Brazilian Journal of Psychiatry
bjp
Revista Brasileira de Psiquiatria
Brazilian Psychiatric Association
Fully open access
No APCs

BJP PRE-PROOF

(article published as accepted)

Review Article

Therapeutic effects of tDCS on cognitive functions in patients diagnosed with autism spectrum disorders: a systematic review and meta-analysis on randomized sham-controlled trials

Ping-Wen Huang, Shun-Chin Liang, Cheuk-Kwan Sun, Yu-Shian Cheng, Chia-Min Chen, Kuo-Chuan Hung

http://doi.org/10.47626/1516-4446-2026-4808

Submitted: 13-Jan-2026

Accepted: 09-Aug-2026

This is a preliminary, unedited version of a manuscript that has been accepted for publication in the Brazilian Journal of Psychiatry. As a service to our readers, we are providing this early version of the manuscript. The manuscript will still undergo copyediting, typesetting, and review of the resulting proof before it is published in final form. The final version may present slight differences in relation to the present version.

Therapeutic effects of tDCS on cognitive functions in patients diagnosed with autism spectrum disorder: a systematic review and meta-analysis on randomized sham-controlled trials

Short title: tDCS and ASD

Ping-Wen Huang[1]*, Shun-Chin Liang[2,3,4]*, Cheuk-Kwan Sun[5,6]*, Yu-Shian Cheng[7], Chia-Min Chen[8], Kuo-Chuan Hung[9*]

*Ping-Wen Huang, Shun-Chin Liang, and Cheuk-Kwan Sun ccontributed equally as first authors

[1] Department of Emergency Medicine, Show Chwan Memorial Hospital, Changhua City, Taiwan.
[2] Department of Psychiatry, Jianan Psychiatric Center, Ministry of Health and Welfare, Tainan, Taiwan
[3] Department of Center for General Education, University of Kun Shan, Tainan, Taiwan
[4] Department of Optometry, University of Chung Hwa of Medical Technology, Tainan, Taiwan
[5] Department of Emergency Medicine, E-Da Hospital, I-Shou University, Kaohsiung City, Taiwan
[6] School of Medicine for International Students, College of Medicine, I-Shou University, Kaohsiung City, Taiwan
[7] Department of Psychiatry, Tsyr-Huey Mental Hospital, Kaohsiung Jen-Ai's Home, Taiwan
[8] Department of Natural Biotechnology, Nanhua University, Chiayi, Taiwan
[9] Department of Anesthesiology, Chi Mei Medical Center, Tainan City, Taiwan

[*]Corresponding author: Kuo-Chuan Hung, MD
Department of Anesthesiology, Chi Mei Medical Center, Tainan, Taiwan
Chi Mei Medical Center, No.901, ChungHwa Road, YungKung Dist, Tainan 71004, Taiwan
TEL: +886-6-281-2811; FAX: +886-6-283-3806; Email: ed102605@gmail.com

BJP PRE-PROOF

Abstract

OBJECTIVE: This meta-analysis aimed at investigating the effectiveness of transcranial direct current stimulation (tDCS) in improving cognitive functions in individuals with autism spectrum disorder (ASD) and evaluating the effects of potential confounders on therapeutic outcomes.
METHODS: Randomized placebo-controlled trials (RCTs) identified from major databases were reviewed. Continuous data were expressed as effect size based on standardized mean difference (SMD) with 95% confidence intervals.
RESULTS: Meta-analysis of thirteen RCTs involving 347 participants diagnosed with ASD (mean age=15.76) revealed significant improvements in social cognition among those receiving tDCS treatment compared to sham controls (SMD=1.14, 95% CI=0.70–1.58, p<0.01, seven studies, n=172). Subgroup analysis showed no significant impact regarding location of anode placement, combination with cognitive/behavioral training, and number of sessions. Our secondary analyses demonstrated significantly greater improvements in processing speed of patients receiving tDCS than their sham controls (SMD=0.50, 95% CI=0.22–0.77, p<0.01, five studies, n=208) but not in attentional function, inhibitory control, and working memory.
CONCLUSION: Our study supported the use of tDCS for improving social cognition and processing speed in individuals with ASD. Nevertheless, the impact of potential confounders on therapeutic outcomes, including treatment duration and target brain region, warrants elucidation by further large-scale investigations.
Keywords: tDCS, autism spectrum disorder, ASD and meta-analysis

Introduction

Autism spectrum disorder (ASD) is a neurodevelopmental condition usually with an early onset.[1] It is characterized by repetitive and restricted patterns of interests or activities combined with behavioral issues related to communication and socialization [1]. A heightened public awareness of the behavioral symptoms and changes in diagnostic criteria may contribute to its high prevalence of up to 2.3% and 2.2% in children and adults, respectively [1]. It is also a major cause of emergency visits for children and adolescents due to the manifestation of irritability/emotional lability [2,3]. Nevertheless, the only pharmacological treatments approved by the U.S. Food and Drug Administration (FDA) are those targeting ASD-associated irritability instead of its core symptoms related to social interaction and communication or

BJP PRE-PROOF

behavioral patterns, resulting in the choice of intensive behavioral therapies starting at early childhood as a standard treatment strategy [1] despite its controversial cost- and time-effectiveness [4]. Such a lack of therapeutic options has led to the integration of complementary and alternative medicine (CAM) into the standard treatment protocol among caregivers of individuals diagnosed with ASD, notwithstanding its questionable efficacy [5]. One of the most extensively investigated approaches is neuromodulation that involves the delivery of electrical stimuli to the target brain regions [6,7] in an attempt to treat various psychiatric and neurodevelopmental ailments such as ASD [8].

Among different neuromodulation techniques, transcranial direct current stimulation (tDCS) has been extensively studied for the treatment of ASD [8]. One proposed mechanism is an imbalance between neuronal excitation and inhibition (E/I) through altered glutamatergic and GABAergic neurotransmission, respectively [9]. As an noninvasive method of modulating neuronal activity, tDCS can alter the resting membrane potential of cortical neurons, causing a shift toward increased or decreased neural excitability [10]. This effect is achieved by applying a weak electrical current via anodal and cathodal surface electrodes to the scalp [10]. Although tDCS has been applied to different brain locations in several RCTs in an attempt to improve the symptoms of ASD [11-23] the dorsolateral prefrontal cortex (DLPFC) was the most popular stimulation target [11-23], as the DLPFC is known to play a pivotal role in the broad neural network underpinning social cognition [24]. In addition to the altered patterns of brain activation in various functional domains of the brain among those diagnosed with ASD, the functional connectivity patterns of the entire brain during task performance and at rest were also found to be different between individuals with ASD and those without [10]. Apart from the modulation of activities in various brain regions, tDCS has been shown to induce changes in functional as well as resting state connectivity [10], thereby exerting a wider effect than that confined to the stimulation of a single brain region.

A recent network meta-analysis demonstrated the effectiveness of tDCS placing anode at the F3 region of the brain in improving the overall symptoms of ASD compared with sham-tDCS [8]. However, the strength of evidence derived from that study was limited by the inclusion of only three trials in that tDCS treatment arm (i.e. placing anode at the F3) and even fewer trials in the other arms (i.e., one trial for most treatment arms) [8]. Similarly, although a previous meta-analysis also reported positive therapeutic effects of tDCS

BJP PRE-PROOF

against the behavioral symptoms of ASD, it included mainly single-arm trials and merely explored the changes in behavioral symptoms after tDCS treatment in the same group rather than comparing tDCS interventions with other control groups [25].

It has been proposed that improvements at the endophenotypic level (e.g., neurocognitive functioning) may precede observable behavioral changes. Therefore, the observed therapeutic effect of tDCS against neurocognitive dysfunctions may be earlier and a more sensitive indicator of ASD improvement compared with changes in behavioral rating [26], further underscoring the potential advantage of detecting cognitive functional improvement over behavioral assessment. However, none of the previous meta-analyses or network meta-analytic studies investigated the therapeutic effects of tDCS against different cognitive dysfunctions in patients with ASD [8,25]. Provided that patients with ASD may exhibit multiple domains of cognitive deficits [27], exploring the cognitive therapeutic aspect of tDCS is of utmost clinical importance.

Hence, the present meta-analysis, which focused on randomized controlled clinical trials (RCTs), aimed to update current evidence of the effectiveness of tDCS in improving cognitive functions among those diagnosed with ASD. In addition, the impact of other factors on therapeutic outcomes, including treatment duration and target brain region, was elucidated.

Methods

Study design and registration

The current meta-analysis, which was conducted in full compliance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [30], was registered in the international prospective register of systematic reviews (PROSPERO CRD42025633828).

Search strategy and eligibility criteria

Electronic databases, including PubMed, Embase, Cochrane CENTRAL, ScienceDirect, and ClinicalTrials.gov, were scrutinized for randomized controlled trials (RCTs) on the therapeutic efficacy of tDCS in improving cognitive functions among ASD patients from inception to Feb 20, 2025. Without language and country restrictions, potentially eligible studies were identified using the main keywords of “ASD + tDCS” as well as appropriate MeSH and Emtree terms through the application of appropriate search

BJP PRE-PROOF

strategies (Supplementary Table S1). The reference lists of the retrieved literature were further screened for articles potentially eligible for the present study. The PICO criteria (i.e., population, intervention, comparator, and outcomes) for determining study eligibility included: (1) Population: participants with a diagnosis of ASD recruited in a RCT, (2) Intervention: tDCS, (3) Comparator: sham-tDCS, and (4) Outcome: changes in cognitive functions. On the other hand, we excluded studies in which (1) tDCS was not an intervention procedure, (2) sham-tDCS was not used for comparison, (3) changes in cognitive functions were not study outcomes, as well as (4) those that were not RCTs.

Data extraction and quality assessment

According to the preset keywords and strategies (Supplementary Table S1), two independent authors (YH Wen and SC Liang) screened the titles and abstracts of the retrieved publications from which they extracted data on study characteristics, sham protocols and outcomes where appropriate. Disagreements on study eligibility or data to be included were resolved by discussion with a third author (CK Sun). Inter-rater reliability was evaluated with kappa coefficients [28]. The corresponding authors of articles without providing necessary information were contacted through emails in an attempt to retrieve the missing data. The quality of the included studies was appraised with Cochrane's “risk of bias” assessment tool [29], In addition, the level of evidence of each outcome was assessed with the Grading of Recommendations Assessment, Development, and Evaluation (GRADE) rating [30]. Any difference in opinions regarding the risk of bias or level of evidence between the two authors was settled through discussion.

Data synthesis and analysis

The primary outcome of the current study was the change in social cognition of patients diagnosed with ASD assessed with social cognition tests (e.g., theory of mind test, test of adolescent social skills knowledge, and facial emotion recognition test), while the secondary outcome encompassed the changes in all other ASD-related cognitive functions such as attention, processing speed, and inhibitory control. Moreover, adverse effects were reviewed and analyzed. For continuous variables, the outcomes of interest were presented as effect sizes (ES) in standardized mean differences (SMD) with 95% confidence intervals (CI). Review Manager 5 (RevMan5.4;

BJP PREPROOF

Copenhagen: The Nordic Cochrane Center, The Cochrane Collaboration, 2014) was used for all statistical analyses. The analysis of continuous data was conducted with the generic inverse-variance approach, while the robustness of study outcomes was assessed using the leave-one-out sensitivity tests. The impact of important factors that may affect the therapeutic effects of tDCS on the cognitive functions of ASD patients was evaluated with subgroup analyses focusing on different age groups (mainly children vs. adolescents/adults), the target brain regions as well as the number and duration of tDCS sessions. The probability of publication bias across the included studies was assessed with funnel plot and Egger's test, while the significance of heterogeneity was evaluated with the I-squared test. The definition of statistical significance based on a probability value (*p*) below 0.05 was applicable to all study outcomes.

Results

Eligible studies and characteristics

The current meta-analysis was conducted in compliance with the PRISMA guidelines [31]. According to the preset keywords and search strategies (Supplementary Table S1), the 436 articles initially retrieved from the electronic databases were subjected to title and abstract screening that excluded 411 articles (Figure 1). A full-text review of the remaining 25 RCTs yielded 13 studies deemed eligible for the present meta-analysis [11-23] (Supplementary Table S2). The variation in age of the 347 participants in total across the studies was notable (range: 6–66 years; mean: 15.76) (Table 1); three studies enrolled only children [13,21,23], two exclusively recruited adolescents [11,19], one involved both children and adolescents [18], four included adolescents and adults [12,16,17,20], and the remaining three solely targeted adults [14,15,22]. Nevertheless, none of the studies recruited preschool children. Although the majority of studies adopted a parallel design [11-13,16-20,23], four were crossover studies [14,15,21,22]. Regarding the frequency of treatment, all four crossover trials conducted only a single tDCS treatment session,[14,15,21,22] while the remaining nine parallel studies adopted a multiple-session approach [11-13,16-20,23]. The median session number was 10 with a median follow-up duration of 14 days. With respect to the location of tDCS stimulation, the prevalent position of anode placement was the left prefrontal cortex (PFC) [11,13,18-20,22,23], followed by the right PFC [12,16,17], the parietal lobe, [21] and both PFC [14,15]. With regard to the position of cathode, the majority of studies chose the side contralateral to the

BJP PRE-PROOF

anode or targeting other locations of the brain [11-13,16,17,19,22,23], while four adopted a position other than the head. [14,15,20,21] However, one study did not provide information about cathode position [18]. The geographical origins of the studies varied widely, namely the USA [11,14,15,22], Hong Kong [12,16,17], Iran [18,21,23], China [13], Austria [19], and Thailand [20].

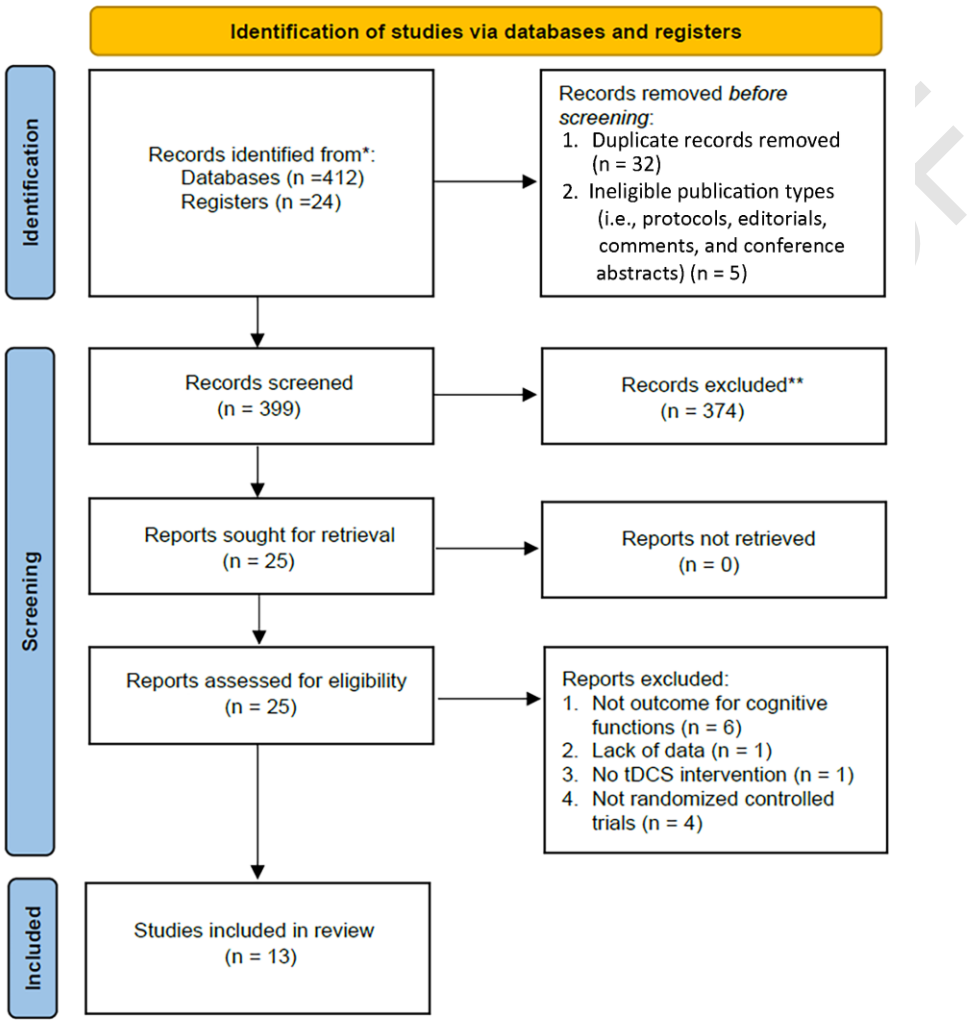


Figure 1. PRISMA diagram of identifying eligible studies. tDCS: transcranial direct current stimulation

Table 1: Summary of characteristics of studies in the current meta-analysis

Study (year)	Diagnosis (Criteria)	Design	Comparison	N	Number of Sessions	Duration	Outcome	Medication use (%)	Mean age (years)	Female (%)	Country
Steenburgh (2017)	ASD (ADOS)	RCT/ Crossover	tDCS: 1.5 Am for 39 mins; Anode-F3; Cathode-F4 Sham-tDCS: stimulation for 1 min on same location	12 12	1	1 day	1.Attention – BTA 2.Working memory - WM composite*	N/A	32.1 (20–66)	20	U.S.
Wilson (2018)	ASD (AQ)	RCT/ Crossover	tDCS: 2 Am for 30 mins; Anode-Cp6; Cathode-E Sham-tDCS: stimulation for 20 seconds on same location	6 6	1	1 day	Processing speed – VF test	33% on antidepressants	28.3 (18-58)	33.3	U.S.
Salehinejad (2021)	ASD (DSM-5)	RCT/ Crossover	tDCS: 1 Am for 20 mins; Anode-Fpz; Cathode-E Sham-tDCS: stimulation for 20 seconds on same location	16 16	1	1 day	Social cognition – TOMT	0%	10.07 (8–12)	42.85	Iran

Wilson (2021)	ASD (AQ)	RCT/ Crossover	tDCS: 1 Am for 30 mins; Anode-Cp6; Cathode-E + FERP training Sham-tDCS: stimulation for 50 seconds on same location + FERP training	7 7	1	1 day	Social cognition – FRT	29% on antidepressants	26.1 (>18)	28.57	U.S.
Han (2022)	ASD (DSM-5)	RCT	tDCS: 1.5 Am for 20 mins; Anode-Fp2; Cathode-F3 + CRT Sham-tDCS: no stimulation + CRT	20 21	10	2 weeks	1.Social cognition – CANTAB ERT 2.Processing speed –CANTAB IPE	N/A	17.7 (14–21)	7.31	Hong Kong
Zemestani (2022)	ASD (DSM-5)	RCT	tDCS: 1.5 mA for 15 min; Anode-F3; Cathode-F4 Sham-tDCS: stimulation for 60 seconds on same location	17 15	10	5 weeks	Social cognition –ToM test	0%	10.16 (7–12)	28.13	Iran
Chan (2023)	ASD (DSM-5)	RCT	tDCS: 1.5 mA for 20 min; Anode-Fp2; Cathode-F3	30	10	2 weeks	Processing speed – IPE	36.7%	16.69 (14–21)	0.15	Hong Kong

			Sham-tDCS: stimulation for 60 seconds on same location	30						
Han (2023)	ASD (DSM-5)	RCT	tDCS: 1.5 mA for 20 min; Anode-Fp2; Cathode-F3 + CRT Sham-tDCS: stimulation for 60 seconds on same location + CRT	34 33	10	2 weeks	1.Processing speed – 3FPT 2.Working memory – CANTAB OTS component 3.Inhibitory control - CANTAB mFK	34.3% on psychotropic medications	16.88 (14–21)	0.16	Hong Kong
Nazari (2023)	ASD	RCT	tDCS: 2 mA for 15 min; Anode-left DLPFC Sham-tDCS: stimulation for 20 seconds on same location	11 11	10	N/A	Social cognition – ERT	N/A	9.42 (6-17)	0	Iran
Chen (2024)	ASD (DSM-5)	RCT	tDCS: 1.5 mA for 20 min; Anode-F3; Cathode-F4 + ICT Sham-tDCS: stimulation for 60 seconds on same location + ICT	14 14	8	8 days	1.Attention - CPT ACC 2.Processing speed - CPT RT 3.Inhibitory control – DNST	N/A	8.8 (6-12)	42.86	China

Prillinger (2024)	ASD (ICD-10)	RCT	tDCS: 2 mA for 20 min; Anode-F3; Cathode-Fp2 + ISCT Sham-tDCS: stimulation for 20 seconds on same location + ISCT	11 11	10	2 weeks	Social cognition – ERT	0%	14.1 (12-18)	0	Austria
Ratsapbhayakul (2024)	ASD (DSM-5)	RCT	tDCS: 2 mA for 20 min; Anode-left DLPFC + Cathode-E Sham-tDCS: stimulation for 30 seconds on same location	10 10	10	2 weeks	1.Attention – CTT 2.Inhibitory control – ST 3.Working memory – WMS	40% on psychotropic medications	19 (15–40)	10	Thailand
NCT02998684	ASD (ADOS)	RCT	tDCS: 1.5Am for 30 mins; Anode-F3; Cathode-F4 + SST Sham-tDCS (receive an initial brief dose then automatically decreased to zero) + SST	7 7	14	14 weeks	Social cognition – TASSK	N/A	N/A (14-17)	14.3	U.S.

Abbreviation:

3-min Five-Point Test 3FPT; ACC accuracy; ADOS Autism Diagnosis Observation Schedule; ASD autism spectrum disorder; AQ autism quotient; BTA Brief Test of Attention; CANTAB Cambridge Neuropsychological Test Automated Battery; CTT Color Trail Test; CPT continuous

performance test; CRT cognitive remediation training; DNST Day/Night Stroop Task; DLPFC dorsolateral prefrontal corte; DSM-5 The Diagnostic and Statistical Manual of Mental Disorders, fifth edition; E extracranial; ERT Emotion Recognition Task; FERP Facial Emotion and Recognition and Processing; FERT facial emotional recognition test; ICT inhibitory control training; ICD-10 International Classification of Diseases 10th edition; IPE information processing efficiency; ISCT intrastimulation social cognition training; mFK modified Flanker task; OTS One Touch Stocking; RCT randomized controlled trial; RT reaction time; SST social skill training; ST Stroop Test; TASSK Test of Adolescent Social Skills Knowledge; tDCS Transcranial direct current stimulation; ToM Theory of mind; TOMT Theory of mind test; VF verbal fluency; WMS Wechsler Memory Scale

ToM test* Theory of mind test was calculated by summing the mean scores from ‘Yoni’, ‘Tricky Triangles’ and ‘Reading the Mind in the Voice’ Tasks

WM composite* Working memory composite including Wechsler Memory Scale, 3rd Edition spatial span backward, digit span backward, Spatial n-back accuracy and Letter n-back accuracy

BJP PRE-PROOF

Risk of bias appraisal

The Cochrane Collaboration's tool showed a low risk of bias in randomization sequence in over half of the trials (i.e., seven out of 13). In contrast, the majority of the included studies (i.e., nine of 13) provided no information about allocation concealment (Figure 2). The detection and performance biases were both deemed low in most studies due to their sham-controlled design. Nevertheless, despite the use of sham controls, two trials were assigned a high risk of detection bias because they did not blind the investigators.[13,22] Another two trials were regarded as having unknown risks of detection and performance biases owing to a lack of information on blinding [11,18] (Figure 2). On the other hand, reporting bias was considered low in all studies because of their targeting changes in cognitive functions among ASD patients as their primary outcomes. Regarding attrition bias, most studies were assigned a low risk because of their low dropout rates except for one that reported a dropout rate of over 25% [11].

BJP PRE-PROOF

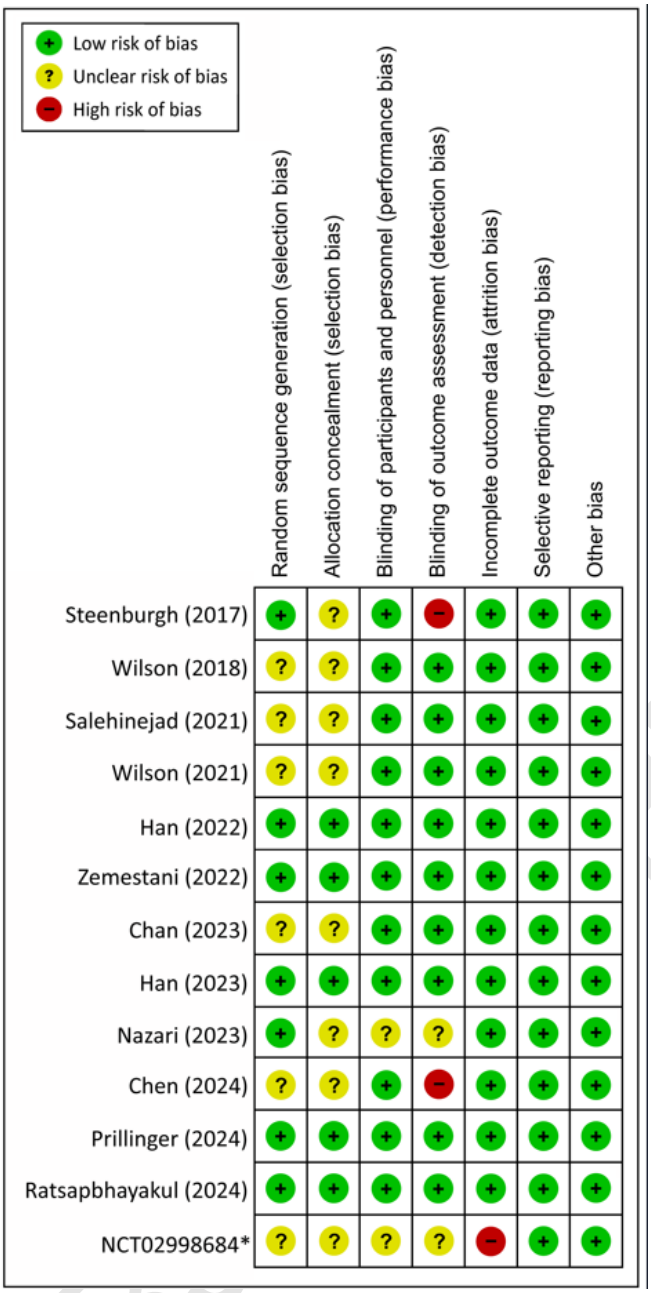


Figure 2. Risk of bias for eligible studies

Primary outcome

The present meta-analysis showed significant improvement in social cognition among ASD patients who received tDCS treatment compared to the sham-controls (SMD=1.14, 95% CI: 0.70–1.58, p<0.01, seven studies, 172 participants) (Figure 3). Although the level of heterogeneity (I^2=40% and p=0.12) was statistically non-significant, the moderate heterogeneity (i.e., I^2 value of 40%) and the limited statistical power of Q-test because of a small number of included studies (i.e., n=7) to detect true between-study variability

mandate a cautious interpretation of the pooled effect size. On the other hand, publication bias based on funnel plot inspection (Supplementary Figure S1) and Egger's regression test (p=0.076) were non-significant across the included studies. In addition, no study had a significant impact on the overall outcomes on leave-one-out sensitivity analysis. Moreover, because of the variety of tools used for social cognition assessment, we conducted sensitivity tests on different types of social cognition tasks (i.e., only facial emotional recognition vs. wider social skills) and found no significant changes in study results. Moreover, an additional sensitivity analysis conducted to exclude the two studies that used self-developed cognitive assessment tools (15, 20) also showed no significant changes in the overall results (SMD=1.17, p<0.01). Subgroup analysis targeting the impact of the number of treatment sessions on study outcomes demonstrated no significant difference between the subgroup of studies adopting a single tDCS session and that conducting multiple sessions (SMD=1.16 vs. 1.14, respectively, p=0.89) (Figure 3). Similarly, no significant difference was noted between the subgroup of studies combining tDCS with cognitive or behavioral training and that using only tDCS without concomitant cognitive or behavioral training (SMD=1.14 vs. 1.15, respectively, p=0.98) (Supplementary Figure S2). Likewise, no significant difference was evident between the subgroup of studies placing anode at the left PFC and that choosing other brain regions (SMD=1.31 vs. 1.05, respectively, p=0.61) (Supplementary Figure S3). Finally, no significant difference in the improvements of social cognition was evident between the subgroup of studies recruiting mainly children and those including mainly adolescents/adults (SMD=1.15 vs. 1.13, respectively, p=0.98) (Supplementary Figure S4). However, given the limited number of available trials (n=7), the results of subgroup analyses were considered underpowered and should be interpreted as exploratory.

BJP PRE-PROOF

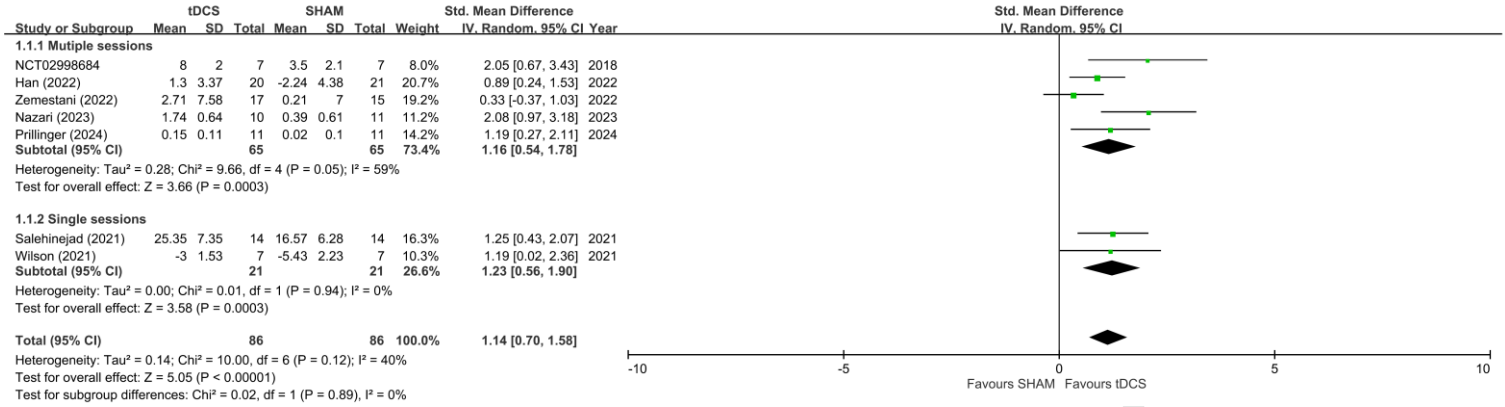


Figure 3. Forest plot of effect size comparing the difference between tDCS and sham groups in social cognition improvement with subgroup comparison between tDCS with single treatment session and tDCS with multiple treatment sessions
CI: confidence interval; Std: standardized; SE: standard error.

Secondary outcomes

Our secondary analyses demonstrated a significantly greater improvement in the processing speed of ASD patients subjected to tDCS compared with their sham controls (SMD=0.50, 95% CI: 0.22–0.77, p<0.01, five studies, 208 participants) (Supplementary Figure S5). In contrast, no significant difference in other secondary outcomes was noted between the tDCS and sham-controlled groups regarding attentional function (Supplementary Figure S6), inhibitory control (Supplementary Figure S7), and working memory (Supplementary Figure S8). Sensitivity analysis demonstrated consistency in all findings with none of the included studies having a significant impact on the secondary outcomes. Besides, heterogeneity (Supplementary Figures S5-S7) as well as asymmetry on funnel plot inspection (Supplementary Figures S8-S11) and Egger's regression test was non-significant for processing speed, attentional function, inhibitory control, and working memory (p=0.95, 0.26, 0.92 and 0.06, respectively). We were unable to analyze the prevalence of adverse reactions due to the limited number of trials providing such information, as most studies did not report any detailed information regardign side effects except three [12,16,19], which reported occasional adverse effects including stimulation site itchiness, burning sensation, and mild tingling. There were no serious adverse events were not reported in our included studies [11-23]. In addition, most side effects were well-tolerated with only one study reporting withdrawal of participation in two children due to intolerance of burning sensation.

BJP PRE-PROOF

Certainty of evidence

Based on the GRADE ranking guidelines, the evidence of primary outcomes focusing on the improvement in social cognition among ASD patients was downgraded to moderate because of the limited number of available studies (n=7) (Supplementary Table S3). The evidence on processing speed was also downgraded to low due to the small number of available studies (n=6) and indirectness of outcomes of interest. Furthermore, the evidence regarding other secondary outcomes including attentional function, inhibitory control, and working memory was downgraded to very low by reason of an even more limited number of available studies (n=3) and indirectness of the outcomes of interest.

Discussion

To our best knowledge, this is the first meta-analysis to investigate the positive effects of tDCS on the cognitive functions of patients diagnosed with ASD. Our results, which were derived from thirteen studies that involved 347 participants, revealed greater improvements in social cognition among those receiving tDCS treatment compared with the sham tDCS controls. In addition, subgroup comparisons focusing on the number of treatment sessions (multiple vs. single), target location (left PFC vs. other brain locations), and treatment strategy (tDCS alone or combined with cognitive or behavioral therapies) showed no significant impact on therapeutic outcomes. Consistent with our primary outcome, our secondary analysis demonstrated significantly greater improvements in processing speed among patients subjected to tDCS treatment compared to their sham controls. However, no significant difference in attentional function, inhibitory control, and working memory was found between the two groups. Besides supporting the findings of previous studies that showed improvements in the overall symptoms of ASD [8,25], our study further demonstrated an association of tDCS with improvements in social cognition and processing speed. Nevertheless, with the availability of only seven trials for our primary outcome, the robustness of evidence derived from the current investigation needs to be verified by further large-scale RCTs.

With regard to the location of anode placement, the left PFC was the most commonly chosen site (i.e., seven out of the 13 studies) as it has been repeatedly shown to be a pivotal area responsible for social cognition in a number of functional near infrared spectroscopy and neuroimaging studies [32-36]. Our results of subgroup analysis that focused on the left PFC compared

BJP PRE-PROOF

with sham controls were also consistent with such a finding. Nevertheless, the limited number of included trials contributed to a reduced power of our subgroup analyses, which should only be considered exploratory. On the other hand, our analysis showed similar improvement in social cognition (ES = 1.19) in one of the 13 included studies that chose the location of anode placement other than PFC (i.e., the right temporoparietal junction, rTPJ) [14]. The finding of that study seems rational, given that rTPJ is also part of an extensive neural network involved in social cognition [37]. Nevertheless, because most of our included studies focused on different brain regions with the largest number (i.e., seven trials) targeting the left PFC, our results regarding the optimal locations of anode and cathode remain conclusive.

Unlike the finding of a previous network meta-analysis that only showed the effectiveness of tDCS with a relatively large number of treatment sessions (i.e., more than five) in improving the behavioral symptoms of ASD [8], the current study demonstrated significantly improved social cognition in those treated with either single or multiple sessions of tDCS compared with the sham controls. Our findings may be attributable to the adoption of assessment tasks that enable more sensitive detection of the improvement in social cognitions compared with behavioral ratings from observation. However, the improvement in social cognition in patients diagnosed with ASD receiving only a single session of tDCS treatment in the current study may not be extrapolated to the behavioral level, which is also a pivotal outcome in the real-world scenario. Moreover, limited availability of trials adopting small numbers of therapeutic sessions in this study and the previous network meta-analysis (i.e., only two trials in both studies) [8] precluded the conduction of meta-regression to elucidate the impact of the number of treatment sessions on therapeutic outcomes. Future large-scale RCTs on the therapeutic use of tDCS targeting both cognitive and behavioral outcomes as well as different number of treatment sessions are warranted to elucidate these issues.

Focusing on other cognitive functions of ASD patients, our secondary investigation revealed a higher processing speed in those receiving tDCS treatment than that in sham controls. In line with our finding, a previous study showed an improvement in verbal fluency associated with the application of tDCS anodal stimulation to the left DLPFC [38]. Given the possible correlation between impaired social communication abilities in ASD patients and their frequently observed decrease in processing speed [39,40], improvement in processing speed may be beneficial to their performance of social tasks. On

the other hand, despite the reported positive effects of tDCS on working memory and attention in a prior meta-analysis recruiting patients with a wider range of neurocognitive disorders [41], our study demonstrated no significant difference in attentional function, inhibitory control, and working memory between those receiving tDCS treatment and their sham controls. The strength of evidence regarding our secondary outcomes was weakened by the availability of only three trials for most outcomes so that the possible effects of tDCS on those cognitive functions in patients with ASD remain to be explored.

With regard to the safety of tDCS, no serious adverse events were noted in our included studies [11-23]. Of the reported mild side effects, most were well-tolerated with only one study documenting withdrawal of participation in two children due to intolerance of burning sensation. However, given the limited sample sizes, short follow-up durations, and potential underreporting of adverse effects in included studies (i.e. only 3 out of 13 studies reported detailed infomration about side effects), the safety of tDCS application in the ASD population requires elucidation from further large-scale investigations.

The present study had several limitations. First, of the 13 trials in total for this meta-analysis, merely seven were available for our primary outcomes. Likewise, our secondary outcomes focusing on some cognitive functions were derived from a small number of trials (e.g., only three for attentional performance). In particular, the results of subgroup analyses were considered underpowered due to the limited number of available trials and should be interpreted as preliminary. Second, the wide variety of tools for social cognition assessment across our included trials may be a source of potential bias; although five out of the 13 studies used standardized social cognition tests [11,17,18,21,23], two adopted self-developed tools [14,19]. Moreover, while some studies assessed a wide range of social skills [11,19,21,23], others solely targeted facial emotional recognition [14,17,18]. Nevertheless, our sensitivity tests showed no significant impact of the type of social cognition tests (i.e., facial emotional recognition vs. other social skills) on the overall outcome. Third, although we attempted to evaluate the influence of targeting different brain regions on the therapeutic effects of tDCS, we could only perform subgroup analysis comparing the effect of stimulating the left PFC with that associated with other brain regions due to a lack of available trials. In addition, meta-regression was not performed because none of our outcomes had more than 10 studies for reliable assessment of the influence of different confounders. Therefore, our findings of non-significant impact of age and number of sessions on the

BJP PRE-PROOF

therapeutic outcomes of tDCS in individuals diagnosed with ASD require more robust data and advanced statistical validation from future studies for verification. Fourth, one study [11] from an unpublished source (ClinicalTrials.gov) showed an unclear risk of bias for allocation, randomization, performance and detection bias, as well as a high risk of reporting bias due to its high dropout rate. Despite the lack of statistically significant impact of that study on our overall results on leave-one-out sensitivity analysis, the effect of that study on pooled estimates remains unclear and requires further elucidation after its being fully published. Finally, the wide range of treatment protocols including the adoption of different follow-up durations and numbers of treatment sessions (i.e., ranging from 1 to 20) as well as an inadequate number of trials for conducting regression analysis precluded a robust elucidation of their confounding influence on study outcomes. These issues need to be adequately addressed by further large-scale clinical investigations before the incorporation of tDCS into the standard treatment protocol for patients diagnosed with ASD.

Conclusions

Our study suggested a potential of tDCS for improving social cognition and processing speed in patients diagnosed with ASD. However, evidence derived from the current study was still not robust enough to establish a standard protocol regarding the optimal location of electrode placement and number of treatment sessions that warrant further large-scale clinical studies for elucidation.

Ethics approval and consent to participate

Not applicable

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests:

The authors declare that there is no conflict of interest.

Funding

This research received no specific grant from any funding agency,

BJP PRE-PROOF

commercial or not-for-profit sectors.

Authors' contributions

PW Huang, SC Liang and CK Sun conceived and designed the study; YS Cheng, and CK Sun contributed to data extraction; CM Cheng and YS Cheng analyzed the data; PW Huang, SC Liang, and CK Su and KC Hung were major contributors to writing the manuscript. All authors contributed sufficiently to this work. All authors read and approved the final manuscript.

Edited by: Dr. Lais Razza

References

1 Hirota, T. & King, B. H. Autism Spectrum Disorder: A Review. *JAMA* **329**, 157-168, doi:10.1001/jama.2022.23661 (2023).

2 Kalvin, C. B., Gladstone, T. R., Jordan, R., Rowley, S., Marsh, C. L., Ibrahim, K. *et al.* Assessing Irritability in Children with Autism Spectrum Disorder Using the Affective Reactivity Index. *Journal of autism and developmental disorders* **51**, 1496-1507, doi:10.1007/s10803-020-04627-9 (2021).

3 Lobato Machado, M. C., Hibner, M. E. R. B., Nogueira, D. B., Rezende, M. M., Bórem, I. L., da Cunha, L. R. *et al.* Irritability in an open-door pediatric psychiatric emergency service in a middle-income country. *Neuropsychiatrie de l'Enfance et de l'Adolescence* **70**, 336-342, doi:https://doi.org/10.1016/j.neurenf.2022.05.007 (2022).

4 Hodgson, R., Biswas, M., Palmer, S., Marshall, D., Rodgers, M., Stewart, L. *et al.* Intensive behavioural interventions based on applied behaviour analysis (ABA) for young children with autism: A cost-effectiveness analysis. *PLoS One* **17**, e0270833, doi:10.1371/journal.pone.0270833 (2022).

5 Brondino, N., Fusar-Poli, L., Rocchetti, M., Provenzani, U., Barale, F. & Politi, P. Complementary and Alternative Therapies for Autism Spectrum Disorder. *Evid Based Complement Alternat Med* **2015**, 258589, doi:10.1155/2015/258589 (2015).

6 Johnson, M. D., Lim, H. H., Netoff, T. I., Connolly, A. T., Johnson, N., Roy, A. *et al.* Neuromodulation for brain disorders: challenges and opportunities. *IEEE transactions on bio-medical engineering* **60**, 610-624, doi:10.1109/tbme.2013.2244890 (2013).

BJP PREPROOF

7 Tracy, D. K. & David, A. S. Clinical neuromodulation in psychiatry: the state of the art or an art in a state? *BJPsych Advances* **21**, 396-404, doi:10.1192/apt.bp.115.014563 (2018).

8 Chen, Y. B., Lin, H. Y., Wang, L. J., Hung, K. C., Brunoni, A. R., Chou, P. H. *et al.* A network meta-analysis of non-invasive brain stimulation interventions for autism spectrum disorder: Evidence from randomized controlled trials. *Neuroscience and biobehavioral reviews* **164**, 105807, doi:10.1016/j.neubiorev.2024.105807 (2024).

9 Uzunova, G., Pallanti, S. & Hollander, E. Excitatory/inhibitory imbalance in autism spectrum disorders: Implications for interventions and therapeutics. *The world journal of biological psychiatry : the official journal of the World Federation of Societies of Biological Psychiatry* **17**, 174-186, doi:10.3109/15622975.2015.1085597 (2016).

10 Luckhardt, C., Boxhoorn, S., Schütz, M., Fann, N. & Freitag, C. M. in *Progress in Brain Research* Vol. 264 (eds Roi Cohen Kadosh, Tino Zaehle, & Kerstin Krauel) 233-257 (Elsevier, 2021).

11 (eds Health Eunice Kennedy Shriver National Institute of Child & Development Human) (2016).

12 Chan, M. M. Y., Choi, C. X. T., Tsoi, T. C. W., Shea, C. K. S., Yiu, K. W. K. & Han, Y. M. Y. Effects of multisession cathodal transcranial direct current stimulation with cognitive training on sociocognitive functioning and brain dynamics in autism: A double-blind, sham-controlled, randomized EEG study. *Brain stimulation* **16**, 1604-1616, doi:10.1016/j.brs.2023.10.012 (2023).

13 Chen, L., Du, B., Li, K., Li, K., Hou, T., Jia, F. *et al.* The effect of tDCS on inhibitory control and its transfer effect on sustained attention in children with autism spectrum disorder: An fNIRS study. *Brain stimulation* **17**, 594-606, doi:10.1016/j.brs.2024.04.019 (2024).

14 Esse Wilson, J., Trumbo, M. & Tesche, C. Transcranial Direct Current Stimulation (tDCS) Improves Empathy and Recognition of Facial Emotions Conveying Threat in Adults with Autism Spectrum Disorder (ASD): A Randomized Controlled Pilot Study. *NeuroRegulation* **8**, 87-95, doi:10.15540/nr.8.2.87 (2021).

15 Esse Wilson, J., Trumbo, M. C., Wilson, J. K. & Tesche, C. D. Transcranial direct current stimulation (tDCS) over right temporoparietal junction (rTPJ) for social cognition and social skills in adults with autism spectrum disorder (ASD). *Journal of neural transmission (Vienna,*

BJP PRE-PROOF

Austria : 1996) **125**, 1857-1866, doi:10.1007/s00702-018-1938-5 (2018).

16 Han, Y. M., Chan, M. M., Shea, C. K., Mo, F. Y., Yiu, K. W., Chung, R. C. *et al.* Effects of prefrontal transcranial direct current stimulation on social functioning in autism spectrum disorder: A randomized clinical trial. *Autism : the international journal of research and practice* **27**, 2465-2482, doi:10.1177/13623613231169547 (2023).

17 Han, Y. M. Y., Chan, M. M. Y., Shea, C. K. S., Lai, O. L., Krishnamurthy, K., Cheung, M. C. *et al.* Neurophysiological and behavioral effects of multisession prefrontal tDCS and concurrent cognitive remediation training in patients with autism spectrum disorder (ASD): A double-blind, randomized controlled fNIRS study. *Brain stimulation* **15**, 414-425, doi:10.1016/j.brs.2022.02.004 (2022).

18 Nazari, G., Mousavi, M. & Sadeghi-Firoozabadi, V. Effectiveness of Anodal Transcranial Direct Current Stimulation of Left Dorsolateral Prefrontal Cortex in Facial Emotion Recognition and Clinical Symptoms of Boys with Autism Spectrum Disorder. *Iranian Journal of Psychiatry and Behavioral Sciences* **17**, doi:10.5812/ijpbs-121995 (2023).

19 Prillinger, K., Amador de Lara, G., Klöbl, M., Lanzenberger, R., Plener, P. L., Poustka, L. *et al.* Multisession tDCS combined with intrastimulation training improves emotion recognition in adolescents with autism spectrum disorder. *Neurotherapeutics : the journal of the American Society for Experimental NeuroTherapeutics* **21**, e00460, doi:10.1016/j.neurot.2024.e00460 (2024).

20 Ratsapbhayakul, T., Keeratitanont, K., Chonprai, C., Auvichayapat, N., Suphakunpinyo, C., Patjanasoontorn, N. *et al.* Anodal transcranial direct-current stimulation and non-verbal intelligence in autism spectrum disorder: A randomized controlled trial. *Developmental medicine and child neurology* **66**, 1244-1254, doi:10.1111/dmcn.15874 (2024).

21 Salehinejad, M. A., Paknia, N., Hosseinpour, A. H., Yavari, F., Vicario, C. M., Nitsche, M. A. *et al.* Contribution of the right temporoparietal junction and ventromedial prefrontal cortex to theory of mind in autism: A randomized, sham-controlled tDCS study. *Autism research : official journal of the International Society for Autism Research* **14**, 1572-1584, doi:10.1002/aur.2538 (2021).

22 van Steenburgh, J. J., Varvaris, M., Schretlen, D. J., Vannorsdall, T. D. &

BJP PRE-PROOF

Gordon, B. Balanced bifrontal transcranial direct current stimulation enhances working memory in adults with high-functioning autism: a sham-controlled crossover study. *Molecular autism* **8**, 40, doi:10.1186/s13229-017-0152-x (2017).

23 Zemestani, M., Hoseinpanahi, O., Salehinejad, M. A. & Nitsche, M. A. The impact of prefrontal transcranial direct current stimulation (tDCS) on theory of mind, emotion regulation and emotional-behavioral functions in children with autism disorder: A randomized, sham-controlled, and parallel-group study. *Autism research : official journal of the International Society for Autism Research* **15**, 1985-2003, doi:10.1002/aur.2803 (2022).

24 Weissman, D. H., Perkins, A. S. & Woldorff, M. G. Cognitive control in social situations: a role for the dorsolateral prefrontal cortex. *NeuroImage* **40**, 955-962, doi:10.1016/j.neuroimage.2007.12.021 (2008).

25 García-González, S., Lugo-Marín, J., Setien-Ramos, I., Gisbert-Gustemps, L., Arteaga-Henríquez, G., Díez-Villoria, E. *et al.* Transcranial direct current stimulation in Autism Spectrum Disorder: A systematic review and meta-analysis. *European neuropsychopharmacology : the journal of the European College of Neuropsychopharmacology* **48**, 89-109, doi:10.1016/j.euroneuro.2021.02.017 (2021).

26 Carter Leno, V., Vitoratou, S., Kent, R., Charman, T., Chandler, S., Jones, C. R. G. *et al.* Exploring the neurocognitive correlates of challenging behaviours in young people with autism spectrum disorder. *Autism : the international journal of research and practice* **23**, 1152-1164, doi:10.1177/1362361318769176 (2018).

27 Pellicano, E., Maybery, M., Durkin, K. & Maley, A. Multiple cognitive capabilities/deficits in children with an autism spectrum disorder: "weak" central coherence and its relationship to theory of mind and executive control. *Development and psychopathology* **18**, 77-98, doi:10.1017/s0954579406060056 (2006).

28 McHugh, M. L. Interrater reliability: the kappa statistic. *Biochem Med (Zagreb)* **22**, 276-282 (2012).

29 Higgins, J. P., Thomas, J., Chandler, J., Cumpston, M., Li, T., Page, M. J. *et al. Cochrane handbook for systematic reviews of interventions*. (John Wiley & Sons, 2019).

BJP PRE-PROOF

30 Guyatt, G. H., Oxman, A. D., Vist, G. E., Kunz, R., Falck-Ytter, Y., Alonso-Coello, P. *et al.* GRADE: an emerging consensus on rating quality of evidence and strength of recommendations. *BMJ* **336**, 924, doi:10.1136/bmj.39489.470347.AD (2008).

31 Moher, D., Shamseer, L., Clarke, M., Ghersi, D., Liberati, A., Petticrew, M. *et al.* Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement. *Syst Rev* **4**, 1 (2015).

32 Van Overwalle, F. Social cognition and the brain: a meta-analysis. *Hum Brain Mapp* **30**, 829-858, doi:10.1002/hbm.20547 (2009).

33 Mundy, P. Annotation: the neural basis of social impairments in autism: the role of the dorsal medial-frontal cortex and anterior cingulate system. *J Child Psychol Psychiatry* **44**, 793-809, doi:10.1111/1469-7610.00165 (2003).

34 Xu, P., Peng, S., Luo, Y. J. & Gong, G. Facial expression recognition: A meta-analytic review of theoretical models and neuroimaging evidence. *Neuroscience and biobehavioral reviews* **127**, 820-836, doi:10.1016/j.neubiorev.2021.05.023 (2021).

35 Carrington, S. J. & Bailey, A. J. Are there theory of mind regions in the brain? A review of the neuroimaging literature. *Hum Brain Mapp* **30**, 2313-2335, doi:10.1002/hbm.20671 (2009).

36 Barreto, C., Curtin, A., Topoglu, Y., Day-Watkins, J., Garvin, B., Foster, G. *et al.* Prefrontal Cortex Responses to Social Video Stimuli in Young Children with and without Autism Spectrum Disorder. *Brain Sci* **14**, doi:10.3390/brainsci14050503 (2024).

37 Kennedy, D. P. & Adolphs, R. The social brain in psychiatric and neurological disorders. *Trends Cogn Sci* **16**, 559-572, doi:10.1016/j.tics.2012.09.006 (2012).

38 Schneider, H. D. & Hopp, J. P. The use of the Bilingual Aphasia Test for assessment and transcranial direct current stimulation to modulate language acquisition in minimally verbal children with autism. *Clinical linguistics & phonetics* **25**, 640-654, doi:10.3109/02699206.2011.570852 (2011).

39 Johnston, K., Murray, K., Spain, D., Walker, I. & Russell, A. Executive Function: Cognition and Behaviour in Adults with Autism Spectrum Disorders (ASD). *Journal of autism and developmental disorders* **49**, 4181-4192, doi:10.1007/s10803-019-04133-7 (2019).

BJP PREPROOF

40 Haigh, S. M., Walsh, J. A., Mazefsky, C. A., Minshew, N. J. & Eack, S. M. Processing Speed is Impaired in Adults with Autism Spectrum Disorder, and Relates to Social Communication Abilities. *Journal of autism and developmental disorders* **48**, 2653-2662, doi:10.1007/s10803-018-3515-z (2018).

41 Begemann, M. J., Brand, B. A., Ćurčić-Blake, B., Aleman, A. & Sommer, I. E. Efficacy of non-invasive brain stimulation on cognitive functioning in brain disorders: a meta-analysis. *Psychological medicine* **50**, 2465-2486, doi:10.1017/s0033291720003670 (2020).

BJP PRE-PROOF

Supplementary material

Supplementary Table S1. Applied keywords and the search results from each database

Database	Keywords	Filter	Date (yyyy/mm/dd)	Result
PubMed	("Transcranial Direct Current Stimulation"[MeSH Terms] OR "Transcranial Direct Current Stimulation"[Title/Abstract] OR "tDCS"[Title/Abstract]) AND ("Autism Spectrum Disorder"[MeSH Terms] OR "Autistic Disorder"[MeSH Terms] OR "Autism"[Title/Abstract] OR "Autism Spectrum Disorder"[Title/Abstract] OR "ASD"[Title/Abstract] OR "Autistic disorder"[Title/Abstract] OR "Asperger syndrome"[Title/Abstract] OR "Pervasive Developmental Disorder"[Title/Abstract]) Filter: Randomized Controlled Trial [Publication Type]	RCT	2025/02/20	22
Embase	('transcranial direct current stimulation'/exp [Emtree term] OR 'transcranial direct current stimulation':ti,ab OR 'tDCS':ti,ab) AND	RCT	2025/02/20	244

BJP PRE-PROOF

	('autism'/exp [Emtree term] OR 'autism spectrum disorder':ti,ab OR 'autism':ti,ab OR 'ASD':ti,ab OR 'autistic disorder':ti,ab OR 'Asperger syndrome':ti,ab OR 'pervasive developmental disorder':ti,ab) AND [randomized controlled trial]/lim			
Cochrane CENTRAL	#1 MeSH descriptor: [Transcranial Direct Current Stimulation] explode all trees #2 ("Transcranial Direct Current Stimulation" OR "tDCS"):ti,ab,kw #3 #1 OR #2 #4 MeSH descriptor: [Autism Spectrum Disorder] explode all trees #5 MeSH descriptor: [Autistic Disorder] explode all trees #6 ("Autism Spectrum Disorder" OR "Autism" OR "ASD" OR "Autistic disorder" OR "Asperger syndrome" OR "Pervasive Developmental Disorder"):ti,ab,kw #7 #4 OR #5 OR #6 #8 #3 AND #7 Filter: Trials	Trials	2025/02/20	112

BJP PRE-PROOF

ScienceDirect	Title, abstract, or author-specified keywords: ("Transcranial Direct Current Stimulation" OR "tDCS") AND ("Autism Spectrum Disorder" OR "Autism" OR "ASD") Filter: Research articles Note: ScienceDirect does not support MeSH/Emtree controlled vocabulary or advanced field-specific Boolean syntax. The search was conducted using the platform's native title/abstract/keyword fields.	Research articles	2025/02/20	34
Clinicaltrials.gov	Condition or disease: Autism Spectrum Disorder OR Autism OR ASD Intervention/treatment: Transcranial Direct Current Stimulation OR tDCS Note: ClinicalTrials.gov was searched using the structured search interface fields (Condition/Disease and Intervention/Treatment) provided by the registry platform.	Nil	2025/02/20	24

Abbreviations: NA, not applied; RCT, randomized controlled trial

BJP PRE-PROOF

Supplementary Table S2 Reasons for study exclusion

Reason	Number of excluded studies	References
Not outcome for cognitive functions	6	[1-6]
Lack of data	1	[7]
No tDCS intervention	1	[8]
Not randomized controlled trials	4	[9-12]

tDCS transcranial direct-current stimulation

BJP PRE-PROOF

References

1. Amatachaya, A., et al., *Effect of anodal transcranial direct current stimulation on autism: a randomized double-blind crossover trial.* Behav Neurol, 2014. **2014**: p. 173073.
2. Hadoush, H., et al., *Therapeutic Effects of Bilateral Anodal Transcranial Direct Current Stimulation on Prefrontal and Motor Cortical Areas in Children with Autism Spectrum Disorders: A Pilot Study.* Autism Res, 2020. **13**(5): p. 828-836.
3. Qiu, J., et al., *Transcranial Direct Current Stimulation (tDCS) over the Left Dorsal Lateral Prefrontal Cortex in Children with Autism Spectrum Disorder (ASD).* Neural Plast, 2021. **2021**: p. 6627507.
4. Auvichayapat, P., et al., *Long-term effects of transcranial direct current stimulation in the treatment of autism spectrum disorder: A randomized controlled trial.* Dev Med Child Neurol, 2023. **65**(6): p. 811-820.
5. Sun, C., et al., *Effect of Transcranial Direct Current Stimulation on the Mismatch Negativity Features of Deviated Stimuli in Children With*

Autism Spectrum Disorder. Front Neurosci, 2022. **16**: p. 721987.

6. Wang, Y., et al., *High definition transcranial direct current stimulation of the Cz improves social dysfunction in children with autism spectrum disorder: A randomized, sham, controlled study.* Autism Res, 2023. **16**(10): p. 2035-2048.
7. Gómez, L., et al., *Non-Invasive Brain Stimulation for Children with Autism Spectrum Disorders: A Short-Term Outcome Study.* Behav Sci (Basel), 2017. **7**(3).
8. Cheung, T., et al., *Effects of transcranial pulse stimulation on autism spectrum disorder: a double-blind, randomized, sham-controlled trial.* Brain Commun, 2023. **5**(5): p. fcad226.
9. Rothärmel, M., et al., *A Prospective Open-Label Pilot Study of Transcranial Direct Current Stimulation in High-Functioning Autistic Patients with a Dysexecutive Syndrome.* Neuropsychobiology, 2019. **78**(4): p. 189-199.
10. D'Urso, G., et al., *Transcranial direct current stimulation for autistic disorder.* Biol Psychiatry, 2014. **76**(5): p. e5-6.
11. Schneider, H.D. and J.P. Hopp, *The use of the Bilingual Aphasia Test for assessment and transcranial direct current stimulation to modulate language acquisition in minimally verbal children with autism.* Clin Linguist Phon, 2011. **25**(6-7): p. 640-54.
12. Costanzo, F., et al., *Evidence for reading improvement following tDCS treatment in children and adolescents with Dyslexia.* Restor Neurol Neurosci, 2016. **34**(2): p. 215-26.

BJP PREPROOF

Supplementary Table S3. Grading of Recommendations Assessments, Development and Evaluation (GRADE) assessment of the strength of evidence for standard weighted meta-analysis

Outcome	Design	Risk of bias	Indirectness	Inconsistency	Imprecision	Publication bias	Grade Quality
Social cognition	RCT x 7	No Serious	No indirectness	No serious inconsistency	Serious imprecision	Undetected	⊕⊕⊕O[4]
Processing speed	RCT x 5	No Serious	Serious indirectness	No serious inconsistency	Serious imprecision	Undetected	⊕⊕OO[2,4]
Attentional function	RCT x 5	No Serious	Serious indirectness	No serious inconsistency	Serious imprecision	Undetected	⊕OOO[2,4*]
Working memory	RCT x 3	No Serious	Serious indirectness	No serious inconsistency	Serious imprecision	Undetected	⊕OOO[2,4*]
Inhibitory control	RCT x 4	No Serious	Serious indirectness	No serious inconsistency	Serious imprecision	Undetected	⊕OOO[2,4*]

*Risk of bias was estimated using Cochrane risk of bias, studies were classified as having low risk of bias if none of the domains above was rated as high risk of bias and three or less were rated as unclear risk; moderate if one was rated as high risk of bias or none was rated as high risk of bias but four or more were rated as unclear risk, and all other cases were assumed to pertain to high risk of bias.

Down-graded due to: [1] risk of bias, [2] indirectness, [3.] Inconsistency, [4.] Imprecision, [5.] publication bias

[4*] Down-graded two levels due to very low sample sizes

Abbreviation: ASD autism spectrum disorder, RRB Repetitive and restricted behaviors

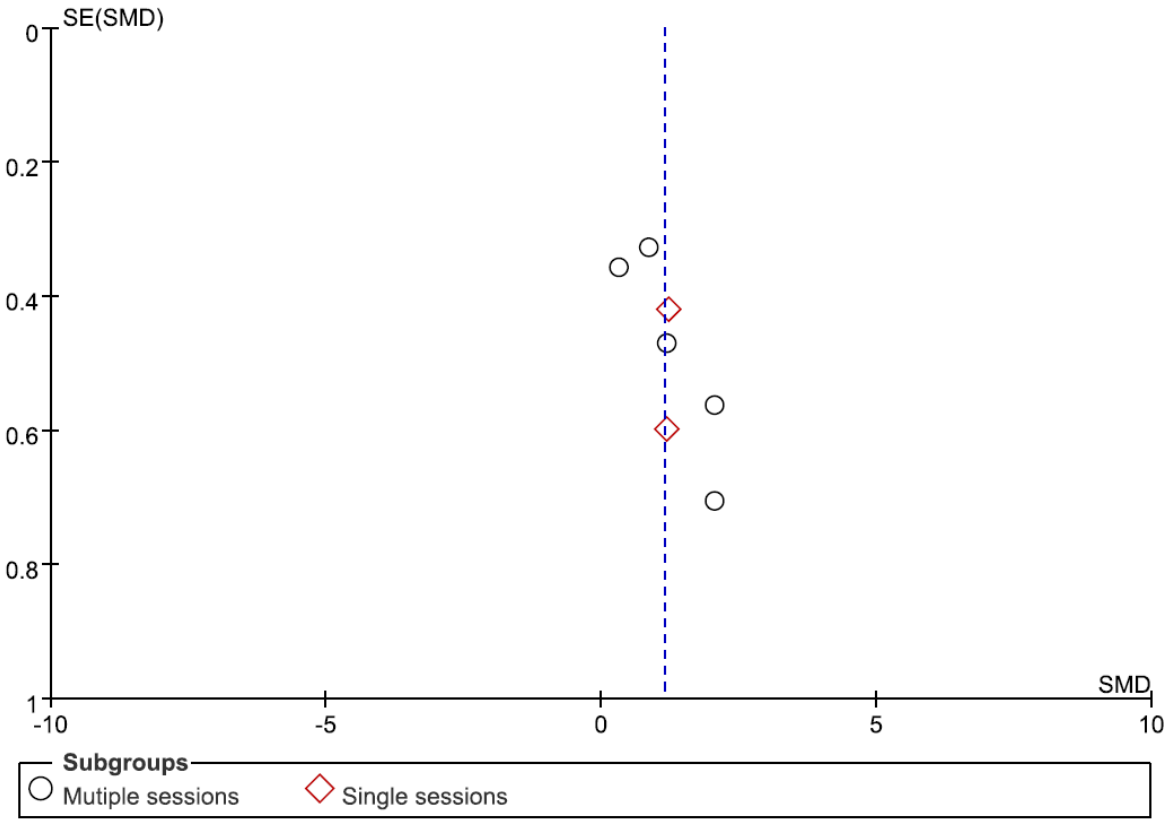
GRADE Working Group grades of evidence:

BJP PRE-PROOF

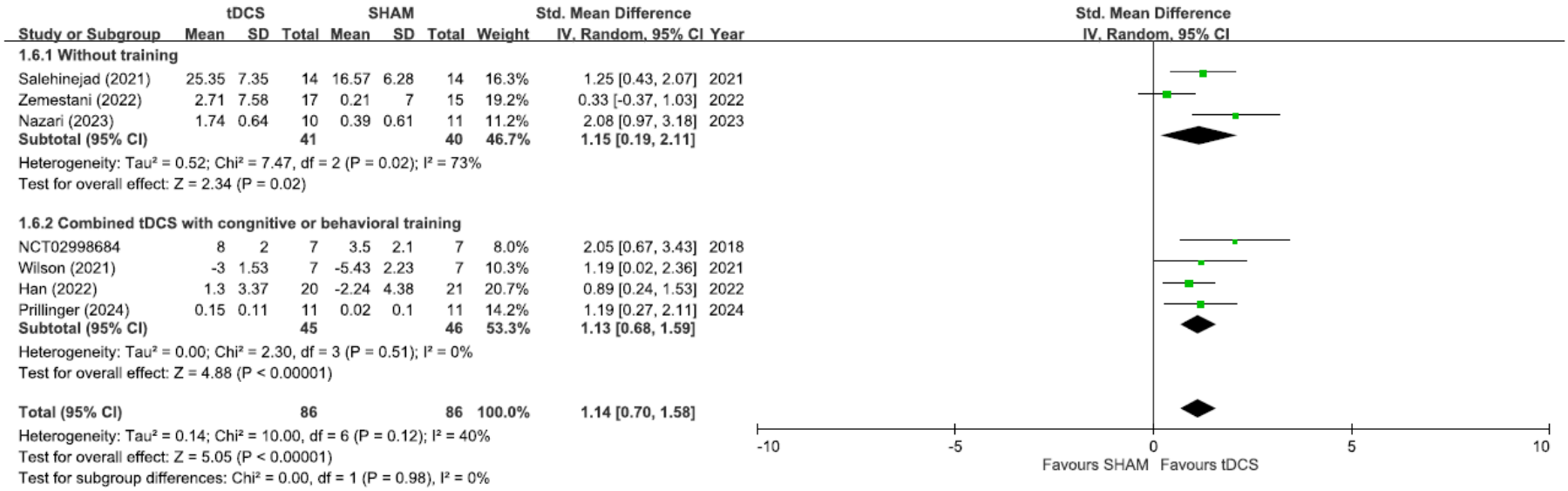
-**High certainty**: We are very confident that the true effect lies close to that of the estimate of the effect
-**Moderate certainty**: We are moderately confident in the effect estimate: The true effect is likely to be close to the estimate of the effect, but there is a possibility that it is substantially different.
-**Low certainty**: Our confidence in the effect estimate is limited: The true effect may be substantially different from the estimate of the effect.
-**Very low certainty**: We have very little confidence in the effect estimate: The true effect is likely to be substantially different from the estimate of effect.

BJP PRE-PROOF

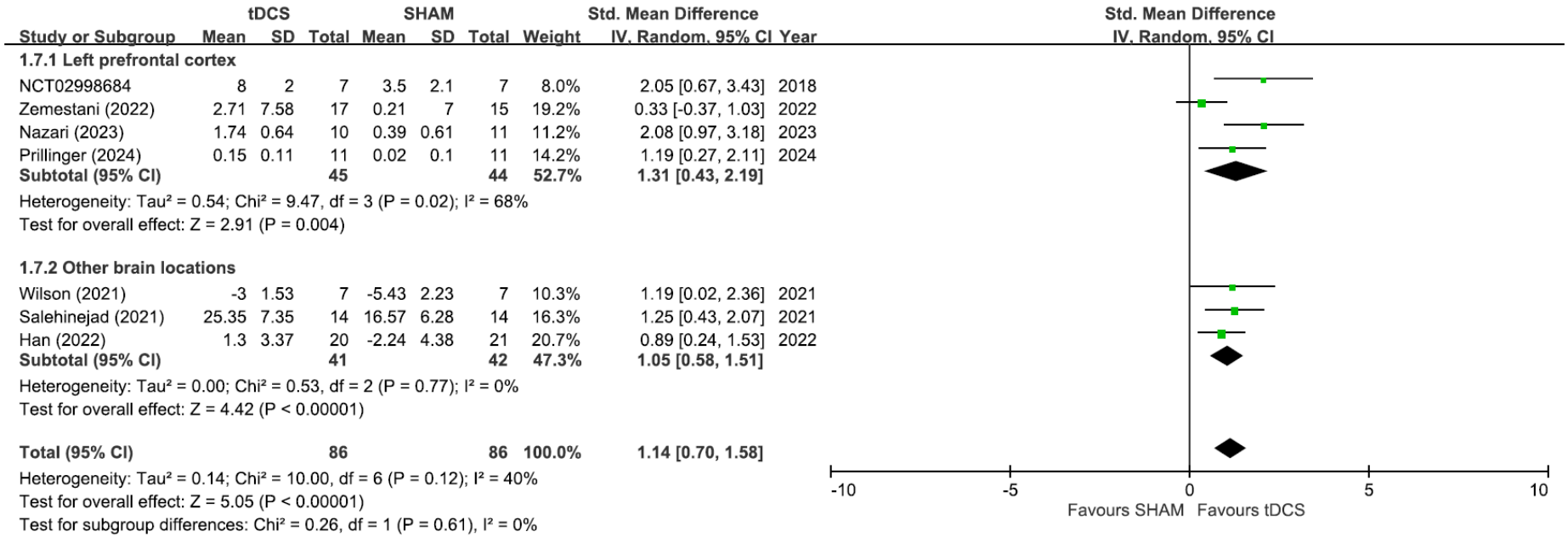
Supplementary Figure S1. Funnel plot – social cognition



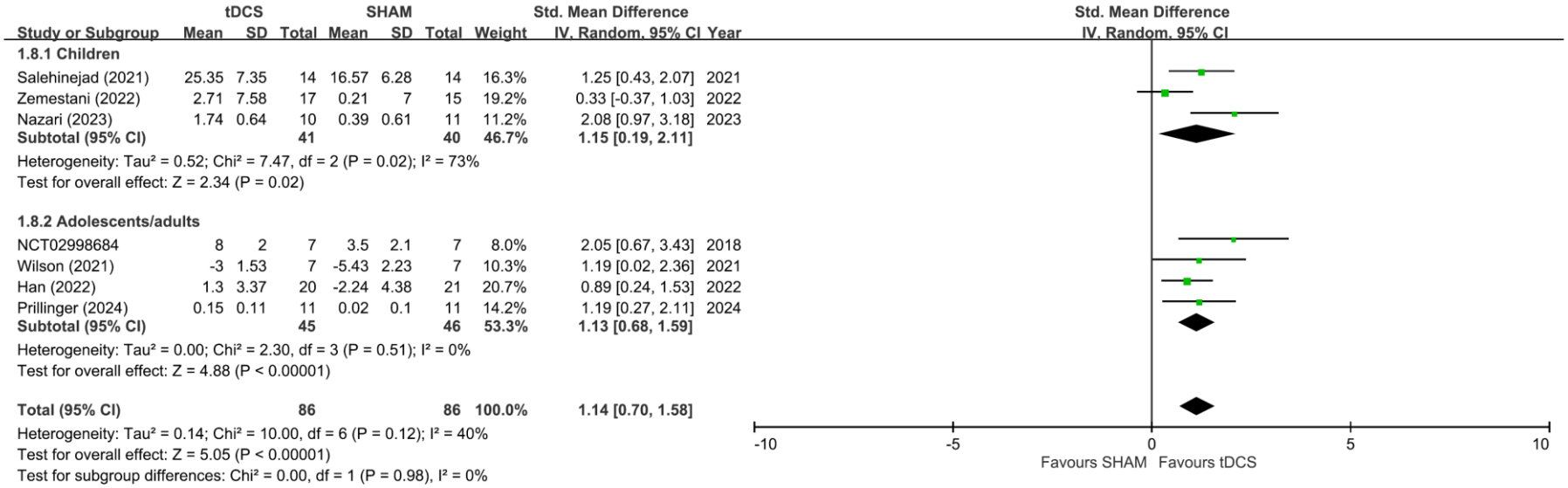
Supplementary Figure S2. Forest plot of effect size for comparing the difference between tDCS and sham groups for the social cognition with subgroups comparison between tDCS alone and tDCS combined with cognitive or behavioral training



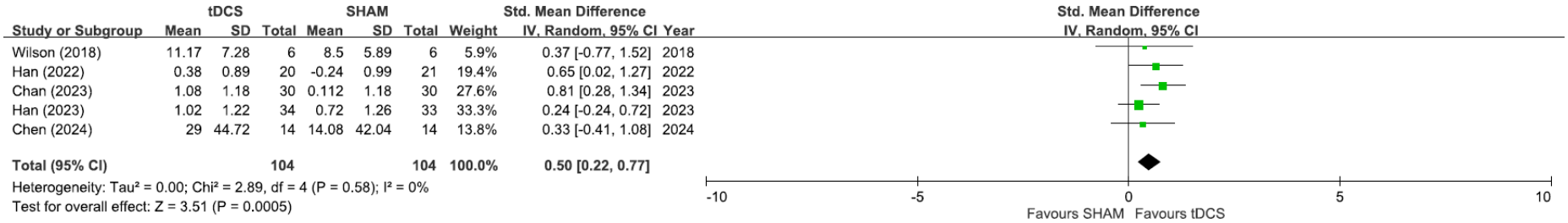
Supplementary Figure S3. Forest plot of effect size for comparing the difference between tDCS and sham groups for the social cognition with subgroups comparison between tDCS placing anode at left prefrontal cortex and tDCS placing anode at other locations of brain.



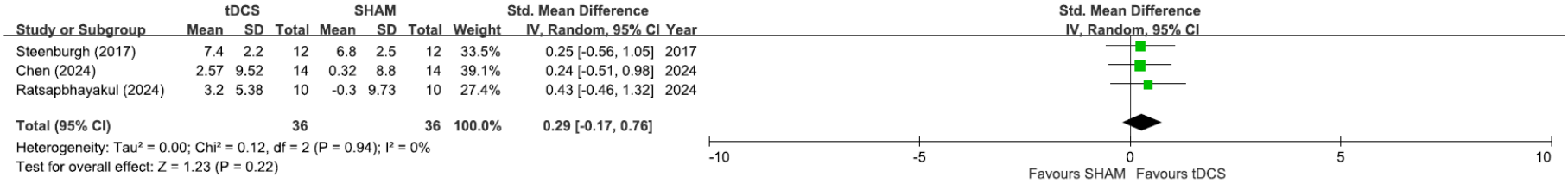
Supplementary Figure S4. Forest plot of effect size for comparing the difference between tDCS and sham groups for the social cognition with subgroups comparison between studies including mainly children and those including mainly adolescents/adults.



Supplementary Figure S5. Forest plot of effect size for comparing the difference between tDCS and sham groups for processing speed



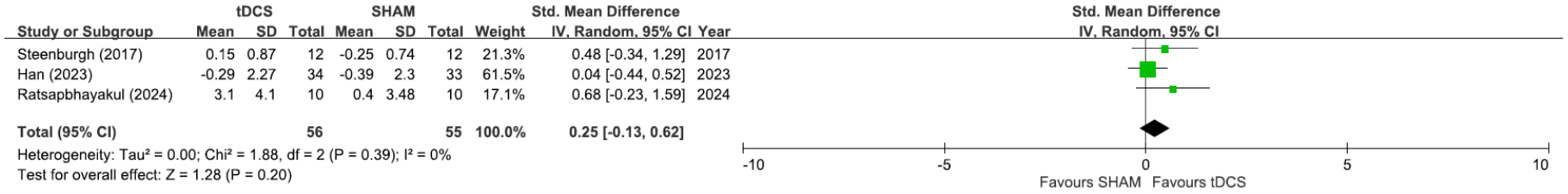
Supplementary Figure S6. Forest plot of effect size for comparing the difference between tDCS and sham groups for attentional function



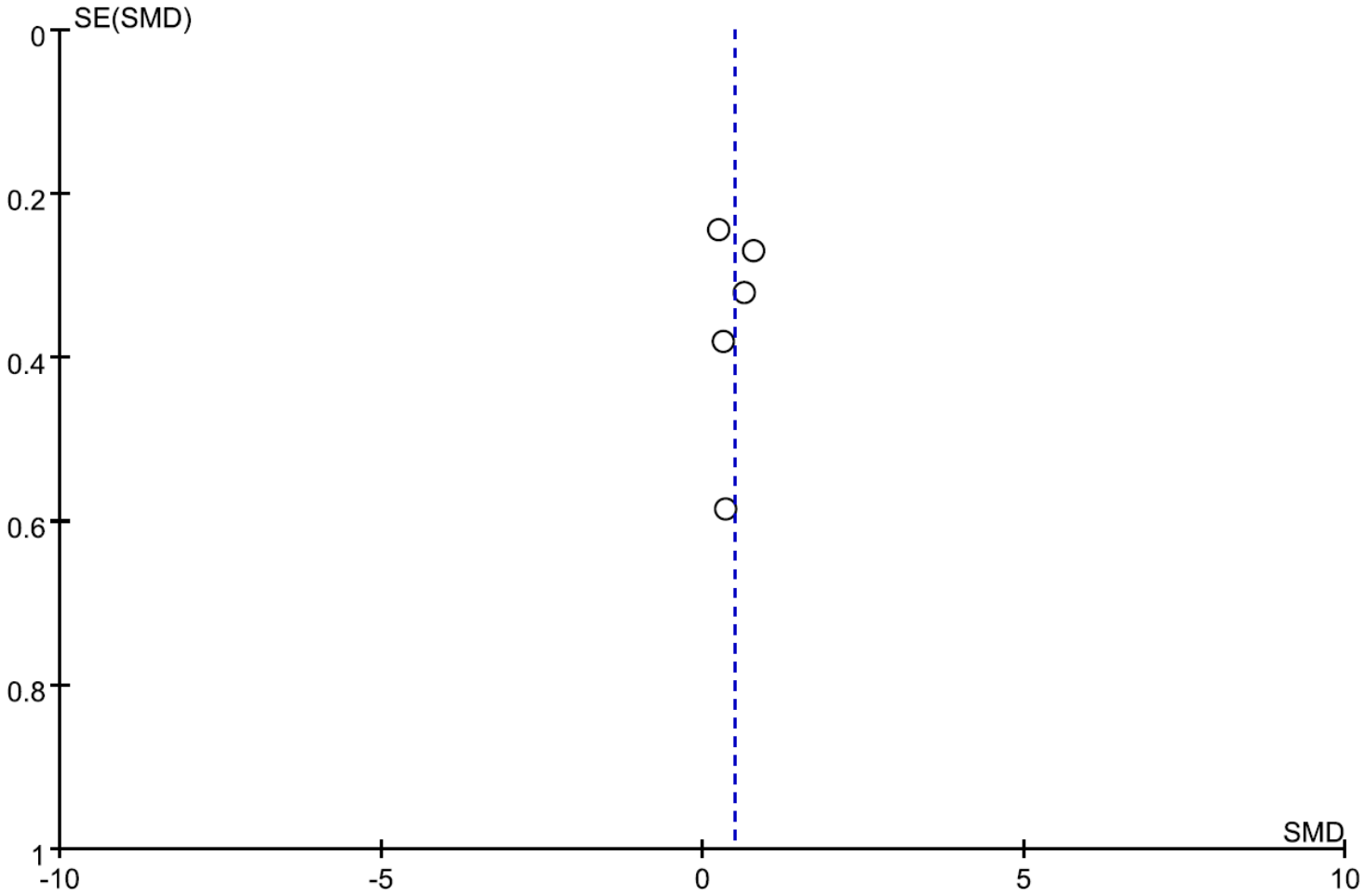
Supplementary Figure S7. Forest plot of effect size for comparing the difference between tDCS and sham groups for inhibitory control



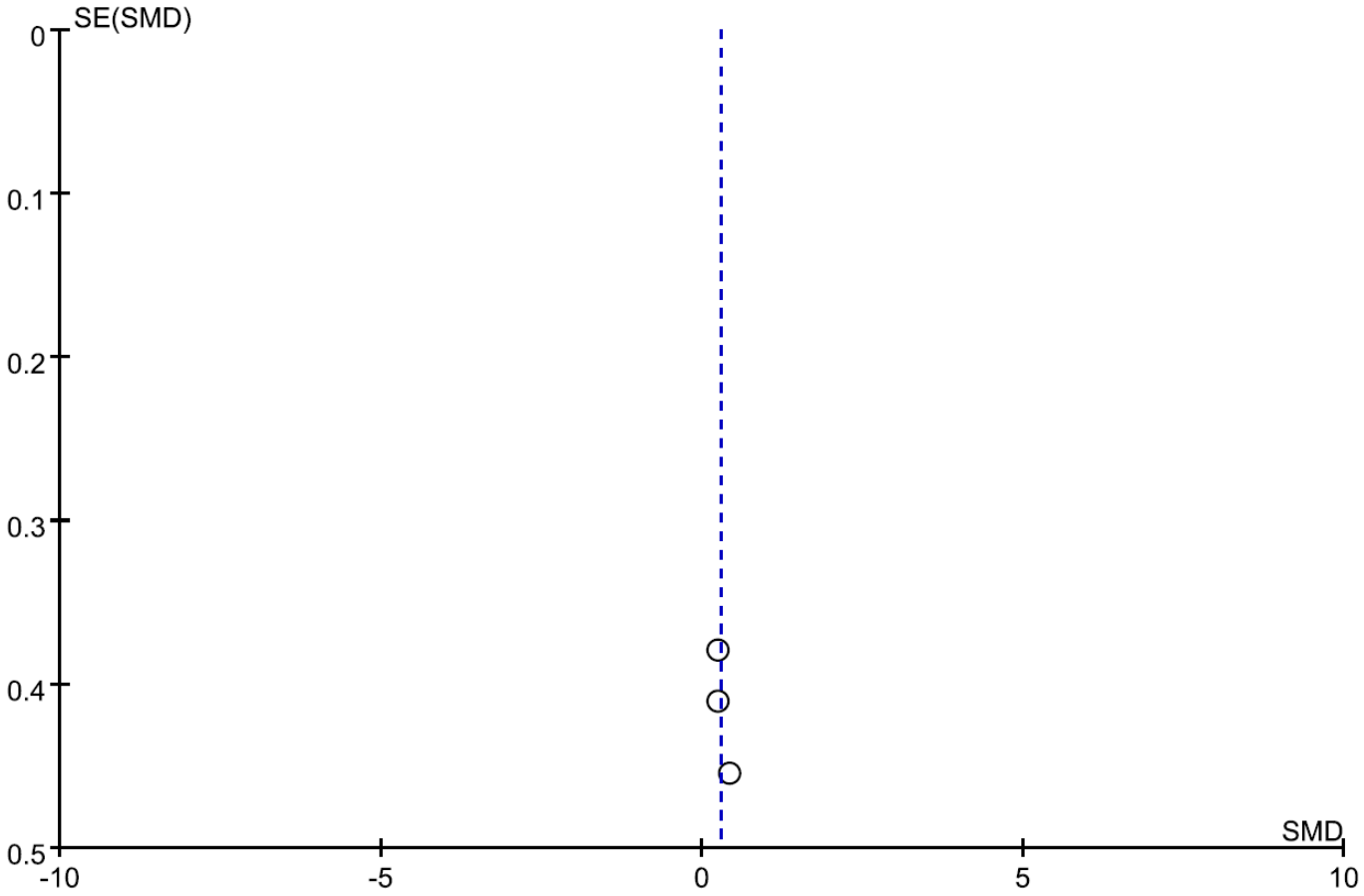
Supplementary Figure S8. Forest plot of effect size for comparing the difference between tDCS and sham groups for working memory



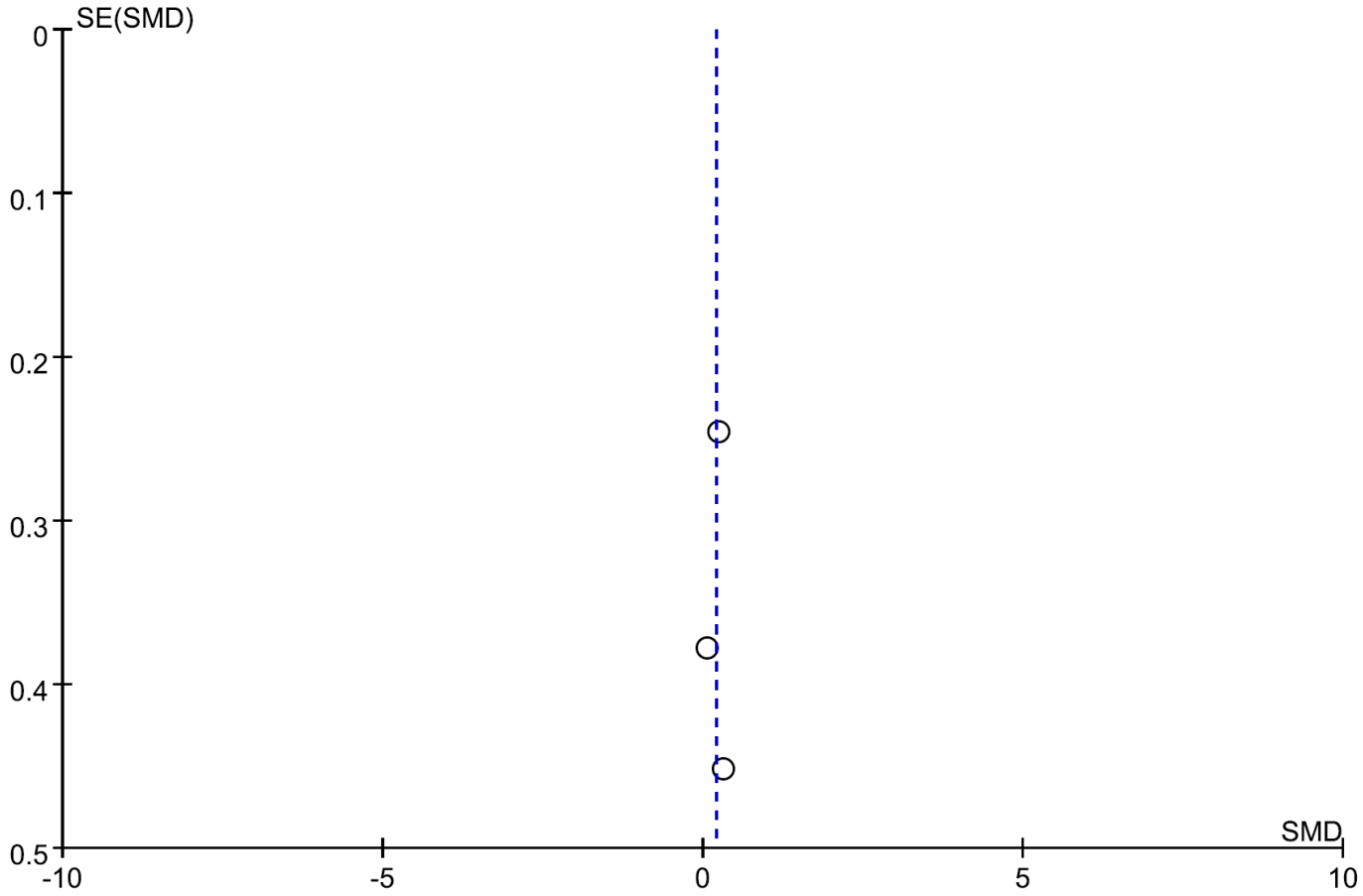
Supplementary Figure S9. Funnel plot – processing speed



Supplementary Figure S10. Funnel plot – attentional function



Supplementary Figure S11. Funnel plot – inhibitory control



Supplementary Figure S12. Funnel plot – working memory

