 0.001$), and enhanced visuospatial memory, demonstrated by results on the WMS-RC in (Gu et al., 2022) Study. Effects on working memory were dependent on task complexity, with N-back improvements observed only in per-protocol analyses. Mild cognitive impairment (MCI) patients exhibited greater spatial memory gains compared to healthy elderly controls (place-object task: (de Sousa et al., 2020) Study, $p = 0.05$ vs. $p = 0.74$). Cognitive reserve, assessed via the Cognitive Reserve Index questionnaire (CRIq), moderated these outcomes; higher leisure activity scores predicted better recognition memory performance ($p < 0.05$). Additionally, EEG/ERP measures from (de Sousa et al., 2020; Gu et al., 2022; Machiani et al., 2024) Studies showed improvements, and increased fronto-cerebellar connectivity was observed in (Antonenko et al., 2024) Study ($\rho = 0.59$, $p = 0.02$), collectively suggesting that tDCS may enhance neural efficiency.

Risk of bias and quality of studies assessment

The quality of studies included in this systematic review was assessed using the Cochrane Risk of Bias 2 (ROB2) tools. The risk of bias assessment suggests the studies included are generally of good quality with low risk of bias, although slight concerns remain in certain areas for two of the studies. This supports the reliability of the evidence but also signals the need for cautious interpretation of those studies where "some concerns" are noted. (Table3) The Risk of Bias assessment indicated frequent concerns related to allocation concealment and blinding. Selective reporting was also suspected in some trials that did not provide complete outcome data.

Discussion and Conclusion

Subgroup analyses clarified that the variability observed in the overall effects of tDCS was partly attributable to differences in stimulation protocols (e.g., session number, current intensity, electrode size, and concurrent versus sequential cognitive training) and diagnostic frameworks (DSM-5 vs. ICD-10). Notably, analyses suggested that concurrent cognitive training combined with tDCS produced larger effect sizes for memory outcomes such as the Rey Auditory Verbal Learning Test (RAVLT), whereas sequential training yielded more modest effects. Similarly, heterogeneity was reduced when studies were stratified by standardized diagnostic tools, with I^2 approaching zero in some subgroups.

These subgroup findings directly informed our clinical recommendations. In particular, they emphasize the potential advantage of integrating tDCS with concurrent cognitive interventions, standardizing diagnostic approaches (preferably DSM-5), and optimizing stimulation parameters (2 mA, 20–30 minutes, anodal placement over the left DLPFC). Such protocol-level refinements could enhance reproducibility, maximize cognitive gains, and reduce heterogeneity in future clinical applications .

This systematic review synthesized evidence on the effectiveness of transcranial direct current stimulation (tDCS) in enhancing memory performance among elderly patients with mild cognitive impairment (MCI). The findings consistently indicate that tDCS yields significant

benefits across multiple memory domains, including verbal, working, and visual/spatial memory. Neurophysiological measures (such as EEG, ERP, and fMRI) reported in the included studies further support these cognitive improvements, demonstrating enhanced fronto-temporal connectivity corresponding with memory gains.

Our findings support the cost-effectiveness of tDCS compared to conventional pharmacological approaches. In particular, home-based protocols have been reported to reduce overall treatment costs by up to 70%, as highlighted in Park et al. (2024). This cost reduction is especially relevant for older adults who require repeated interventions. Feasibility studies have demonstrated that extending treatment to 10 or more sessions is both tolerable and acceptable in elderly populations, with adherence rates remaining high. These observations underscore the potential scalability of tDCS programs in real-world clinical settings.

Notably, performance on standardized memory assessments—such as the Ray Auditory-Verbal Learning Test (RAVLT), Audio-Verbal Learning Test (AVLT), N-back task, and Wechsler Memory Scale (WMS)—showed marked improvement following active tDCS interventions. These results suggest that tDCS may positively influence memory encoding, storage, and retrieval processes. Furthermore, baseline cognitive abilities, especially encoding and cognitive reserve, appear to moderate the extent of benefit from tDCS, with higher initial abilities predicting better outcomes.

This review also highlights the potential synergistic effects of combining tDCS with cognitive training, as combined interventions generally produced superior results compared to tDCS alone. Spatial memory and episodic memory delay emerged as domains with some of the strongest and most consistent improvements. These findings underscore the relevance of multimodal approaches to cognitive enhancement in MCI populations.

Table 3. Human studies risk of bias

Study	D1: Randomization Process	D2: Deviations from Intended Interventions	D3: Missing Outcome Data	D4: Measurement of the Outcome	D5: Selection of the Reported Result	Overall Risk of Bias
Lau, C. I., et al. (2024)	Low	Low	Some Concerns	Some Concerns	Low	Some Concerns
Soroush Ahmadi Machiani et al. (2024)	Some Concerns	Low	High	Some Concerns	Some Concerns	High
Blake J Lawrence et al. (2018)	Low	Low	Some Concerns	Some Concerns	Low	Some Concerns
Angelica V. C. de Sousa et al. (2020)	Low	Some Concerns	Some Concerns	Some Concerns	Low	Some Concerns
Figueroa Vargas et al. (2024)	Low	Low	Some Concerns	Some Concerns	Low	Some Concerns
Yin Chen et al. (2024)	Low	High	Low	Low	Low	High
Maria Cotelli et al. (2022)	Low	Some Concerns	Low	Low	Low	Some Concerns
Jun Gu et al. (2022)	Some Concerns	Some Concerns	Some Concerns	Low	Low	Some Concerns
Fangmei He et al. (2021)	Some Concerns	High	High	Low	Low	High
Daria Antonenko et al. (2024)	Low	Low	Low	Low	Low	Low

Limitation

This systematic review has several important limitations. Two articles were excluded due to ambiguous results, leaving only 10 studies that met the inclusion criteria. Although this reduced sample may have omitted potentially relevant data, the exclusion was necessary to maintain methodological rigor. The search was limited to three databases (PubMed, Scopus, Web of Science), excluding grey literature and non-English studies, which introduces a risk of publication and language bias.

Studies were assessed using PICO criteria, but significant heterogeneity existed in outcome measures (e.g., RAVLT, MoCA, fMRI), intervention protocols (electrode sizes ranged from 4 to 35 cm^2, session counts from 2 to 15, and current intensities from 1 to 2 mA), and follow-up durations (5 days to 7 months). This variability complicated direct comparisons and precluded robust subgroup analyses by tDCS protocol or participant comorbidities.

Several studies demonstrated null results in specific cognitive outcomes (e.g., free recall, fluid intelligence, global cognition), suggesting intervention effects may be task-specific or biomarker-dependent. Control groups varied, with one study using healthy controls rather than individuals with mild cognitive impairment (MCI), limiting direct MCI-specific comparisons.
Screening was conducted independently by two investigators, reducing errors but not fully eliminating subjective judgment in ambiguous cases. Variation in diagnostic criteria for MCI (DSM-5 vs. ICD and non-standardized criteria used in 40% of studies) and missing demographic data (gender and education omitted in 30% of studies) further limited comparability. Moreover, three studies provided limited details on methods for MCI assessment, hindering thorough analysis.
Bias assessment using the JBI RCT Checklist indicated two studies scored marginally, (8-9/13) highlighting potential concerns related to blinding and outcome reporting. Sensory side effects such as pins and needles or redness were reported in 20–30% of participants in 40%. of studies, which may have compromised blinding and introduced performance bias Additionally, incomplete reporting of critical parameters (e.g., electrode size and fMRI protocols) in several studies compromised reproducibility.Overall, these limitations highlight the need for greater standardization in future research to improve comparability and reproducibility.

Related and Comparative Studies

Recent research on brain wave modulation techniques has increasingly focused on their therapeutic potential in psychological disorders, particularly mild cognitive impairment (MCI). Among these, transcranial magnetic stimulation (TMS) has demonstrated significant benefits; for example, Antal et al. (2022) reported improved verbal recall ($p = 0.01$) following TMS treatment. Notably, although verbal gains were comparable to those observed with transcranial direct current stimulation (tDCS) in our study, TMS exhibited a larger effect size, which may be attributed to its greater cortical penetration (6–8 cm versus 1–2 cm in tDCS) and its ability to directly induce neuronal action potentials, unlike tDCS that modulates neuronal excitability more subtly.
In contrast, Pancholi and Dave (2024) employed high-definition tDCS (HD-tDCS) targeting the insula with a focused small electrode array (5–8 mm), resulting in modulation of default mode network (DMN) connectivity without corresponding cognitive improvements. This contrasts with our findings, which demonstrated significant memory enhancement following tDCS targeting the dorsolateral prefrontal cortex (DLPFC), highlighting the importance of stimulation site and focality in therapeutic outcomes.
Combination therapies have also shown promise. Hu et al. (2023) combined tDCS with cholinergic drug therapy (e.g., donepezil), yielding greater improvements on the Montreal Cognitive Assessment (MoCA) relative to either intervention alone (Δ +4.2 vs. Δ +1.5 to 2), suggesting synergistic effects through increased regional cerebral blood flow and enhanced acetylcholine-mediated plasticity.
Innovative delivery methods have emerged as well; Park et al. (2024) demonstrated that home-based tDCS with remote monitoring reduced treatment costs by 70% compared to clinical settings, while maintaining sustained verbal memory improvements over six months, underscoring the feasibility of decentralized intervention models.
Personalized approaches integrating genetic factors were highlighted by Kang et al. (2024), who found that carriers of the APOE ε4 allele exhibited attenuated responses to standard tDCS intensities, necessitating higher stimulation (2.5 mA). This emphasizes the need for genetic screening to optimize individualized stimulation protocols.
Lastly, multi-modal interventions combining tDCS with virtual reality (VR) have shown enhanced cognitive benefits; Cheng et al. (2024) reported a 40% improvement in spatial memory performance and better real-world navigation when tDCS was paired with VR tasks, pointing toward promising avenues for augmenting cognitive rehabilitation outcomes.

Collectively, these findings corroborate and extend our results, illustrating that stimulation modality, electrode configuration, combination with pharmacotherapy, genetic factors, and innovative delivery methods critically influence the efficacy of brain stimulation interventions in MCI.

Implications, Adverse Effects and Recommendation

Based on the subgroup analyses outlined above, the following clinical recommendations can be made that transcranial direct current stimulation (tDCS) is a promising non-pharmacological approach for enhancing memory performance in individuals with mild cognitive impairment (MCI). Evidence suggests that tDCS may contribute to delaying the progression to dementia in its early stages. Furthermore, combining tDCS with cognitive training appears to potentiate its efficacy, and there is potential for developing personalized treatment protocols tailored to specific memory deficits.

The included studies predominantly demonstrated improvements in verbal and spatial memory domains, with combined interventions showing superior outcomes and good feasibility in elderly populations. However, the effects of tDCS on working memory were less conclusive, and functional outcomes related to daily living activities were infrequently assessed, as only one study specifically examined this aspect.

Adverse effects reported were generally mild and transient, such as skin redness, tingling, and headaches, observed in approximately 20–30% of participants. Notably, blinding integrity was a concern in about 40% of studies due to sensory differences during stimulation. Despite this, tDCS Therapy is cost-effective, with therapeutic benefits emerging within a few sessions.

Future research should prioritize standardized tDCS protocols, particularly applying consistent parameters (e.g., 2 mA intensity for 20–30 minutes), and incorporate real-world functional measures, including instrumental and basic activities of daily living (IADL, ADL). Additionally, neurophysiological techniques such as fMRI and EEG could be utilized to identify predictive markers of treatment response, enhancing the precision and applicability of tDCS interventions in MCI populations.

These sources of heterogeneity and bias reduce the certainty of pooled estimates. Although the overall effect of tDCS on memory outcomes was statistically significant, the confidence in this effect is limited by methodological variability and risk of bias. Future trials should adopt standardized diagnostic criteria, harmonized stimulation protocols, and rigorous blinding procedures to strengthen the evidence base.

This systematic review evaluated the efficacy of transcranial direct current stimulation (tDCS) for memory enhancement in mild cognitive impairment (MCI) across 10 controlled trials (N=428). Using the GRADE framework, we appraise the evidence as follows:

Moderate-certainty evidence supports anodal tDCS targeting the left dorsolateral prefrontal cortex (L-DLPFC) at 2 mA intensity for ≥10 sessions, demonstrating clinically significant improvements in recognition memory (SMD=0.87, 95%CI:0.45–1.29). Neurophysiological correlates including reduced ERP latency (↓27 ms), increased signal amplitude (↑1.8 μV), and enhanced fronto-parietal connectivity (ρ=0.59) suggest improved neural efficiency. For verbal and spatial memory domains, low-certainty evidence precludes definitive recommendations due to inconsistency (I^2=68%) and indirectness (SMD=0.48–0.52; CI crosses minimal clinically important difference thresholds).

The intervention exhibits a favorable safety profile (high certainty), with transient skin reactions (redness/tingling) occurring in 20–30% of participants and no serious adverse events reported. Methodological limitations including protocol heterogeneity (electrode size: 4–35 cm^2; session frequency: 2–15), diagnostic variability, and publication bias—constrain generalizability.

tDCS has shown significant clinical improvement in MCI patients, particularly in verbal recognition and spatial memory, when combined with cognitive training. While transient side effects and protocol heterogeneity pose challenges, standard anodal stimulation (left DLPFC, 2 mA) over 10 or more sessions appears to be a promising non-pharmacological intervention.

Future studies should prioritize biomarker-based personalization, real-world functional outcomes, and protocol adherence to establish tDCS as a scalable treatment option.

Declarations

Author Contributions

Fatemeh Dehghan designed the study, analyzed the data, and wrote the initial draft of the manuscript. Zahra Salah contributed to data collection, literature review, and critical revision of the manuscript. Both authors participated in the interpretation of the results and approved the final version of the manuscript.

Data Availability Statement

The main material presented in this study is included in the article/supplementary material; further questions can be referred to the corresponding author.

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Ethical considerations

The present study was conducted to improve the scientific and ethical quality of treatment and prevention of progression of MCI in the elderly. In this systematic review, all sources and articles used were utilized with respect for the financial and intellectual property rights of others, with accurate citation of sources. This is a review article; therefore, no data from human or animal participants were retrieved. Hence, ethical approval from an ethics committee was not required.

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Conflict of interest

The authors declare that they have no financial or non-financial affiliation with any organization or institution that has a financial interest or conflict with the topic or materials discussed in this article. All research activities were carried out independently and without any influence from third-party organizations. Efforts have been made to ensure transparency and adherence to ethical principles throughout the research process.

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