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Review articles

# Efficacy of transcranial direct current stimulation in central auditory processing disorder: A systematic review and meta-analysis

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## ABSTRACT

**Purpose:** to evaluate the effect of transcranial direct current stimulation (tDCS) on central auditory processing disorder (CAPD).

**Methods:** a systematic literature review following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) recommendations, registered with PROSPERO under number CRD42023389318. It sought to answer the following question: "What are the effects of tDCS on individuals with CAPD, compared to individuals without CAPD, considering behavioral assessments of central auditory processing (CAP) and/or auditory evoked potentials?" This question followed the PICO format and the review included cross-sectional and observational studies and clinical trials, with no restrictions on year of publication or language. The databases used were PubMed, LILACS, Scopus, Cochrane, SciELO, and Google Scholar, with an additional search in the grey literature (Google Scholar, OpenGrey) and manual search of references. The descriptors used were Transcranial Direct Current Stimulation AND Auditory Perception OR Transcranial Direct Current Stimulation AND Auditory Perceptual Disorders OR Transcranial Direct Current Stimulation AND Correction of Hearing Impairment OR Neuromodulation AND Auditory Perception OR Neuromodulation AND Correction of Hearing Impairment. Data analysis: Initially, the titles and abstracts of all retrieved studies were analyzed, followed by a full reading of eligible studies and bias analysis.

**Literature Review:** nine studies were included. The most frequently used configuration was anodal tDCS applied to the left temporal cortex. Most studies that applied this stimulation configuration significantly improved temporal processing and auditory attention, suggesting that tDCS may be effective in improving specific aspects of CAP. The quality of the evidence was considered low.

**Conclusion:** anodal tDCS applied to the left temporal cortex is a promising intervention in the treatment of CAPD, with positive effects on temporal processing and auditory attention.

**Keywords:** Transcranial Direct Current Stimulation; Auditory Perception; Auditory Perceptual Disorders; Correction of Hearing Impairment; Transcutaneous Electric Nerve Stimulation

## INTRODUCTION

Central auditory processing (CAP) is the ability of the central auditory nervous system (CANS) to utilize auditory information efficiently and effectively[1], which involves specific skills that are essential for auditory comprehension[2]. This complex function of the CANS not only facilitates the decoding of auditory information but also plays a fundamental role in cognition, learning, and social interaction[3].

Some individuals may experience significant difficulties with auditory skills, characterized by CAP disorder (CAPD). This condition impairs the ability to analyze and interpret auditory stimuli, even when peripheral hearing is within normal limits[4]. People with CAPD may have difficulty understanding speech in noisy environments, following information when speech is rapid, or distinguishing similar sounds. Furthermore, they may have difficulty locating and selecting auditory stimuli, following verbal commands, and maintaining auditory attention[5].

Auditory training is the primary intervention for CAP-related difficulties. This therapeutic strategy is based on the principles of neuroplasticity – i.e., the ability of the central nervous system to adapt and change in response to sensory experiences[6]. It utilizes listening tasks that require skills such as detection, discrimination, recognition, and comprehension of auditory information. This approach has been proven to effectively improve and develop impaired auditory skills[7-10].

Transcranial direct current stimulation (tDCS) likewise uses the principle of neuroplasticity. This non-invasive technique is recognized for its ability to modulate neuronal activity and promote brain plasticity. tDCS involves applying a low-intensity electrical current through electrodes positioned on the surface of the skull to modulate cortical excitability in specific areas of the brain[11].

Unlike other non-invasive brain stimulation tools, such as transcranial magnetic stimulation, tDCS does not directly induce brain activity. Instead, it alters spontaneous brain activity and excitability by modulating neuronal membranes. Specific protocols capable of inducing lasting changes in excitability and cortical activity are required to achieve acute effects on brain function, similar to the processes of long-term potentiation and depression.

Neuroplastic processes are fundamental to various cognitive functions, such as learning and memory formation. Several neurological and psychiatric diseases present pathological alterations involving cognitive functions[12], justifying the growing interest in tDCS as a therapeutic tool. In recent years, this resource has been widely studied as a promising therapeutic option, with the potential to directly influence brain activity. Research has focused particularly on its effects on motor aspects and human cognition[13-16].

Although auditory training is the standard of care due to its proven effectiveness in promoting neural plasticity and improving auditory skills, tDCS appears as a complementary intervention with great therapeutic potential. However, the impacts of tDCS on CAP are still poorly understood[17,18].

According to a systematic review with meta-analysis[19], the effects of tDCS approaches and their influence on CAPD demonstrated that tDCS does indeed have an effect on modulating cortical excitability and general auditory abilities, with anodal tDCS being significantly more effective than cathodal tDCS when compared to placebo. This is also the case in individuals with learning disabilities, whose improvements in reading speed and accuracy can be observed after tDCS, whether combined or not with other cognitive-linguistic and reading stimulation[20].

In this context, tDCS has become the focus of scientific studies as an innovative and promising therapeutic modality in health, including speech-language-hearing interventions.

Given recent advances in neuromodulation and new therapeutic modalities, especially those with few adverse effects and low cost, such as tDCS[21,22], this study sought to answer the following question: “What are the effects of tDCS on individuals with CAPD compared to those without it, considering behavioral assessments of CAP and/or auditory evoked potentials?” Thus, this review aimed to evaluate the effects of tDCS on CAPD.

## METHODS

### Protocol and Registry

The protocol of this review was registered in the International Prospective Register of Systematic Reviews - PROSPERO (https://www.crd.york.ac.uk/prospero/) under registration number CRD42023389318. This review followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-analyses) guidelines[23,24] to systematically review studies that investigated the effectiveness of tDCS on CAPD.

## Eligibility criteria

The study was based on the following research question: "What are the effects of tDCS on individuals with CAPD compared to those without CAPD, considering behavioral assessments of CAP and/or auditory evoked potentials?". This question was organized in the PICO format (Patient, Intervention, Comparison, Outcomes). Thus, the acronym (P) consists of individuals with CAPD, (I) consists of the application of tDCS as a form of intervention, (O) consists of any post-intervention effect on the behavioral assessment of CAP and/or auditory evoked potentials, (C) consists of children/adults without CAPD (Table 1).

**Table 1.** Table with PICO and eligibility criteria

| PICO | Description | Eligibility Criteria |
|---|---|---|
| P (Patient/Population) | Individuals with central auditory processing disorder (CAPD) | ✓ Humans (children and adults)<br>✓ Diagnosis of CAPD<br>✓ Studies that performed at least one behavioral test to assess CAP |
| I (Intervention) | Transcranial direct current stimulation (tDCS) | ✓ Application of tDCS in the study population |
| C (Comparison) | Individuals without CAPD | ✓ Comparison groups composed of children or adults without a diagnosis of CAPD |
| O (Outcome) | Post-intervention effects on behavioral assessment of CAP and/or auditory evoked potentials | ✓ Assessment of behavioral and/or electrophysiological outcomes related to CAPD after tDCS intervention |
| Inclusion Criteria | - Studies with humans (children and adults)<br>- Application of tDCS<br>- Behavioral assessment of CAP and/or auditory evoked potentials<br>- Publications between January 1, 2010, and August 30, 2024<br>- Clinical studies (randomized or non-randomized, multicenter, etc.) | |
| Exclusion Criteria | - Studies with non-experimental methods (e.g., reviews, meta-analyses, editorials)<br>- Studies with unavailable full texts | |

Keywords were selected from the Medical Subject Headings (MeSH), Health Sciences Descriptors (DeCS), and Virtual Health Library (VHL) terminology, using Boolean operators, in the following databases:

PubMed (Medline); ISI (Web of Science – Main Collection); Cochrane Library (CENTRAL); Virtual Health Library (VHL (Bireme: LILACS, SciELO, SeCS); Capes Journal; PsycINFO (APA); Medline Daily Update (OVID); CINAHL; EMBASE (Elsevier): SCOPUS, and Science Direct, Using the following keywords: Transcranial Direct Current Stimulation AND Auditory Perception OR Transcranial Direct Current Stimulation AND Auditory Perceptual Disorders OR Transcranial Direct Current Stimulation AND Correction of Hearing Impairment OR Neuromodulation AND Auditory Perception OR Neuromodulation AND Correction of Hearing Impairment. The selected filters were the period (January 1, 2010, to August 30, 2024), age (children and adults), humans, and type of study (clinical study, clinical trial, multicenter study, and randomized or uncontrolled trial).

## Selection Criteria

Three researchers (SA; DOL[1]; VLCC) independently and blindly selected studies by screening records based on their titles and abstracts. Human studies that a) addressed children and adults, b) performed at least one behavioral test to assess CAP, and c) applied tDCS were selected for full reading. Duplicate studies were removed using the "endnote" function. The full text was obtained for all studies that met the eligibility criteria. A fourth researcher, DOL[2], resolved and analyzed any disagreements.

Studies with a non-experimental method (reviews, meta-analyses, editorials) and/or whose full text was not available were excluded.

### Data Analysis

The following information was collected: title, author(s), year of publication, country of origin; definition of the study design; tDCS parameters (electrode placement, electrode size, sensitivity to current intensity, current density, stimulation duration, interval between stimulations, number of treatment sessions, measurement methods); and main outcome.

In case of missing or incomplete information, data were extracted from the figures and tables, as much as possible, and emailed to the authors to obtain the mean and standard deviation across all groups and stimulation methods.

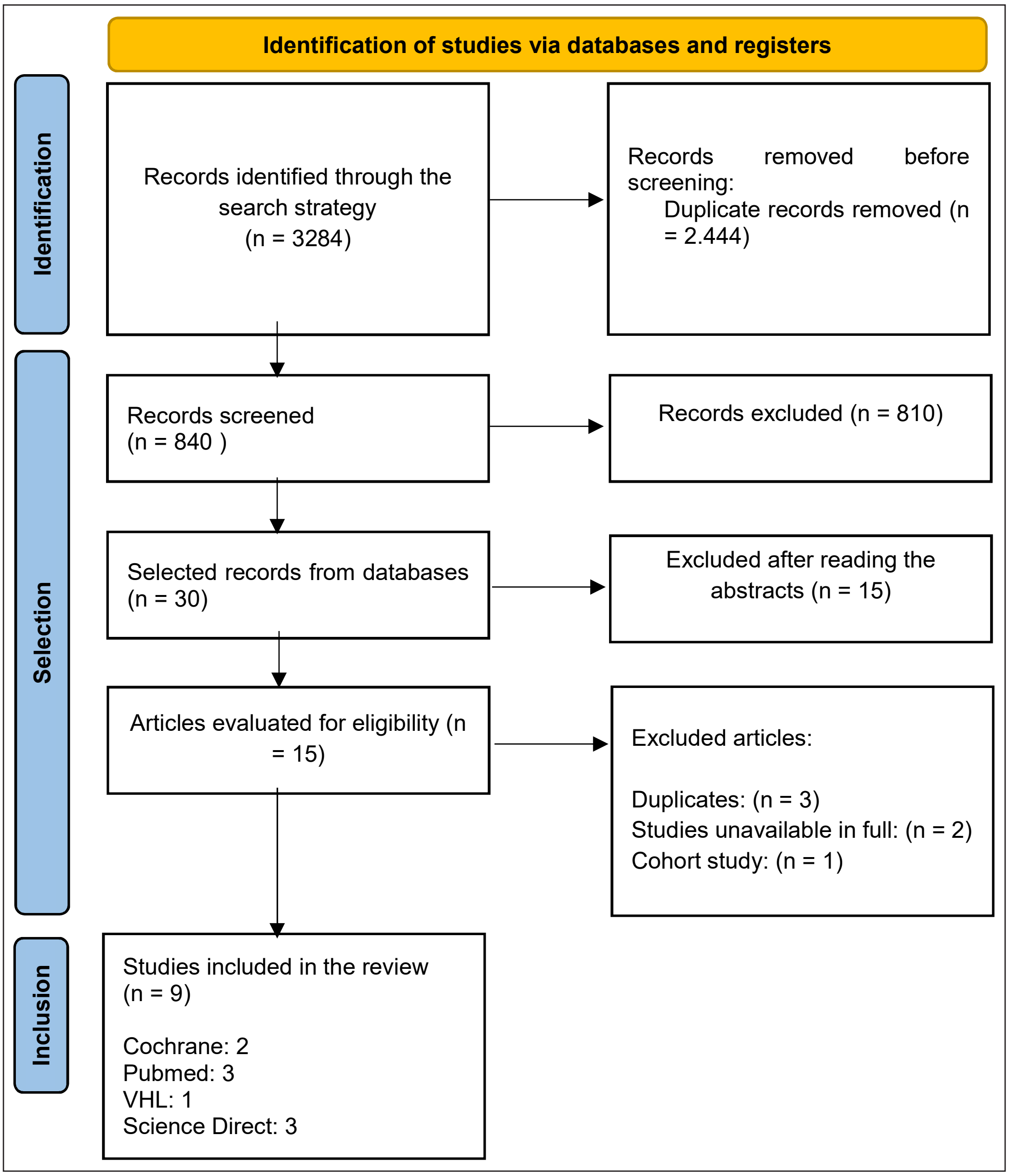
### Analysis of the risk of bias

After selection, the studies were assessed using the Cochrane Risk of Bias 2.0 (RoB 2.0)[25], a specific tool for this purpose. It is structured into five domains, each one responded with "Yes," "No," "Unclear," or "Not Applicable." The domains cover all types of bias that can affect the results of randomized trials: 1. Bias resulting from the randomization process; 2. Bias due to deviations from the intended interventions; 3. Bias due to the lack of outcome data; 4. Bias in outcome measurement; and 5. Bias in the selection of the reported outcome.

## LITERATURE REVIEW

### Study Selection

The first phase of the selection process resulted in 3,284 citations in the electronic databases. After removing duplicates, a total of 840 were evaluated. After reading titles and abstracts, studies that included transcranial stimulation methods other than direct current stimulation were excluded. Fifteen references were selected for full-text reading, resulting in the inclusion of nine studies for qualitative and quantitative assessment (Figure 1).




Source: Adapted from PRISMA 2020

**Figure 1.** Flowchart with literature search and selection criteria

## Interventions Applied

The tDCS parameters used in the included studies are presented in Table 3. Of these, 66.66% (n = 6) had two conditions (anodal and cathodal) and a sham group as a comparator, and 33.3% (n = 3) had one condition (anodal) and a sham group as a comparator.

Regarding the stimulation intensity, 44.4% (n = 4) used a current of 2 mA, 44.4% (n = 4) 1 mA, and only 11.1% (n = 1) a current of 1.2 mA. Also, 88.88% (n = 8) evaluated the application of unihemispheric anodal tDCS, and only 11.1% (n = 1) applied saline bihemispherically. Only 22.2% (n = 2) of studies applied more than one tDCS session to evaluate its effects.

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**Table 2.** Summary of the characteristics of the studies analyzed

| Study | Sample size | Age (mean/ range) | Objectives | Procedures | Main outcome |
|---|---|---|---|---|---|
| Ladeira et al. (2011)[22] | 11 subjects | 20 to 25 years | To modulate temporal aspects through CAP tDCS in healthy individuals without hearing impairment. | Random Gap Detection Test (RGDT). | Improved performance in the temporal resolution task. |
| Lewald, (2019)[23] | 24 subjects | Mean of 22.6 years | To induce more intense, long-lasting, and bilaterally symmetrical effects on performance in a noisy listening task ("cocktail party task") after using tDCS. | Four-syllable words (numerals) were used as stimuli, with four different words (one target and three distractors per trial), spoken simultaneously by four different speakers in four separate locations. | Improved auditory attention. |
| Tang et al. (2013)[24] | 20 subjects | Mean of 23 years | To verify whether the application of tDCS could improve participants' ability to learn to discriminate sound frequencies. | Frequency discrimination task. | Positive effects of anodal tDCS on frequency discrimination by affecting temporal coding mechanisms. |
| Isik et al. (2023)[25] | 16 subjects | Not reported | To analyze whether tDCS applied to the left auditory cortex has a polarity-specific behavioral effect on the categorical perception of speech sounds whose temporal characteristics are modulated. | Phonetic categorization task including auditory stimuli with voice onset time. | A single session of tDCS on the unilateral left auditory cortex does not significantly affect the categorical perception of speech sounds. |
| Zink, (2020)[26] | 30 subjects | Mean of 25.7 years (SD = 3.4 years). | To investigate how atDCS can improve the performance and efficiency of the brain's communication network in situations with different levels of attentional-perceptual conflicts. | Dichotic listening task.<br>EEG recording and preprocessing. | Positive effects on the efficiency of EEG-based network communication under high demands of attentional control. |
| Rahimi et al. (2019)[27] | 17 subjects | 9-12 years<br>(SD: 10.35) | To investigate the effect of tDCS on temporal resolution variables and long-latency auditory evoked potentials of speech with two electrode sets in the superior temporal gyrus. | Gap in Noise (GIN).<br>LLAEP before and after intervention. | Significant reductions in threshold values and increases in the percentage of correct responses in the GIN test. Increased amplitude and decreased latency of the P1, N1, and P2 waves. |
| Hanenberg et al. (2019)[28] | 39 subjects | Two age groups, one younger<br>(n = 20, ages 18–30 years)<br>(n = 19, ages 66–77 years). | To explore the effects of tDCS on the posterior temporal cortex on neurophysiological correlates of auditory selective spatial attention, with a specific focus on the N2. | Free-field multiple-talker auditory localization task.<br>ERP recording. | Improved inhibitory attentional aspects, with an increase in the amplitude of the N2 component. The localization error was improved after anodal tDCS. |
| Lerud et al. (2021)[29] | 26 participants Experiment 1: 14 participants.<br>Experiment 2: 12 participants. | 21-40 years | To investigate the causal influence of the left SMG gyrus on auditory short-term memory for tone. | Experiment 1: Tone memory task. Experiment 2: Tone memory task and visual memory task.<br>EEG recording and analysis. | Positive effect of anodal tDCS on auditory memory for tones. |
| Adelhöfer et al. (2019)[30] | 32 subjects | 20 to 30 years. (Mean of 24.7) | To use anodal tDCS to increase cortical excitability to causally investigate the role of the attentional network in resolving attentional-perceptual conflict during auditory processing. | EEG and syllable pairs presented in dichotic listening with focused and modulated attention. | AtDCS stimulation improves prefrontal control mechanisms for resolving attentional-perceptual conflicts. It also increases the amplitude of the C-cluster, which is associated with conflict resolution and response selection. |

**Table 3.** Stimulation parameters of the studies included in the meta-analysis

| Study | Intervention (Group) | Current density | Nominal target | Stimulation Intensity (mA) | Laterality | Anode | Cathodal site | Sessions (duration) | Follow-up |
|---|---|---|---|---|---|---|---|---|---|
| Ladeira et al. (2011)[22] | Anodal (11) sham (11) | 0.057 mA/cm² | L+R AC | 2 mA | Bihemispheric | T7 and T8 | DM | 1 (10 min) Real and simulated sessions separated by 48 hours | ND |
| Lewald J, (2019)[23] | Anodal (18) Sham (18) | 0.03 mA/cm2 under the target electrodes and 0.01 mA/cm2 at the return electrode | L AC | 1 mA | Unilateral | Between C5 and T7 and C6 and T8 | DM | 1 session simultaneously for 1 (32 min) | Assessed with a questionnaire about the individual's sensation and symptoms during application |
| Tang et al. (2013)[24] | Anodal Cathodal Sham | 0.0177 mA/cm² | R AC | 1 mA | Unilateral | 1 cm below the midpoint of C4 and T4 | Fp2 | One 20-minute session | Frequency discrimination task after 2 and 3 months |
| Isik et al. (2023)[25] | Anodal, cathodal, and sham | ND | L AC | 2 mA | Unilateral | T7 | Fp2 | One 30-minute session | ND |
| Zink, (2020)[26] | Anodal, cathodal, and sham | ND. | Prefrontal and R AC | 2 mA | Unilateral | Between T8 and F8 | L DM | One 20-minute session before and after dichotic listening task | ND |
| Rahimi et al. (2019) [27] | Anodal Cathodal Sham | ND | L AC | 1 mA | Unilateral | T7 | DM | Four 20-minute sessions with 1-week intervals | ND |
| Hanenberg et al. (2019)[28] | Anodal, cathodal, and sham | ND | R AC | 1 mA | Unilateral | C6 and T8 | Fp2 | Three 15-minute sessions, 7 days apart | ND |
| Lerud et al. (2021)[29] | Cathodal, anodal, and sham | 0.07 mA/cm2 | Supramarginal gyrus (parietal lobe) | 1.2 mA | Unilateral | CP3 and T7 | DM | Two 20-minute sessions | ND |
| Adelhöfer et al. (2019)[30] | Anodal and Sham | 0.08 mA/cm2 | prefrontal | 2 mA | Unilateral – Right fronto-parietal lobe | T4 and F8 | L DM | One 20-minute session + dichotic hearing task | ND |

Captions: ND = not described; AD = auditory cortex; DM = deltoid muscle; L DM = left deltoid muscle.

## Meta-Analysis of the intervention effect

The data were stratified by outcomes (auditory attention and temporal processing) and combined in a meta-analysis using Review Manager (RevMan) software. The meta-analysis analyzed the effect of tDCS on two outcomes: (1) effects on temporal processing, and (2) auditory attentional aspects.

The statistical synthesis of continuous data used the inverse variance method, with random-effects modeling, adopting the standardized mean difference (SMD) as the effect measure, accompanied by the corresponding 95% confidence interval (95% CI). The outcomes were established considering the response time in tests that assess temporal resolution ability (milliseconds - ms).

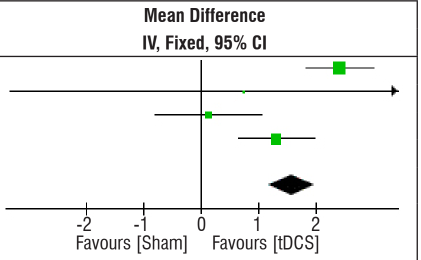
Heterogeneity was assessed using the chi-square (Chi²) test, considering $p < 0.05$ statistically significant, and the $I^2$ index, with values greater than 75% indicating substantial heterogeneity. Forest plots were also visually inspected. When substantial heterogeneity was detected (Chi² $p < 0.10$ and $I^2 > 75\%$), the data were synthesized qualitatively.

## (1) Effects on Temporal Processing (Figure 2)

The pooled mean difference of 1.57 (CI: 1.18 to 1.97; Z = 7.79, $p < 0.00001$; n = 4 studies with 60 participants) suggests that tDCS has a positive effect compared to sham, with a statistically significant result ($p < 0.00001$), but with high heterogeneity (83%) between studies ($I^2 = 83\%$). This heterogeneity can be attributed to differences in methods, populations, or protocols. Significant heterogeneity ($Chi^2 = 17.80$, df = 3 (P = 0.0005) $I^2 = 83\%$) (Figure 2) was observed after stimulation with anodal tDCS.

| Study or Subgroup | tDCS Mean | tDCS SD | tDCS Total | Sham Mean | Sham SD | Sham Total | Weight | Mean Difference IV, Fixed, 95% CI | Year |
|---|---|---|---|---|---|---|---|---|---|
| Ladeira, et al.(2011) | 7.8 | 0.02 | 11 | 5.4 | 1 | 11 | 44.7% | 2.40 [1.81, 2.99] | 2019 |
| Lerud, et al.(2021) | 30.08 | 3.6 | 12 | 29.33 | 3.58 | 4 | 0.9% | 0.75 [-3.31, 4.81] | 2019 |
| Rahimi V., et al. (2019) | 7.35 | 1.45 | 17 | 7.23 | 1.3 | 17 | 18.2% | 0.12 [-0.81, 1.05] | 2019 |
| Tang, et al.(2013) | 5.7 | 0.009 | 20 | 4.4 | 1.5 | 20 | 36.1% | 1.30 [0.64, 1.96] | 2020 |
| Total (95% CI) | | | 60 | | | 52 | 100.0% | 1.57 [1.18, 1.97] | |

Heterogeneity: $Chi^2 = 17.80$, df = 3 (P = 0.0005); $I^2 = 83\%$
Test for overall effect: Z = 7.79 (P < 0.00001)




Forest plot showing the mean difference between the transcranial direct current stimulation (tDCS) and sham groups. Individual study results (Ladeira et al., 2011; Lerud et al., 2021; Rahimi V. et al., 2019; Tang et al., 2013) are represented with their respective 95% confidence intervals (CI). The size of the squares represents the weight of each study in the pooled analysis. The vertical line indicates no effect (mean difference = 0). The overall pooled estimate indicates a significant positive effect of tDCS compared to sham (mean difference: 1.57 [95% CI: 1.18 to 1.97], $p < 0.00001$). The heterogeneity test shows significant variability between studies ($I^2 = 83\%$).

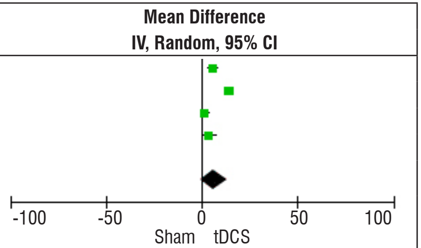
**Figure 2.** Forest plot of the meta-analysis of the effects of transcranial direct current stimulation on auditory processing

## (2) Effects on Auditory Attention (Figure 3)

The meta-analysis included four studies that compared the effects of tDCS with sham (placebo), evaluating their impact on auditory attention. The combined analysis of the studies revealed an overall mean difference of 6.20 (95% CI: -0.44 to 12.84), with a Z value = 1.83 and p = 0.07. These data indicate a trend favorable to tDCS; however, the observed difference was not statistically significant ($p > 0.05$). Extremely high heterogeneity was observed between the studies ($Tau^2 = 44.29$; $Chi^2 = 102.01$; df = 3; $p < 0.00001$; $I^2 = 97\%$), suggesting wide variation in individual results. This discrepancy can be attributed to differences in intervention protocols (such as number of sessions and current density and intensity), participant characteristics, and assessment methods used.

| Study or Subgroup | tDCS Mean | tDCS SD | tDCS Total | Sham Mean | Sham SD | Sham Total | Weight | Mean Difference IV, Random, 95% CI | Year |
|---|---|---|---|---|---|---|---|---|---|
| Adelhöfer, et al., 2019 | 30.15 | 2.78 | 16 | 24.55 | 4.09 | 16 | 25.1% | 5.60 [3.18, 8.02] | 2019 |
| Hanenberg C., et al., 2019 | 87.4 | 2.4 | 20 | 73.3 | 2.7 | 19 | 25.5% | 14.10 [12.49, 15.71] | 2019 |
| Lewald J., et al., 2019 | 68.2 | 2.8 | 12 | 66.9 | 2.6 | 12 | 25.2% | 1.30 [-0.86, 3.46] | 2019 |
| Zink et al., 2020 | 45.9 | 4.2 | 15 | 42.3 | 5.5 | 15 | 24.2% | 3.60 [0.10, 7.10] | 2020 |
| Total (95% CI) | | | 63 | | | 62 | 100.0% | 6.20 [-0.44, 12.84] | |

Heterogeneity: $Tau^2 = 44.29$; $Chi^2 = 102.01$, df = 3 (P < 0.00001); $I^2 = 97\%$
Test for overall effect: Z = 1.83 (P = 0.07)

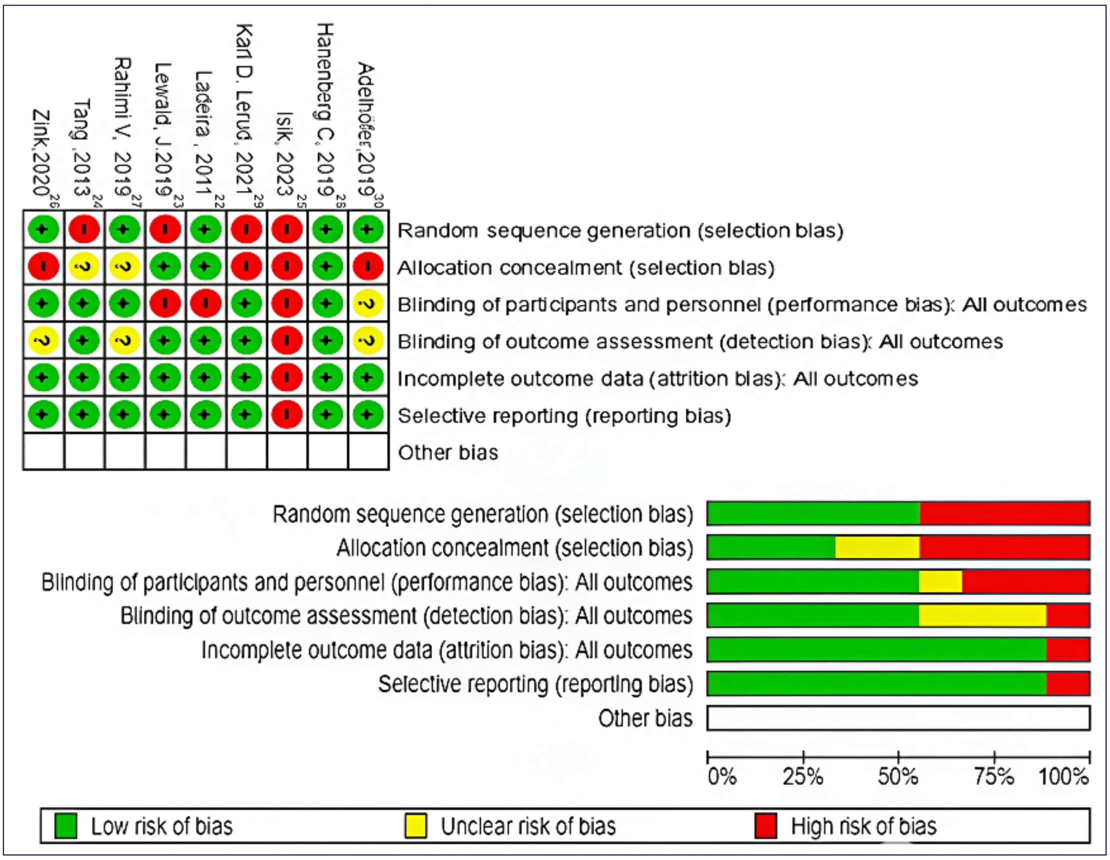



Results from the four studies included in the meta-analysis comparing the effects of tDCS with placebo (sham) stimulation. Mean differences and 95% confidence intervals (95% CI) are presented for each individual study and for the combined analysis. The vertical line represents no effect (mean difference equal to zero). High heterogeneity ($I^2 = 97\%$) indicates significant inconsistency across studies.

**Figure 3.** Forest plot of the meta-analysis of the effects of transcranial direct current stimulation on auditory attention

## Risk of bias for individual studies

In the risk of bias assessment (Figure 4), two articles[27,28] were described as having a low risk of bias. Of the six domains assessed, only one of them[27] had an unclear risk of bias in domains 2 and 4 of the questionnaire. One article[25] was assessed as having a high risk of bias because it presented a high risk in all domains. The remaining articles presented an unclear risk of bias.




Detailed assessment of the risk of bias in the included studies. The figure presents a matrix indicating the risk of bias in different domains, such as random sequence generation, allocation concealment, blinding of participants and personnel, incomplete data, selective reporting, and other bias. Green circles represent low risk of bias, yellow circles indicate unclear risk, and red circles indicate high risk of bias. The bar chart on the right summarizes the proportion of risk of bias in each domain assessed.
Source: Prepared in Cochrane version 6.5.

**Figure 4.** Risk of bias assessment for included studies

The results of the nine eligible articles demonstrate positive effects of tDCS on the auditory cortex, particularly on temporal processing abilities, with an emphasis on auditory attention. These effects were more significant when anodal polarity was used compared to cathodal polarity.

The positive effects of tDCS on temporal processing[16,22,24,27] stood out, suggesting its potential for clinical applications in temporal disorders. These findings corroborate those of Ladeira et al. (2011)[22], who observed that tDCS facilitates neural synchrony and improves the processing of temporal information.

However, researchers[16] expanded on these findings by demonstrating that tDCS not only improves temporal processing in healthy populations but can also be effective in clinical populations, such as individuals with neurological disorders. These findings were significant for the development of new therapeutic interventions. Thus, when exploring[27] the mechanisms underlying tDCS, researchers suggested that improvements in temporal processing may be related to the modulation of cortical excitability and synaptic plasticity.

Still from the perspective of the effects of tDCS on temporal processing, researchers observed[31] left hemispheric dominance for the ability of temporal resolution, demonstrating the ability of tDCS to alter the processing of temporal information in the auditory system.

tDCS has also been shown to influence the auditory cortex, specifically at 4000 Hz, during the random gap detection test (RGDT) to assess auditory temporal resolution, an important skill for auditory discrimination. Performance improved with anodal stimulation and worsened with cathodal stimulation[32]. Furthermore, changes in the basal activity of the auditory cortex at this frequency, as demonstrated by short-latency auditory evoked potentials[22], impair frequency discrimination, affecting temporal coding mechanisms[24], but improve the perception of temporal aspects of hearing.

In another study, tDCS was shown to effectively modulate temporal resolution by significantly reducing threshold values and increasing the percentage of correct responses in the Gap in Noise (GIN) test[27]. In addition, positive results were observed in evoked potentials, with reduced latency and increased amplitude of the P1, N1, and P2 waves, demonstrating the potential effects of tDCS in improving CAP characteristics, especially temporal information processing in children and adolescents[27].

It has also been observed that tDCS plays an important role in short-term auditory storage and influences cognitive performance. A study[29] found that, after applying tDCS to the left auditory cortex, there were significant positive effects on short-term auditory memory of tones for anodal polarity compared to cathodal polarity.

A study of two age groups[28] observed positive effects of anodal tDCS on selective auditory attention, with a current of 1 mA and current densities of 0.03 mA/cm$^2$ applied to the temporal cortex (between C6 and T8) for 16 minutes. Neurophysiological findings (event-related auditory potential) increased the amplitude of the N2 wave, demonstrating that anodal tDCS on the temporal cortex can reduce deficits in selective auditory attention.

Another study observed an improvement in selective auditory attention in a “cocktail” situation after applying a single dose of bihemispheric tDCS. This was done through two stimulators in the right and left temporal cortex, between C5 and T7 and C6 and T8, respectively, for 30 minutes, with a current of 1 mA[23]. Zink et al. (2020)[26] applied tDCS stimulation with a current of 2 mA for 20 min before starting the dichotic listening task, and tDCS had effects on auditory attentional control.

Regarding auditory comprehension results, researchers[33] found that tDCS over the left inferior frontal gyrus induces greater accuracy in a sentence comprehension task compared to sham stimulation. In agreement, another study[34] provided evidence that noninvasive anodal electrical stimulation can modulate sentence comprehension in healthy adults through anodal tDCS applied over the inferior frontal gyrus, between T3-Fz and F7-Cz, for 15 minutes with a current of 1 mA.

However, according to a recent study[25], a single session of tDCS applied to the unilateral left auditory cortex did not significantly affect the categorical perception of speech sounds, exerting only a polarity-specific effect on the categorical perception of speech sounds whose temporal characteristics are modulated when stimulated for 30 minutes. The effect of tDCS on binaural integration ability is promising. However, further research is needed to determine whether tDCS may have a potential enhancing effect on binaural integration, as the data are still preliminary.

A recent review of experimental studies on temporal processing highlights that this parameter obtains consistent results. Indeed, all studies suggest that tDCS has a positive effect on temporal processing, whereas other possible results are scarce or often conflicting[16].

## Variability in Stimulation Parameters

It is important to consider the variability in stimulation parameters across the analyzed studies. Current density ranged from 0.0177 mA/cm$^2$ to 0.08 mA/cm$^2$; stimulation intensity was predominantly 1 mA or 2 mA; session duration ranged from 10 to 32 minutes, with one to four sessions. Regarding laterality, some studies applied stimulation unilaterally (e.g., T7 or T8), while others opted for bihemispheric stimulation (T7 + T8). This heterogeneity in parameters may influence the results of the meta-analysis and contribute to the high heterogeneity (high $I^2$) observed in the forest plot. Studies with different protocols may produce different effects, making direct comparisons difficult.

Electrode locations and nominal targets also varied considerably, using the following cortical targets: left auditory cortex (L AC) regions near T7 or T8; prefrontal cortex (Fp2), and supramarginal gyrus (CP3). Some applications involved bilateral auditory cortex (e.g., T7 and T8). This variety of targets reflects different hypotheses about the mechanisms by which tDCS might improve auditory processing. While some studies aim to modulate the auditory cortex directly, others explore areas associated with auditory attention and executive control.

Non-invasive anodal tDCS is a new therapeutic approach, in addition to traditional cognitive and rehabilitation methods, as it can be proportional to the stimulation polarity and duration, increasing cortical activity[29,32]. The studies presented to date combined tDCS with an auditory task[30], increasing the task's effectiveness, auditory attention, and the effects on auditory behavior. Furthermore, protocols need to be developed to standardize the time and number of sessions required to ensure positive and long-lasting effects, as most studies used protocols with one to four sessions.

Speech-language-hearing studies demonstrate[35] that the application of tDCS on consecutive days combined with another intervention (20 minutes per session with a current intensity of 2 mA) in patients with dyslexia improved reading skills and phonological awareness, with effects lasting for at least 3 months. Thus, similar studies may provide insights into the effects and safety of applying tDCS on consecutive days.

There is a lack of evidence defining the ideal stimulation regimen, in terms of frequency, intensity, and duration, capable of inducing lasting neuroplastic effects. Variability in methodological parameters across studies compromises the comparability of results and hinders the consolidation of clinical recommendations. However, better performance in auditory comprehension, sentence comprehension, reading, and phonological awareness activities has been observed in cases associated with tDCS[36-38]. Therefore, considering that classical auditory training with eight to 12 sessions has been shown to effectively improve auditory skills[39], it is suggested that tDCS be accompanied by auditory task protocols consistent with findings in the literature. Future research should prioritize designs that combine these tasks with repetitive tDCS protocols to assess the effectiveness of cumulative stimulation and its contribution to functional auditory rehabilitation.

## Risk of Bias

According to the tool, most of the included studies presented biases related to methodological quality, mainly related to the lack or inadequacy of randomized allocation of participants into groups and blinding of outcome assessors. Also, the quality of the evidence was considered low. Such findings can affect the quality of the results and increase variability between studies; therefore, caution is required when interpreting the results.

## Level of Evidence

The analysis used the GRADE (Grading of Recommendations Assessment, Development and Evaluation) system criteria through the GRADEpro GDT tool to evaluate the quality of the evidence of the identified outcomes. It considered the two outcomes evaluated: temporal processing and auditory attention.

For the temporal processing outcome, the meta-analysis demonstrated a standardized mean difference (SMD) of 1.57 (95% CI: 1.18 to 1.97; $p < 0.00001$), indicating a statistically significant positive effect of tDCS compared to sham. However, the evidence was classified as low quality due to a risk of methodological bias in some of the included studies and high heterogeneity among the results ($I^2 = 83\%$).

Regarding auditory attention, the data showed a favorable but not statistically significant trend (SMD = 6.20; 95% CI: -0.44 to 12.84; $p = 0.07$), with extremely high heterogeneity ($I^2 = 97\%$). The quality of the evidence for this outcome was classified as very low, due to the combination of high risk of bias, inconsistency between studies, and imprecision in the results.

In summary, the GRADE-based analysis suggests that, although anodal tDCS may offer benefits for temporal processing and auditory attention in individuals with CAPD, the currently available evidence is limited and unreliable. Future studies, with greater methodological rigor and standardized protocols, are needed to confirm these findings and strengthen clinical recommendations.

## Limitations

The wide variability in stimulation parameters and participant characteristics, as well as studies with small or insufficient sample sizes, may influence the interpretation of the combined results. Biases in studies can compromise the validity of the findings.

The high heterogeneity observed in the analyses can be explained by methodological and clinical factors. There is significant variability in stimulation parameters, such as current intensity, number of sessions, electrode placement, and intervention duration. Furthermore, sample characteristics vary across studies, including age, audiological profile, and presence of cognitive or neurological comorbidities, which can directly affect responsiveness to neuromodulation. The instruments used to assess outcomes (various hearing tests or behavioral scales) also contribute to inconsistent results. Finally, the lack of standardization in defining protocols and conducting studies compromises comparability between them and reinforces the need for clinical trials with greater methodological rigor, which consider the standardization of key variables and appropriate sample stratification.

Thus, future studies should prioritize the standardization of stimulation protocols, especially regarding intensity, duration, and application location, in addition to adopting greater methodological rigor to confirm the efficacy of tDCS in this population and improve the quality of the evidence. It is also necessary to investigate the association between auditory stimulation techniques and the optimal number of sessions to promote functional improvements. Although tDCS safety criteria are well established in the literature, there are still gaps regarding the number of sessions required to achieve consistent therapeutic effects.

It is important to note that this study helps identify specific stimulation parameters and guides the clinical application of tDCS in the study population, guiding future studies and supporting evidence-based practice. Moreover, the social impact on this population is reflected in improvements in quality of life, educational inclusion, and cost reduction, as effective treatment can reduce the need for long-term therapies and stimulate technological innovation.

## CONCLUSION

The results indicate that tDCS, when applied with a 2 mA current and anodal stimulation in the left auditory cortex, increases the speed of temporal processing through improved auditory identification and discrimination. Furthermore, there is a positive influence on auditory attention through the management of auditory information in the presence of interference or in noise situations with spatial cues. However, the number of sessions has not yet been established, as most studies analyzed the effect of tDCS on CAP in a single session, and the quality of this evidence is considered low. Therefore, although tDCS shows promising potential for improving auditory abilities related to CAP, more controlled clinical trials with larger samples and a greater number of sessions are needed to confirm its efficacy in this population.

Despite the promising results, tDCS should still be considered an exploratory technique for improving auditory skills and CAPD. Its clinical use requires more robust evidence, obtained through controlled clinical trials with larger sample sizes and well-defined protocols for analyzing its efficacy in this population.

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**Authors' contributions:**

DOL: Conceptualization; Writing - Original draft.

SA: Data analysis; Visualization.

DOL: Data curation.

ACM: Resources.

MLM: Methodology.

VLCC: Investigation; Writing - Review & editing.

MRDR: Project administration.

ES: Supervision.

**Data Sharing Statement:**

The authors of this study, with transparency and commitment, declare that all data obtained and analyzed in the development of this review will be available for consultation and reuse by other researchers and interested parties, without access restrictions or expiration dates. The data available for sharing include lists of selected articles, inclusion and exclusion criteria, details of relevant information, search strategies for the review, analysis methods, and other data that make up the study plan, analysis results, figures, tables, summaries of the included studies, and any other useful information. All data will be made available through publicly accessible material or by direct request to the authors. We reiterate that we are available to collaborate with researchers interested in conducting new analyses or adding to the data analyses presented in this study. The authors can be contacted via email. We appreciate and encourage the ethical use of the shared information.