Transcranial direct current stimulation (tDCS) and sporting performance: A systematic review and meta-analysis of tDCS effects on physical endurance, muscular strength, and visuomotor skills

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Abstract

Transcranial direct current stimulation (tDCS) is a non-invasive brain stimulation technique that has been linked with a range of physiological and cognitive enhancements relevant to sporting performance. As a number of positive and null findings have been reported in the literature, the present meta-analysis sought to synthesise results across endurance, strength and visuomotor skill domains to investigate if tDCS improves any aspect of sporting performance. Online database searches in August 2020 identified 43 full-text studies which examined the acute effects of tDCS compared to sham/control conditions on physical endurance, muscular strength, and visuomotor skills in healthy adults. Meta-analysis indicated a small overall effect favouring tDCS stimulation over sham/control (standardized mean difference (SMD) =0.25, CI95%[0.14;0.36]). Effects on strength (SMD=0.31, CI95%[0.10;0.51]) and visuomotor (SMD=0.29, CI95%[0.00;0.57]) tasks were larger than endurance performance (SMD=0.18, CI95%[0.00;0.37]). Meta-regressions indicated effect sizes were not related to stimulation parameters , but other factors such as genetics, gender, and experience may modulate tDCS Effects. The results suggest tDCS has the potential to be used as an ergogenic aid in conjunction with a specified training regime.

Keywords; ergogenic; neurodoping; neuroenhancement; sport; performance

1. Introduction

Successful sporting performance is dependent on an athlete’s ability to consistently perform at their peak. In the increasingly competitive sporting environment, there is heightened pressure to mitigate factors that limit physical and cognitive performance for accelerated results (Davis, 2013), which has prompted athletes to seek an advantage through ergogenic aids and neuroenhancement (Banissy and Muggleton, 2013). Transcranial direct currents timulation (tDCS) is a form of brain stimulation that has been linked with a range of performance improvements in cognitive function (Banissy and Muggleton, 2013), exercise endurance (Cogiamanian et al, 2007) and muscular strength (Hazime et al, 2017). tDCS has a number of practical advantages over other methods of brain stimulation, such as transcranial magnetic stimulation (TMS), due to the cost, safety, and portability of stimulation devices (Davis, 2013; Bikson et al, 2016). The attraction for athletes is clear and tDCS has moved outside of controlled laboratories to the wider community, with stimulation kits being endorsed by athletes as a quick alternative to improve performance (Mansfield, 2016; Edwards, 2017). Yet, the accessibility of tDCS, rather than robust research findings, may have driven adoption of the technique.

Transcranial stimulation paradigms have grown in popularity due to their potential to provide a non-invasive method of modulating cognition and behaviour by increasing (anodal) or reducing (cathodal) cortical excitability (Stagg and Nitsche, 2011). tDCS has been explored in a variety of clinical conditions (Bennabi and Haffen, 2018; Inoue and Taneda, 2019; Lima and Fregni, 2008), but as well as treating clinical Conditions and impairments, tDCS has also been touted as a method of performance enhancement or ‘neurodoping’ (Davis, 2013). The inhibitory effects of stimulation have also found to be promising. For instance, TMS can suppress cortical activity to reduce the amplitude of tremors, resulting in improved motor control (Kang and Cauraugh, 2017). Alternatively, cathodal-tDCS also has the potential for performance enhancement effects via a reduction in declarative processing, in favour of more procedural processing (McKinley et al., 2016).

If reliable, emerging tDCS effects could signal considerable benefits in sport and related fields (e.g., the military or aviation) through improvements in physiology, cognition, and motor learning. For instance, single session tDCS may mitigate against the negative effects of cognitive fatigue on endurance performance (Reardon, 2016), improve cognitive performance through exciting higher brain areas via cross-activation and modulating neuroplasticity (Stagg and Nitsche, 2011), and improve motor performance or accelerate motor learning via excitation of motor cortex when used in conjunction with a pre-established training regime (von Rein et al., 2015). However, the ethical and practical applications of cognitive enhancement should be considered alongside these observed benefits, as outlined by Davis (2017).

tDCS induces a weak but constant electrical current from a cathode (negative electrode) to an anode (positive electrode) which modulates the activity of cortical neurons near the electrode, and diffuse locations nearby (Stagg and Nitsche,2011). tDCS stimulation is proposed to facilitate neural activity through reducing the negative polarisation across the neural membrane at the anode or inhibit activity through hyperpolarisation at the cathode. The polarity-dependent effects of tDCS may, however, be over-simplistic as a result of a non-linear dose-response (i.e. possible anodal inhibition or cathodal excitation) (Esmaeilpour et al., 2018; Jamil et al., 2016). Most tDCS devices use rubber electrodes, between 25-35cm^2 in size, applied to the scalp over a targeted brain region determined by the intended effect. These electrodes provide current at a range of 1-2mA, typically activated for 10-. 20min Side effects are minimal with a mild tingling sensation being the most commonly reported (70.6%) and insomnia (0.98%) being the worst (Poreisz et al., 2007).

The motor cortex (M1) is typically a target for stimulation due to its role in sustaining neural drive within motor neurons, thereby improving performance by compensating for central fatigue (Papale and Hooks., 2018).
Derosière et al. (2014) showed increased ipsilateral M1 activation during a unilateral handgrip task when the force was above 30% maximum voluntary contraction (MVC), indicating a cross-activation effect. The cross-activation/ facilitation hypothesis is supported by evidence from Hendy et al. (2014) who report application of anodal tDCS to ipsilateral M1 resulted in an increase in maximal strength and cross-activation. The results support a hypothetical model proposed by Lang et al. (2004), that tDCS can increase the synaptic effectiveness of corticospinal cells though cross-activation making them last longer than the duration of

polarisation. Studies have also shown stimulation of motor regions can influence motor learning retention and corticospinal excitability in participants for up to an hour after delivery (Nitsche and Paulus, 2007). These findings suggest tDCS may be effective for enhancing the learning and/or execution of fine motor skills required in elite sporting endeavours and related domains (e.g., surgery – see Cox et al., 2020). Consequently, stimulation of M1 for either strength or motor skill performance appears promising, which partially explains its popularity as a target for sport performance studies (Frazer et al, 2017).

Application of tDCS is not limited to the motor cortex, an alternative target for stimulation is the dorsolateral prefrontal cortex (DLPFC). The prefrontal cortex is theorised to play a role in fatigue-related feedback, and decreased prefrontal cortical oxygenation results in Performance failure in a time to exhaustion (TTE) cycling task (Thomas and Stephane,2007). Therefore, stimulating the area could increase neuronal activity to reinforce muscle feedback by strengthening cognitive ability to delay exercise termination (Grandperrin etal., 2020). This effect has been explored by Latteri et al. (2018) who found activating the DLPFC increased exercise tolerance. The benefits of PFC stimulation may also be derived from enhanced working memory activity and its role in cognitive control (Boudewyn, Scangos, Ranganath and Carter, 2020).

While direct brain stimulation has been linked with a range of physiological and cognitive benefits, inconsistent results and differential effects as a result of widely varying stimulation protocols poses a challenge for interpreting overall efficacy (Dedoncker, Brunoni, Baekenand Vanderhasselt, 2016). The duration of stimulation has been reported as a key determinant of the prolongation of tDCS effects on performance outcomes. Nitsche and Paulus (2000) report a significant elevation of motor-cortical excitability up to 40% after 10minutes compared to a stimulus duration of 5min (0.6 mA). Similarly, Williams et al. (2013) found a group receiving stimulation throughout a submaximal isolated isometric (TTF) test had significantly improved endurance, whereas the group receiving stimulation for 50% of the TTF test did not show this improvement.

Moreover, the exact positioning of the surface electrodes influences the cascading effects of stimulation in the brain, which in turn influences performance outcomes. Many studies fail to report a justification or clear hypothesis as to why they target their selected brain region. A further challenge is that individual differences in brain localisation introduce additional Noise effects (Datta et al, 2012). Most tDCS studies report following the international 10:20 EEG system (Klem, Lüders and Jasper, 1999) however this method is limited to a few primary cortices (Woods et al., 2016). Angius et al. (2016) explored these parameters by comparing cephalic and extracephalic tDCS montages, finding that only the extracephalic montage yielded improvements to isometric knee extensors. Differences in the two montages above may be due to alternate current directions– cathodal stimulation negates the positive effects of anodal stimulation by decreasing excitability in the brain area (Angius et al., 2015). tDCS effects are further complicated by the finding that stimulation effects interact with the resting membrane potential of targeted neurons, such that the initial state of the performer modulates the result (Benwell et al., 2015). A pertinent issue given the potentially varying states of arousal or fatigue likely to be present in athletes. Consequently, it may be important to explore how stimulation parameters moderate the performance enhancing effects of tDCS.

tDCS in the field of sport and exercise sciences has begun to be examined in previous systematic reviews which have reported some positive (Alix-Fages et al., 2019) and some inconclusive (Machado et al., 2019; Holgado, et al., 2019) evidence for strength and endurance improvements. These reviews, however, were limited in identifying only a small number of studies (Lattari et al., 2018; Machado et al., 2019) or in grouping together studies that explored disparate exercise dimensions (Holgado, et al., 2019), which may have obscured important differences between physiological domains. These reviews also focused exclusively on exercise dimensions, ignoring the potential of tDCS for enhancing fine motor performance and motor learning (Nitsche et al., 2003). Motor skill execution is a fundamental part of sporting expertise and a number of recent studies have begun to examine the benefits of tDCS in this area (Zhu et al., 2014; Harris et al., 2019). Hence, we aimed to provide an up-to-date analysis of the state of the literature that 1) differentiated studies along physiological dimensions and performed sub-analyses, 2) provided a more comprehensive overview of performance enhancing effects by examining physical endurance, muscular strength, and visuomotor skills, and 3) examined the moderating effects of stimulation parameters.

This review is motivated by the growing interest and non-regulated use of tDCS devices in sport and non-sport contexts (Angius, Hopker, and Mauger, 2017). The current available evidence on the effectiveness of tDCS on sport performance is conflicting and unclear. Additionally, the multifaceted nature of sporting performance, requiring a range of physical and mental attributes, means that findings from a range of cognitive and physiological effects need to be synthesised. The findings will be useful in directing the future direction of tDCS techniques in performance enhancement contexts and ascertaining the prospects of tailoring training using neuromodulation based on individual difference variance and for identifying the domains in which benefits are most likely to be achieved.

In reviewing this literature, we sought to address the following research questions:

i. Is there reliable evidence for performance enhancing effects in tasks relevant to sport?

ii. What is the quality of research in this field?

iii. Are there differing effects of direct current stimulation for strength, endurance, and visuomotor tasks?

iv. Are there moderating effects of stimulation parameters?

2. Methods

2.1 Protocol

A systematic review and meta-analysis was conducted following the guidelines of the Cochrane group (O'Connor, Green and Higgins, 2008) which required reporting of the review procedure, selection of eligible articles based on inclusion/exclusion criteria, quality assessment, data extraction, and a meta-analytic review of the results. This review also adheres to the PRISMA guidelines for systematic reviews (Moher et al, 2009). The PRISMA checklist (and other supplementary files) are available from the Open Science Framework(https://osf.io/8whtv/).

2.2 Literature search

The literature search was carried out using four online databases: PubMed/MedLine; Scopus; Cochrane (Embase); and SportDiscus. These databases were selected as they contain the majority of sports science and neuroscience journals. The databases were searched from inception until 28th August 2020, the date the final search was conducted. The search string contained the following MeSH terms and Boolean operators: “Transcranial direct current stimulation” OR “tDCS” AND “Sports performance”. In addition, further searches were performed by the first author using forward and backward citation chasing, based on the reference list of the collected studies, and email correspondence with relevant researchers to retrieve studies that were not covered by the databases with the search terms.

*2.3 Eligibility Criteri*a

Inclusion criteria:

Studies were included following the **PICOS** inclusion criteria;

Participants – healthy adult men and women (18-85 years) with no history of orthopaedic or psychiatric illness. The healthy participants serve to control for the high variability in tDCS outcomes (Rudroff, Workman, Fietsam and Kamholz,2020).

Intervention – measured the acute effects of tDCS administration prior to or during endurance, strength or visuomotor tasks. Studies were included if they applied tDCS either before or during the test period.

Comparators – use of Sham-tDCS as a placebo or a control condition with no intervention (some studies included both comparators, in which case, the control condition was used). The use of blinded sham or control conditions reduces bias

Outcomes – physical endurance (e.g. time to task failure tasks), strength (e.g. maximal knee extensors), or visuomotor sports tasks (e.g. golf putting) were analysed.

Study design – Randomised control trials that used either a cross-over or parallel study design. Randomisation minimises bias to determine clearly if there is a relationship between the intervention (tDCS) and the outcome (sport performance).

Exclusion criteria:

Studies were excluded if they: (i) were not published in English; (ii) used clinical participants or did not provide adequate information on participant health; (iii) were not published as full text records or did not comply with the purpose of the analysis; (iv) did not use endurance, strength or visuomotor tasks. Endurance tasks were considered any tasks in which the participants were required to perform until they could no longer continue with the requisite level of effort. Strength tasks were considered any that explored maximal strength capabilities and visuomotor tasks were considered those in which participants performed a sport specific procedure that involved the visual guidance of a goal-directed movement (e.g.,throwing a ball). Hence studies relating to other visuomotor tasks such as surgery were not included.

2.4 Study Selection

The primary search returned 3579 potential publications. Thirty-five additional studies were found through other searches (reference list forward citation chasing or correspondence). All records were collated using Mendeley software to remove duplicate articles and screen titles efficiently. Fifty-four duplicate items were found and removed, and as a result of screening by title and abstract 3349 articles were removed. The remaining 176 full-text articles were assessed for eligibility and 43 studies were included in the qualitative analysis of which 41where analysed quantitatively. Figure 1 summarises the PRISMA study selection process (Moher et al, 2009).

2.5 Data Extraction, Analysis, and Synthesis

Studies were read twice by the researcher to enhance familiarity with the data before extracting and synthesising the findings (Cuijpers, 2016; Petticrew & Roberts, 2008). Each study was coded using a predefined Excel spreadsheet for the following variables (based on recommendations in Popay et al., 2006): sample size and participant characteristics (gender and age), characteristics of the tDCS stimulation protocol (including electrode location, size, stimulation intensity and duration), exercise protocol and number of sessions the study required, and performance outcome (improvement/no improvement). To minimise the risk of bias in extraction and increase confidence in the method, the data was extracted twice. In studies that had multiple outcome measures the first assessment following tDCS application was reported as the post-stimulation result. Any ambiguities were discussed amongst researchers. Where data was missing, the authors of the original papers were contacted, or values were extracted using the Webplot digitizer Version 4.4 (https://apps.automeris.io/wpd/).

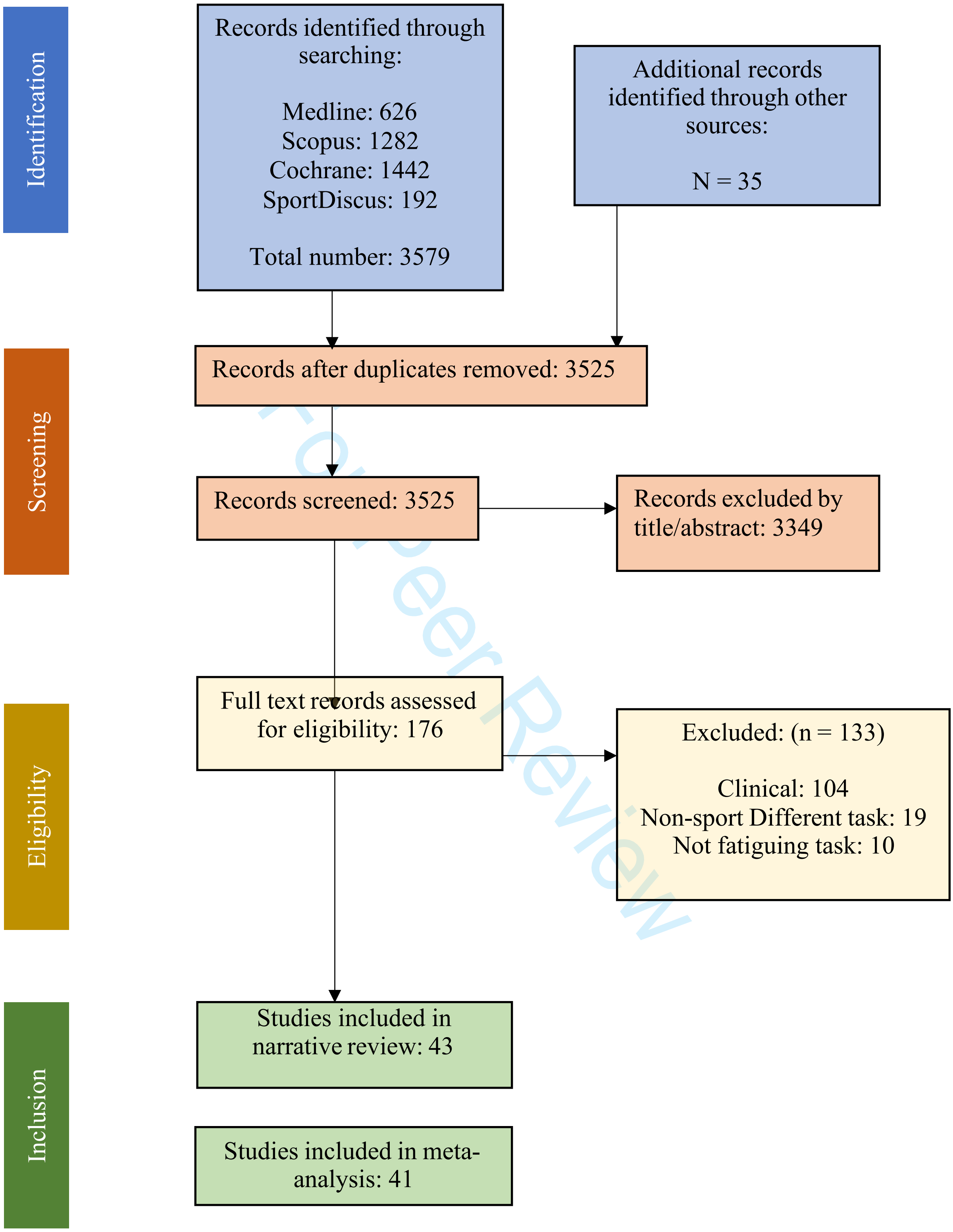


Figure 1. PRISMA study flow diagram illustrating the identification and selection of relevant studies

2.6 Assessment of Methodological Quality

A quality assessment of the included articles was performed using the Physiotherapy Evidence Database (PEDro) scale (http://www.pedro.org.au) (see supplementary materials: https://osf.io/k65c3/). The scale consists of multiple items which assesses internal validity and the statistical replicability of results graded on a 'yes'/'no' basis in which 'yes' corresponds to a point. Points are awarded if the criteria are explicitly satisfied, with a cut offscore of ≥6/10 for a study of high methodological quality (see Figure 2).

As per Cochrane guidelines, further risk of bias was assessed in each included article using Review Manager software (RevMan 5.3.5; Cochrane Collaboration, Oxford, UK). The criteria comprised; (a) assessments for sequence generation (randomization), (b) allocation sequence concealment, (c) blinding of participants and researchers, (d) incomplete outcome data, (e) selective outcome reporting and (f) other bias. Each of these items were deemed as low risk of bias (+), high risk of bias (-) or unclear risk of bias (?) (see supplementary materials: https://osf.io/yv4sz/).

2.7 Statistical Analysis

To calculate pooled effect sizes, outcome measures were identified for endurance, strength and visuomotor tasks and a separate meta-analysis was conducted for each of the three study domains. Studies within each domain (endurance, strength and visuomotor) used varying outcome measures, but as our aim was to examine the broader effect in each domain a quantitative synthesis was deemed to be appropriate (Borenstein et al, 2009).

Meta-analysis and statistical analyses were performed using Jamovi R 'MAJOR' module (version 1.2.27) and R with the 'metafor' package (version 4.1.1). In each article the size of the intervention effect was calculated according to the difference in performance outcome between the experimental and control conditions. The intervention effect was measured by calculating the standardised mean difference (SMD) of the continuous data within the studies at a 95% confidence level ($CI_{95\%}$). SMD and $CI_{95\%}$ were weighted by the inverse variance method. As the studies drew from a different populations and used a range of tasks, a random effects model was chosen to better account for any statistical heterogeneity and dependencies within studies (Borenstein et al., 2009). The use of a random effects model assumes that there is not only one true effect size, but rather a distribution of true effect sizes from which we aim to estimate the mean (Cuijpers, 2016). Cochrane guidelines report standardised mean difference (SDM) using Cohens Effect Size to represent small (≤0.2), moderate (≤0.5) large (≤0.8) and very large (>0.8) effect sizes. Heterogeneity between studies was assessed using τ^2 and I^2 which can be seen in the forest plot (Figure 5). The I^2 statistic was used to assess the degree of heterogeneity, with values from ≤50% indicating low heterogeneity, 50–75% moderate heterogeneity and > 75% high level of heterogeneity. A number of decisions go into

into selecting studies for a meta-analysis and some may have a disproportionate effect on the overall effect estimate. In order to understand whether any studies or subgroups of studies had a disproportionate effect on the overall estimate we first performed a 'leave-one-out' analysis and re-ran the meta-analyses (for each subgroup) leaving out one study in each analysis. The results indicated that the omission of no single study heavily biased the overall effect. SMD estimates ranged from 0.16 to 0.22 for endurance, from 0.27 to 0.34 for strength, and from 0.25 to 0.37 for visuomotor. The full leave-one-out analysis tables are available in the supplementary materials(https://osf.io/nkaej/).

Additionally, we performed a combinatorial meta-analysis which runs a series of Subset analyses based on all possible combinations of the included studies (i.e. 2^k-1). The Graphical Display of Study Heterogeneity (GOSH) plots are presented in Figure 6 and display the range of possible effect sizes for all possible combinations of studies plotted against the I^2 for each combination (Olkin, Dahabreh, & Trikalinos, 2012).

Mixed-effects model meta-regression was used to assess how stimulation parameter choices may have moderated the results. The following variables were meta-regressed: current intensity (mA); current density (mA/cm^2); and stimulation duration (minutes). As stimulation intensity in the included studies fell entirely into two values (1.5mA and 2.0mA) it was treated as a categorical predictor. Borenstein et al. (2011) recommend that 10 studies are required for reliable meta-regressions, so the results for the visuomotor subgroup (k=5) should be interpreted with caution.

3. Results

3.1 Overview

The article identification process produced 3525 unique records for screening, which resulted in 176 full-text records that were assessed for eligibility (Figure 1). The use of a clinical group was the most frequent reason for excluding studies in the screening phase (e.g. Parkinson's disease or strokes). After exclusions, 43 studies were included, of which 41 were included in the final quantitative synthesis (meta-analysis). Two papers were outliers presenting large effect sizes (Cogiamaniam et al. 2007; Rocha et al. 2020).

3.2 Study Characteristics and Quality Assessment

An overview of the study characteristics (sample size, tDCS protocol and study outcomes) is presented in Table 1. The sample consisted of 43 articles published between 2013 and 2020, with most of the work being published recently (86% since 2015). Of the included studies, 20examined strength-based tasks, 17 examined endurance tasks, and 6 examined visuomotor tasks. There were 790 participants in total across the studies; 546 were male and 244 were female. The studies had participants with a range of levels of physical fitness and experience varying from novice to elite athletes. The mean sample size per study was N =15± 6.4 (ranging from 9 to 73 participants), and participant age ranged from 16 to 68. The most common outcome variables were strength, muscular endurance, and accuracy. All the studies were randomised, 35 were crossover and 8 were parallel which satisfied blinding requirements. Studies used a sham and/or control comparator group, of which 4studies included both conditions. The participant populations of the studies varied for level of experience (novices to elite athletes) and fitness (recreationally active to trained).

With regards to tDCS procedures, all of the included studies applied tDCS before exercise using a 1.5- 2mA current for a duration of 10 - 20min (17.2 ± 5.2). Electrode sizes ranged between 12 to 35cm^2. 26 studies (60.5%) reported the effects of tDCS as a standalone -including Huang et al. (2019) who used a Halo device - but 14 studies (32.6%) looked exclusively at anodal-tDCS (a-tDCS) while 1 study (2.3%) looked at cathodal-tDCS (c-tDCS) and 2 studies (4.6%) explored the effects of High-Definition tDCS (HD-tDCS).

The assessment of study quality indicated that the overall quality of the studies was high, with a mean score on the PEDro scale of 7.6 ± 1.0 points out of 10. Additionally, the Cochrane quality assessment showed the studies had low risk of bias overall with a very small percentage of studies presenting high risk for blinding procedures (22%). All studies adequately prescribed to the sham/control methods.

Sample			***tDCS Protocol***				***Study Information***	
Author	**N (M/F)**	**Experience**	**Anode (A)/Cathode (C) Brain Target**	**Current Intensity (mA)**	**Current Density (mA/cm^2)**	**Duration (minutes)**	**Exercise Task**	**Outcome**
Abdelmoula et al. (2016)	11 (8M/3F)	None participated in regular strength training programs	A – left motor cortex (M1) C – Right shoulder	1.5	0.043	10	35% maximal torque of elbow flexors to failure	Improvement - increased endurance time
Alix-Fages et al. (2020)	14 (M)	recreational resistance trained >2 years	A – DLPC C – Right orbitofrontal cortex (opposite for C-tDCS)	2.0	N/S	15	75% 1RM resistance training to failure	Improvement - A-tDCS increased training volume and reduced RPE values
Angius et al. (2017)	12 (8M/4F)	Regular aerobic training >3hrs per week	A – bilateral M1 C – above ipsilateral shoulders (opposite for A-tDCS)	2.0	0.057	10	Cycling TTF test	Improvement - A-tDCS improves endurance performance
Angius et al. (2016)	9 (M)	Recreationally active	A – left M1 C – dorsolateral right prefrontal cortex	2.0	0.057	10	MIVC knee extensors	Improvement – TTE increased
Angius et al. (2019)	12 (9M/3F)	Recreationally active	A – F3 C – Fp2	2.0	0.170	30	Cycling TTF test at 70% of W_{peak}	Improvement – TTE was longer and reduced RPE
Angius et al. (2015)	9 (M)	Recreationally active	A – M1 C – DLPC	2.0	0.057	10	Cycling TTF test	No improvement between conditions
Baldari et al. (2018)	13 (M)	Recreational endurance runners	A – M1 C – Occipital protuberance	2.0	0.057	20	Incremental ramp exercise test	No improvement
Barwood et al. (2016)	8 (M)	≥150-minutes of exercise per week	A - T3 C - Fp2	2.0	0.440	20	Cycling TTF at 75% peak power	No improvement
Bryne et al. (2019)	23 (11M/12F)	Moderately active	A – F3 C – Fp2	2.0	0.057	20	25% MIVC Isometric contraction of leg extensors	No improvement
Ciccone et al. (2019)	20 (10M/10F)	Recreationally active (2-4 times a week)	A – T3 C – Fp2	2.0	N/A	20	Maximal knee extensors	No improvement
Codella et al. (2020)	17 (M)	Physically active	A – M1 C – right DLPFC (C1 to C6)	2.0	0.080	20	Maximal graded exercise running test	Improvement- 12% increaase in endurance running capacity
Cogiamanian et al. (2007)	24 (10M/14F)	Physically active	A – right M1 C – Right shoulder	1.5	0.043	10	35% MVC fatiguing isometric contraction	Improvement – A-tDCS improves muscle endurance
Flood et al. (2017)	12 (M)	Physically active	C3/C4 and 5cm around (HD-tDCS)	2.0	0.057	20	TTF task at 30% MIVC elbow flexors	No improvement

Frazer at al. (2016)	14 (6M/8F)	Physically healthy	A – Left M1 C – right contralateral supra orbital area	2	0.080	20	MIVC wrist flexor	Improvement – A-tDCS increases muscular strength
Frazer et al. (2017)	13 (8M/5F)	Physically healthy	A – right M1 C – contralateral supra orbital area	2	0.080	20	80% 1RM elbow flexion	Improvement – a-tDCS increased muscular strength (12%)
Harris et al. (2019)	73 (37M/36F)	Novice (no golf experience)	Left supraorbital area (10:20 EEG system)	1.5	N/S	5	Golf putting task	No improvement to performance or visual attention
Hazime et al. (2017)	8 (F)	Regional and national competitors	A – C3/C4 C– ipsilateral supraorbital region	2	0.057	20	MIVC shoulder external and internal rotator muscles	Improvement – increased maximal contractions of internal and external shoulder rotators
Hendy et al. (2014)	10 (5M/5F)	Physically active	A – right M1 C – Fp1	2.0	0.080	20	IRM Unilateral strength training of wrist extensor muscles	No Improvement
Holgado et al. (2019)	36 (M)	Trained cyclists	A – DLPFC C – contralateral shoulder	2.0	N/S	20	Cycling TTF test	No improvement
Huang et al. (2019)	9 (M)	Moderately active	Halo sport (vertex of head)	2.0	0.083	20	Repeated sprint cycling task	Improvement – application of tDCS enhanced sprint cycling ability
Kamali et al. (2019)	17 (9M/8F)	Experienced shooters	A– CB2 C – Left DLPFC	2.0	0.057	20	Pistol Shooting task	Improvement – increased shooting scores
Kamali et al. (2019a)	12 (M)	Experienced bodybuilders	C – Right shoulder Second channel: A- T3 C- left shoulder)	2.0	0.057	13	TTF 1RM at 30% of their own weight	Improvement – muscular strength, endurance and electrical activity improved
Kan et al. (2013)	15 (M)	Physically active	A – M1 C – contralateral shoulder	2.0	0.083	10	TTF 30% MVC elbow flexors	No improvement
Kenville et al. (2020)	25 (13M/12F)	Physically active	A – M1 Cathode – Cerebellum	2.0	0.020	20	MVIC barbell squats	Improvement - significant increase using CB-tDCS
Lampropoulou et al. (2013)	12 (4M/8F)	Physically active	A/C – left M1 A/C – Left medial deltoid	1.5	0.061	10	MVIC elbow flexion	No improvement
Lattari et al. (2017)	11 (F)	Physically active	A – left DLPFC C – right OFC	2.0	0.057	20	10RM elbow flexion	Improvement – a-tDCS repetitions were higher
Lattari et al. (2018)	11 (F)	Physically active	A – left DLPFC C – right OFC	2.0	0.057	20	Cycling TTF task at peak power	Improvement - a-tDCS increased exercise tolerance
Mizuguchi et al. (2018)	24 (M)	Novice	A – right cerebellum C – right buccinator muscle	2.0	0.080	20	Dart throws	Improvement – dependent on individual task performance
Montenegro et al. (2016)	14 (M)	Strength training experience >6 months	A – left M1 C – Fp2	2.0	0.057	20	MSEX of concentric isokinetic muscle	No improvement

Muthalib et al. (2013)	15(M)	Physically active	A – right M1 C – right shoulder	2.0	0.083	20	30% of MVIC elbow flexors	No improvement
Okano et al. (2015)	10 (M)	Experienced cyclists	A – T3 C – Fp2	2.0	0.057	20	Maximal incremental cycling test	Improvement – RPE were lower
Oki et al. (2016)	13 (5M/8F)	No participation in resistance exercise training in the prior 3 months	A – M1 C – left supraorbital region	1.5	0.043	20	Time to task elbow flexions	Improvement -
Park et al. (2019)	10(M)	Trained endurance runners	A – CZ C – C5/C6	1.98	N/S	20	TTF constant load test at 80% of V0$_2$ max	No improvement (although increased TTF)
Parma et al. (2020)	48 (24M/24F)	Novice	A – left M1 C- right M1	1.5	0.06	20	Golf putting task	No improvement (although influence depending on individual task performance observed)
Radel et al. (2017)	22 (13M/9F)	Physically active	A – AF4/C2 C – 40mm around A	2	N/S	10	TTF at 30% MVC elbow flexor muscles	No improvement
Rocha et al. (2020)	60 (M)	Skilled vs unskilled	A – right DLPFC C – left supraorbital	2	0.04	20	Pistol shooting task	Improvement – improved shot accuracy
Sales et al. (2016)	19 (M)	Trained	A – T3 C – Fp2	2	0.057	20	MVIC leg extension	Improvement – increased total work
Vargas et al. (2018)	20 (F)	Regional and national competitors	A – C3/C4 C – ipsilateral supraorbital	2	0.057	20	MVIC of knee extensors	Improvement – increased MVIC
Vitor-costa et al. (2015)	11(M)	Physically active	A – Cz C – occipital protuberance	2	0.056	13	TTF cycling task at 80% peak power	Improvement – increased endurance time
Washabaugh et al. (2016)	22 (15M/7F)	Physically active	A/C – M1	2	0.057	12	MVIC knee extensor and flexor torques	Improvement – increased knee extension torques
Williams et al. (2013)	18 (9M/9F)	Physically active	A – M1 C – Fp2	1.5	0.043	20	TTF elbow flexors 20% of maximum strength	Improvement – TTF extended
Wrightson et al. (2020)	20 (11M/9F)	Physically active	A – right VL C – left deltoid	1 / 2	0.029 / 0.057	10	TTF 20% MVIC knee extensor	No improvement
Zhu et al. (2014)	27 (M/F)	Novice	A – FP2 C – F3	1.5	N/S	15-20	Golf putting task	Improvement – enhanced putting performance in training and test phase (multi-tasking)

Table 1: Studies exploring the effects of tDCS on sport performance. Participant characteristics, tDCS protocol and performance outcome of included studies. *Note: F/M= Female/Male, N/A= Not addressed, M1= motor cortex, MVC= maximal voluntary contraction, F3= Frontal region 3, Fp2= frontal-parietal region 2, C3/C4= Central region 3/4, T3= Temporal region 3, CZ= somato-sensory cortex, C5/6= Central region 5/6, AF4= frontal region*

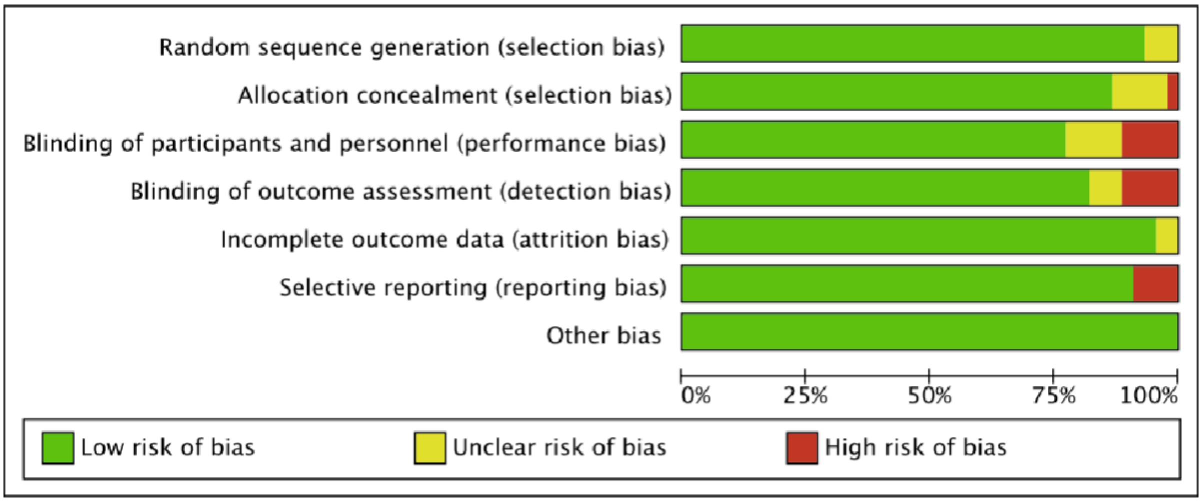


Figure 2. Risk of bias graph showing a review of the authors' judgments acrosseach risk criterion presented as percentages for all included studies.346

3.3 Quantitative Analysis

3.3.1 Overall Effect. Across all studies examined, the meta-analysis indicated that participants showed a small improvement in performance after application of tDCS (SMD=0.25, CI95% [0.13,0.36], $p<.001$). This difference does not appear to be due to differences in study heterogeneity ($I^2=0\%$, $\tau^2=0$, $p=.57$), and reasonably good levels of symmetry can be seen in the funnel plot (Figure 3).

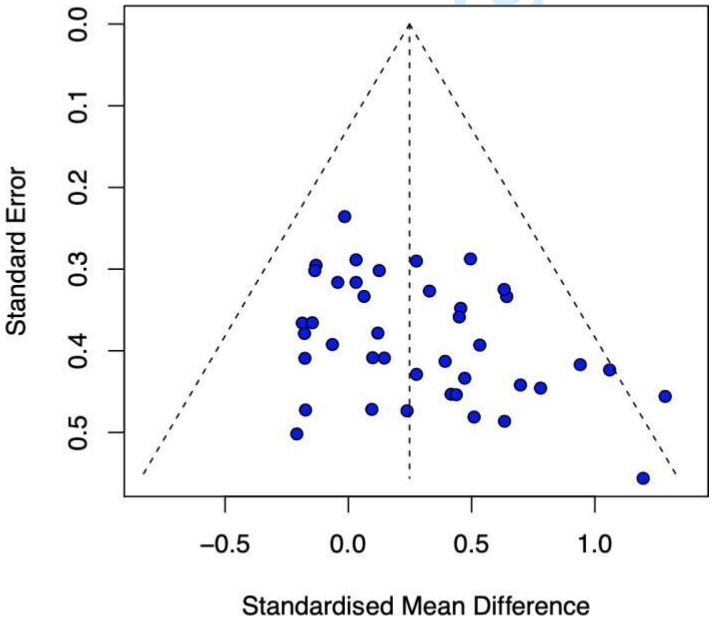


Figure 3. Funnel plot of studies included in the meta-analysis showing effect estimates (SMD) from individual studies against standard error. The effect sizes and precisions

are fairly well spread within the funnel but might indicate some studies with negative effects are missing.

Meta-regressions: For time to fatigue outcomes, meta-regression analysis showed no significant effect of stimulation intensity (β = 0.04, SE = 0.28, p = 0.87, R2=.00), density (β =331 -2.54, SE = 6.74, p = 0.71, R2=.00), or duration (β = 0.00, SE = 0.02, p = 0.90, R2=.00) on reported effect size. For strength related outcomes meta-regressions showed no significant effect of stimulation intensity (β = -0.29, SE = 0.37, p = 0.44, R2=.00), density (β = 7.26, SE= 6.08, p = 0.23, R2=.07), or duration (β = 0.03, SE = 0.03, p = 0.34, R2=.00). Similarly, for visuomotor outcomes, meta-regressions again showed no significant effect of stimulation intensity (β = -0.16, SE = 0.29, p = 0.59, R2=.00), density (β = -16.86, SE=16.05, p = 0.29,R2=.00), or duration (β = -0.02, SE = 0.04, p = 0.67, R2=.00) on effect size. Full details of meta-regression models are available in the supplementary materials, including diagnostic plots and measures of heterogeneity (https://osf.io/vuqre/) and bubble (scatter) plots are presented in figure 4.

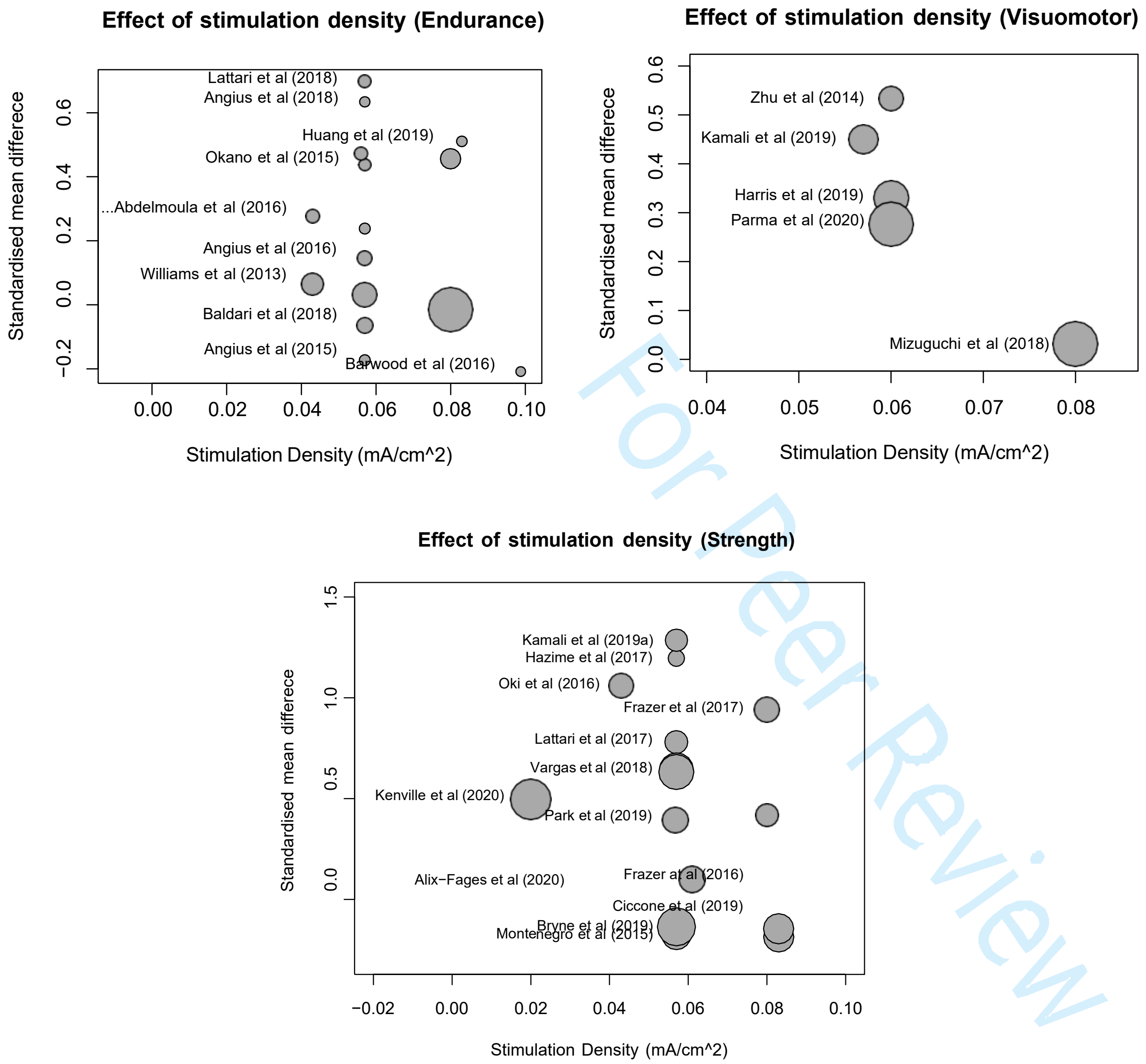
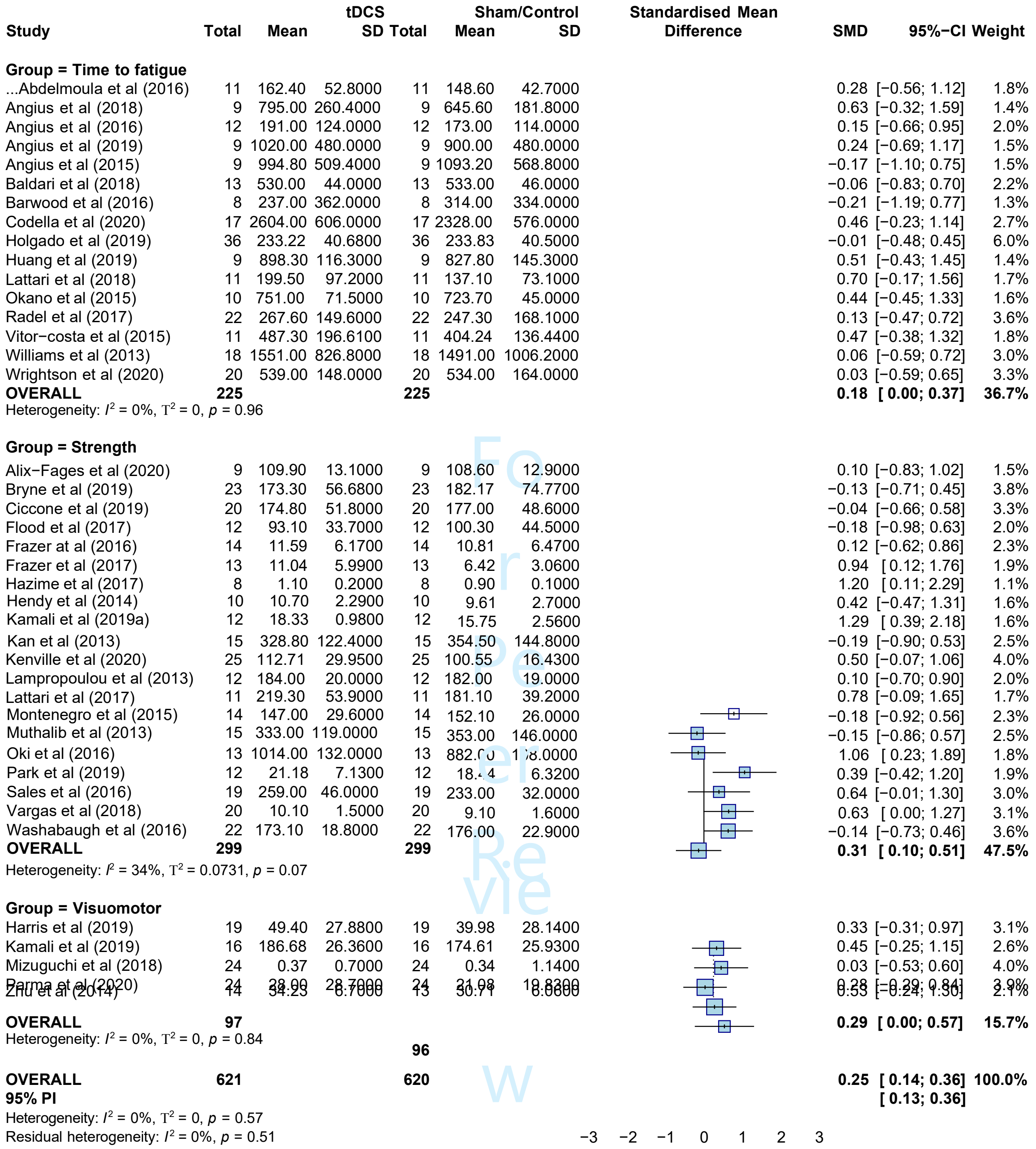


Figure 4. Bubble plots showing the relationship between stimulation density on the x-axis and SMD on the y-axis for each study in each of the three domains. The size of the plotting symbol is inversely proportional to the variance of the reported treatment effect.

3.3.2 Time to fatigue Subgroup Analysis. The literature search originally identified 17 out of 41 studies that examined the effect of tDCS stimulation on time to task failure protocols, including 255 participants. Cogiamaniam et al. (2007) was excluded in the meta-analysis as it was a significant outlier (extreme Cook’s distance) presenting a large positive effect size which biased the overall effect (see: https://osf.io/e2naq/). It was visually identified as a clear outlier, which was confirmed using the GOSH analysis (see Figure 5). The statistical analysis revealed a small effect in favour of tDCS compared to control/sham, but the effect only approached significance (SMD=0.18, $CI_{95\%}$ [0.00; 0.37], *p*=.056). The studies showed low heterogeneity (I^2=0%, τ^2=0, *p*=.96).

3.3.3 Strength Exercise Subgroup Analysis. The literature search identified 20 studies examining strength exercises, assessing 299 participants. The statistical analysis showed a small but significant overall effect (SMD=0.31, $CI_{95\%}$ [0.10; 0.51], *p*=.003) in favour of the stimulation group. The studies showed low heterogeneity (I^2=34%, τ^2=0.0731, *p*=0.07).

3.3.4 Visuomotor Skills Subgroup Analysis. The literature search initially identified six studies that examined the influence of tDCS on visuomotor skills. The study of Rocha et al. (2020) was removed from the final meta-analysis as it provided an extreme positive value (see: https://osf.io/e2naq/). Consequently five studies were suitable for the meta-analysis, a total of 97 participants. The quantitative analysis illustrates a small effect in favour of the tDCS group, which was marginally significant (SMD= 0.29, $CI_{95\%}$ [0.00; 0.57], *p*=.045). The studies showed low heterogeneity (I^2=0%, τ^2=0, *p*=.84).



Study	tDCS Total	Mean	SD	Sham/Control Total	Mean	SD	SMD	95%−CI	Weight
Group = Time to fatigue									
...Abdelmoula et al (2016)	11	162.40	52.8000	11	148.60	42.7000	0.28	[−0.56; 1.12]	1.8%
Angius et al (2018)	9	795.00	260.4000	9	645.60	181.8000	0.63	[−0.32; 1.59]	1.4%
Angius et al (2016)	12	191.00	124.0000	12	173.00	114.0000	0.15	[−0.66; 0.95]	2.0%
Angius et al (2019)	9	1020.00	480.0000	9	900.00	480.0000	0.24	[−0.69; 1.17]	1.5%
Angius et al (2015)	9	994.80	509.4000	9	1093.20	568.8000	−0.17	[−1.10; 0.75]	1.5%
Baldari et al (2018)	13	530.00	44.0000	13	533.00	46.0000	−0.06	[−0.83; 0.70]	2.2%
Barwood et al (2016)	8	237.00	362.0000	8	314.00	334.0000	−0.21	[−1.19; 0.77]	1.3%
Codella et al (2020)	17	2604.00	606.0000	17	2328.00	576.0000	0.46	[−0.23; 1.14]	2.7%
Holgado et al (2019)	36	233.22	40.6800	36	233.83	40.5000	−0.01	[−0.48; 0.45]	6.0%
Huang et al (2019)	9	898.30	116.3000	9	827.80	145.3000	0.51	[−0.43; 1.45]	1.4%
Lattari et al (2018)	11	199.50	97.2000	11	137.10	73.1000	0.70	[−0.17; 1.56]	1.7%
Okano et al (2015)	10	751.00	71.5000	10	723.70	45.0000	0.44	[−0.45; 1.33]	1.6%
Radel et al (2017)	22	267.60	149.6000	22	247.30	168.1000	0.13	[−0.47; 0.72]	3.6%
Vitor−costa et al (2015)	11	487.30	196.6100	11	404.24	136.4400	0.47	[−0.38; 1.32]	1.8%
Williams et al (2013)	18	1551.00	826.8000	18	1491.00	1006.2000	0.06	[−0.59; 0.72]	3.0%
Wrightson et al (2020)	20	539.00	148.0000	20	534.00	164.0000	0.03	[−0.59; 0.65]	3.3%
OVERALL	**225**			**225**			**0.18**	**[0.00; 0.37]**	**36.7%**
Heterogeneity: $I^2 = 0\%$, $\mathrm{T}^2 = 0$, $p = 0.96$									
Group = Strength									
Alix−Fages et al (2020)	9	109.90	13.1000	9	108.60	12.9000	0.10	[−0.83; 1.02]	1.5%
Bryne et al (2019)	23	173.30	56.6800	23	182.17	74.7700	−0.13	[−0.71; 0.45]	3.8%
Ciccone et al (2019)	20	174.80	51.8000	20	177.00	48.6000	−0.04	[−0.66; 0.58]	3.3%
Flood et al (2017)	12	93.10	33.7000	12	100.30	44.5000	−0.18	[−0.98; 0.63]	2.0%
Frazer at al (2016)	14	11.59	6.1700	14	10.81	6.4700	0.12	[−0.62; 0.86]	2.3%
Frazer et al (2017)	13	11.04	5.9900	13	6.42	3.0600	0.94	[0.12; 1.76]	1.9%
Hazime et al (2017)	8	1.10	0.2000	8	0.90	0.1000	1.20	[0.11; 2.29]	1.1%
Hendy et al (2014)	10	10.70	2.2900	10	9.61	2.7000	0.42	[−0.47; 1.31]	1.6%
Kamali et al (2019a)	12	18.33	0.9800	12	15.75	2.5600	1.29	[0.39; 2.18]	1.6%
Kan et al (2013)	15	328.80	122.4000	15	354.50	144.8000	−0.19	[−0.90; 0.53]	2.5%
Kenville et al (2020)	25	112.71	29.9500	25	100.55	16.4300	0.50	[−0.07; 1.06]	4.0%
Lampropoulou et al (2013)	12	184.00	20.0000	12	182.00	19.0000	0.10	[−0.70; 0.90]	2.0%
Lattari et al (2017)	11	219.30	53.9000	11	181.10	39.2000	0.78	[−0.09; 1.65]	1.7%
Montenegro et al (2015)	14	147.00	29.6000	14	152.10	26.0000	−0.18	[−0.92; 0.56]	2.3%
Muthalib et al (2013)	15	333.00	119.0000	15	353.00	146.0000	−0.15	[−0.86; 0.57]	2.5%
Oki et al (2016)	13	1014.00	132.0000	13	882.00	178.0000	1.06	[0.23; 1.89]	1.8%
Park et al (2019)	12	21.18	7.1300	12	18.44	6.3200	0.39	[−0.42; 1.20]	1.9%
Sales et al (2016)	19	259.00	46.0000	19	233.00	32.0000	0.64	[−0.01; 1.30]	3.0%
Vargas et al (2018)	20	10.10	1.5000	20	9.10	1.6000	0.63	[0.00; 1.27]	3.1%
Washabaugh et al (2016)	22	173.10	18.8000	22	176.00	22.9000	−0.14	[−0.73; 0.46]	3.6%
OVERALL	**299**			**299**			**0.31**	**[0.10; 0.51]**	**47.5%**
Heterogeneity: $I^2 = 34\%$, $\mathrm{T}^2 = 0.0731$, $p = 0.07$									
Group = Visuomotor									
Harris et al (2019)	19	49.40	27.8800	19	39.98	28.1400	0.33	[−0.31; 0.97]	3.1%
Kamali et al (2019)	16	186.68	26.3600	16	174.61	25.9300	0.45	[−0.25; 1.15]	2.6%
Mizuguchi et al (2018)	24	0.37	0.7000	24	0.34	1.1400	0.03	[−0.53; 0.60]	4.0%
Parma et al (2020)	24	28.00	28.7000	24	21.08	19.8300	0.28	[−0.29; 0.84]	3.9%
Zhu et al (2014)	14	34.23	6.7000	13	30.71	6.0600	0.53	[−0.24; 1.30]	2.1%
OVERALL	**97**			**96**			**0.29**	**[0.00; 0.57]**	**15.7%**
Heterogeneity: $I^2 = 0\%$, $\mathrm{T}^2 = 0$, $p = 0.84$									
OVERALL	**621**			**620**			**0.25**	**[0.14; 0.36]**	**100.0%**
95% PI								**[0.13; 0.36]**	
Heterogeneity: $I^2 = 0\%$, $\mathrm{T}^2 = 0$, $p = 0.57$									
Residual heterogeneity: $I^2 = 0\%$, $p = 0.51$									

Figure 5. Forest plot of effect sizes (*SMD*) from all 41 studies included in the meta-analysis. Effects > 0 indicate results favouring the stimulation group over the control group. The combined estimate and 95% confidence interval (blue diamond) indicates a small but reliable overall effect of tDCS stimulation over sham control. Time to fatigue (*SMD*=0.18), strength (*SMD*=0.31), and visuomotor (*SMD*=0.29) subgroups all showed effects with 95% CIs that did not cross zero. Light blue squares indicate the weight of the study in the combined analysis (based on sample size).

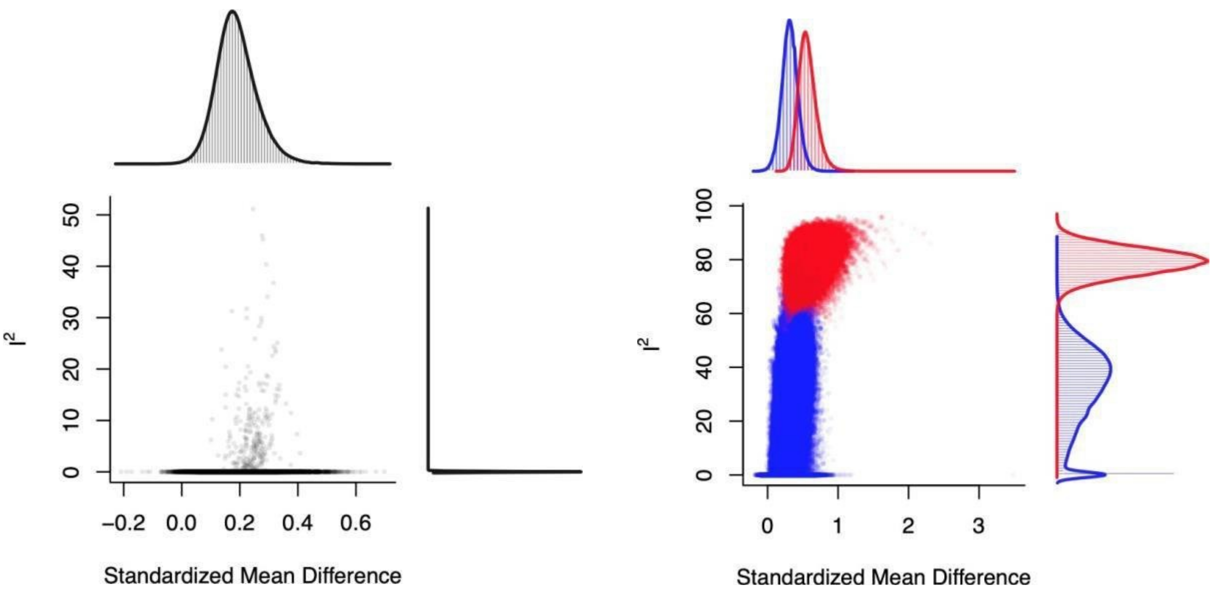


Figure 6. Graphical Display of Study Heterogeneity (GOSH) plots presenting a scatter plot of effect size estimates against heterogeneity for all possible study combinations in each subgroup Left: Time to fatigue studies (all). Right: Strength studies showing study combinations both with (red)and without (blue) the study of Cogiamaniam et al. (2007) which was excluded from the meta-analysis as an outlier. The plot clearly shows that the inclusion of this study would introduce additional heterogeneity as well as shift the overall point estimate. Note: the visuomotor subgroup only included five studies which was not sufficient to perform combinatorial meta-analysis.

4. Discussion

The purpose of this meta-analysis was to explore the ergogenic effects of tDCS on sporting performance and provide a comprehensive overview of the strength of current evidence. Specifically, we examined the impact of stimulation on endurance, strength, and visuomotor domains to examine the potential use of tDCS in the context of sporting performance enhancement. The results supported an overall positive effect of stimulation (SMD=0.25), which was relatively consistent across domains (time to fatigue: SMD=0.18; strength: SMD=0.31; visuomotor: SMD=0.29), although time to fatigue (p=.056) and visuomotor effects (p=.045) were both close to the significance threshold. These findings suggest there may be some potential for utilizing tDCS for performance enhancement in competition or training, although the ethics of such implementation is a debated area (Petersen, 2021).

4.1 Strength Exercise

The meta-analysis indicated that tDCS effects were largest and most reliable in the strength domain. Results from the reviewed studies showed that a-tDCS resulted in improved maximal isometric voluntary contraction (MIVC). One explanation for this observed effect is due to motor unit synchronisation. Previous research has suggested that a-tDCS has the ability to modify motor unit synchronisation (Schade et al., 2012; Krishnan et al., 2014). This a-tDCS mediated effect was reported by Hazime et al. (2014) who observed elevation of isometric strength. Alternatively, Fling et al. (2009) showed that motor unit synchronisation occurs at higher MIVC levels which may explain a lack of effect in the studies reporting no improvement (Farina and Negro, 2015). The effects of a-tDCS on strength are still unclear as the underpinnings of the neurophysiological mechanisms around a-tDCS stimulation are still novel. These results suggest tDCS has potential as a complimentary aid to be used alongside a training regime.

4.2 Endurance exercise

The subgroup analysis demonstrated that tDCS increased exercise endurance in TTE exercise protocols compared to sham and/or control conditions, but the effect was weaker than for strength exercise. These results aligned with the findings of Barwood et al. (2016) and Latteri et al. (2018) who suggested the use of anodal stimulation improved time to exhaustion results in a self-paced cycling test. The primary cortex (M1) is considered the principal determinant for endurance tasks as it drives the motor units. Cogiamanian et al. (2007) proposed that increased physical endurance is due to the increased cortical excitability of these regions as a result of tDCS stimulation. Abdelmoula et al. (2016) found time to task failure in the C2 (second submaximal contraction) was also extended post a-tDCS. Interestingly, a significant difference has been found in blood-lactate levels of tDCS participants (Angius et al., 2017), as well as an improvement in cardiac efficiency, which can be attributed to parasympathetic modulation (Okano et al., 2015). Heart rate (HR) is controlled by the PFC which is especially active during a sustained contraction task. The PFC could modulate sympathetic tone, thereby reducing an athlete’s HR, which may, in part, explain the increased endurance. These findings also explain improved performance in some of the strength studies; for example, Sales et al. (2016) reported the tDCS group had significantly reduced HR compared to the sham-tDCS group. This crossover may account for some variability between studies, but may also prove beneficial in multifaceted sports and exercise tasks that require high endurance and increased MIVC.

4.3 Visuomotor Skills

The directional effect observed in visuomotor protocols indicates a potential for neuromodulation in a visuomotor context, however the results were only weakly significant and limited to 5 studies. This finding is nonetheless promising, and indicates that further studies in this area are warranted. One of the positive effects was observed in a study by Kamali et al. (2019) who simultaneously stimulated the left DLFPC and right cerebellum, finding that the tDCS group had an improved accuracy score in a shooting task. The cerebellum is a key brain area for motor learning, especially in sensory prediction errors (DeZeeuw and Ten Brinke, 2015), which suggests a potential target for future lab-based work exploring visuomotor skills. Both Zhu et al. (2015) and Harris et al. (2019) explored electrical montages over the left DLFPC in the context of golf-putting procedures. Zhu et al. (2015) aimed to promote implicit learning by inhibiting verbal working-memory via cathodal stimulation, which resulted in reduced conscious movement control and improved performance. Contrastingly, Harris et al.(2019) found no true-effect of anodal tDCS of the DLPFC. Consequently there are a range of potential routes for enhancing visuomotor effects through enhancing frontal function, inhibiting conscious processing, and stimulating motor control centers, but more evidence is needed to determine which of these approaches are likely to be successful.

4.4 Moderators of stimulation effects

There was considerable variability with regards to the montage targets between the studies, although the primary motor cortex was the most common. Localisation of the electrode montages for the elected tDCS procedures is a parameter which can greatly influence cortical excitability induced by tDCS (Vitor-Costa et al, 2015). However, we found no evidence that the duration of tDCS, or the intensity or density of the delivered current were related to the subsequent performance effects. Unfortunately, this means that questions about optimal stimulation parameters remain.

Heterogeneity of participants in the form of genetic and environmental diversity also requires consideration. The role of genetics and brain stimulation has been extensively explored in animals but not in humans. There has been evidence that Val(108/158)Met polymorphism in the COMT gene influences c-tDCS induced brain modulation, highlighting an issue with ergogenic aids in which genetic factors influence cognitive performance (Nieratschker et al, 2015). Moreover, the role of BDNF polymorphism in modulating M1 plasticity was explored by Frazer et al. (2016) who found *Val/Val* participants showed greater increase in MEP induction compared to Val/Met genotype group. For progress to be made in brain-stimulation studies these genetic effects need to be studied further. The challenge of examining the studies and variable results also highlights the need for researchers to map out a clear justification for the selected parameters; stimulation intensity and duration, stimulation montage and participant characteristics such as gender and genetics. The neurophysiological mechanisms of brain stimulation also need to be better understood to reduce the variation caused by the existing methodology (see - Datta, et al., 2018 and Davis, 2020).

4.5 Limitations

The present review is, inevitably, subject to limitations of the search strategy, the papers that were defined to be within the current scope, and the limitations of those papers themselves. For instance, randomisation was adequate for the included trials, but 12 of the included studies were unable to explicitly state that analysis of data was not influenced by participant or researcher bias. Further, in general small sample sizes in data analysis are subject to less methodological rigour, so the quality of the studies would improve if larger sample sizes could be obtained for future studies. Differences in methodological approaches (e.g., target areas/type of tDCS) may also have influenced data. In this meta-analysis only two studies explored HD-tDCS electrical montages (Flood et al. 2017, Radel et al. 2017), and non-focal tDCS has the ability to influence unintended cortical areas making it difficult to apply focal stimulation.

4.6 Conclusions

The present systematic review and meta-analysis investigated the potential for tDCS to improve sporting performance with regard to physical endurance (time to fatigue), physical strength, or visuomotor skill. Pooled effect sizes supported the overall efficacy of tDCS, with more reliable findings for strength based studies, and promising but less certain effects for endurance and visuomotor studies. The varying stimulation montages and differential effects of individual differences and initial brain state all make it difficult to provide clear recommendations regarding the use of tDCS for sporting performance enhancement. For prospective studies a clear comparison of different electrical montages should be established with improved localisation of brain areas targeting the desired outcome. The unpredictable nature of tDCS makes it sensitive to a multitude of variables that need to be better controlled by individualising tDCS protocols, such as computational modelling with anatomical targeting using MRI or PET. Newer techniques for brain stimulation such as HD-tDCS should be explored as a potential alternative as it allows a focal stimulation that prevents stimulating unintended areas.

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Figures

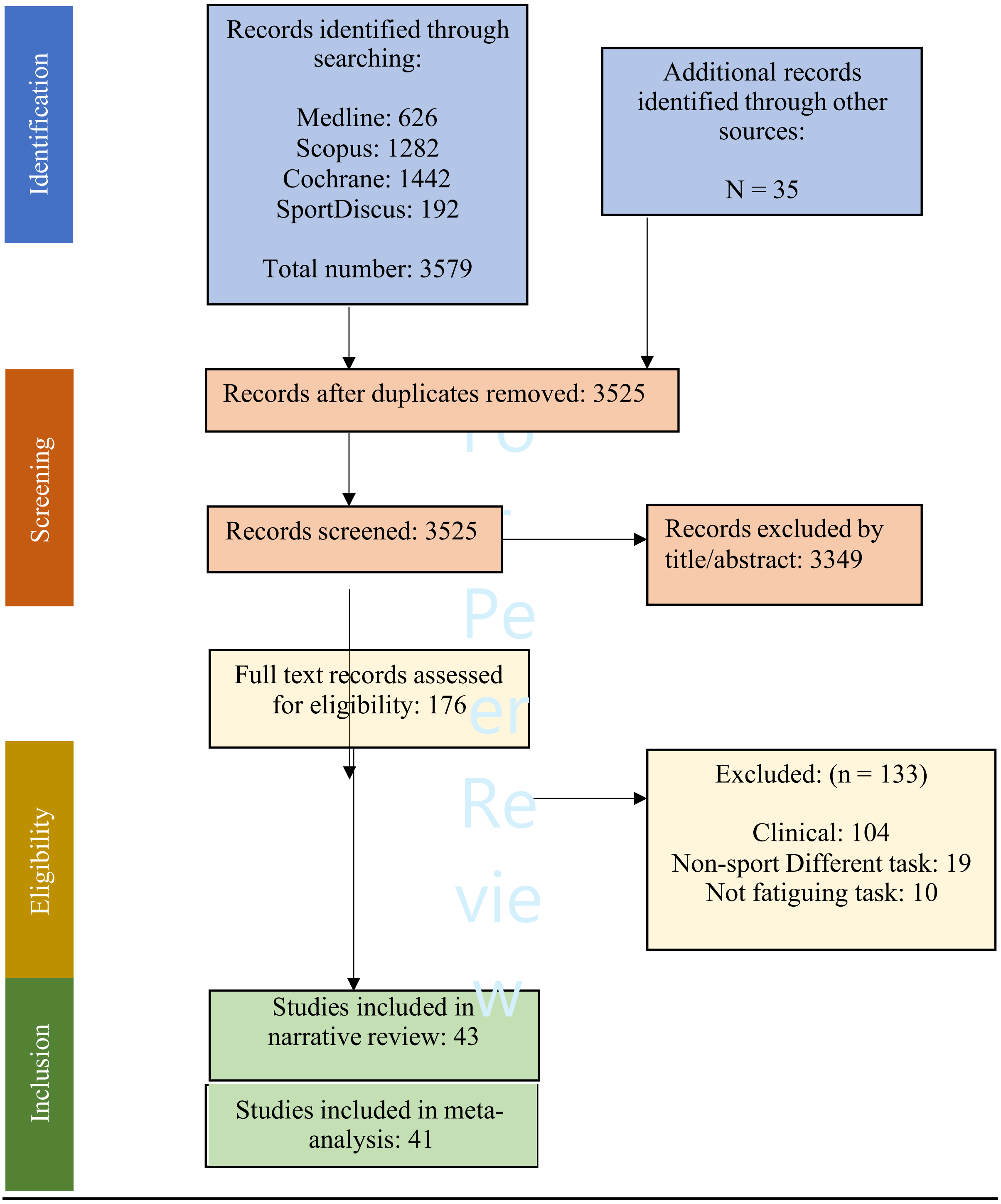


Figure 1. PRISMA study flow diagram illustrating the identification and selection of relevant studies

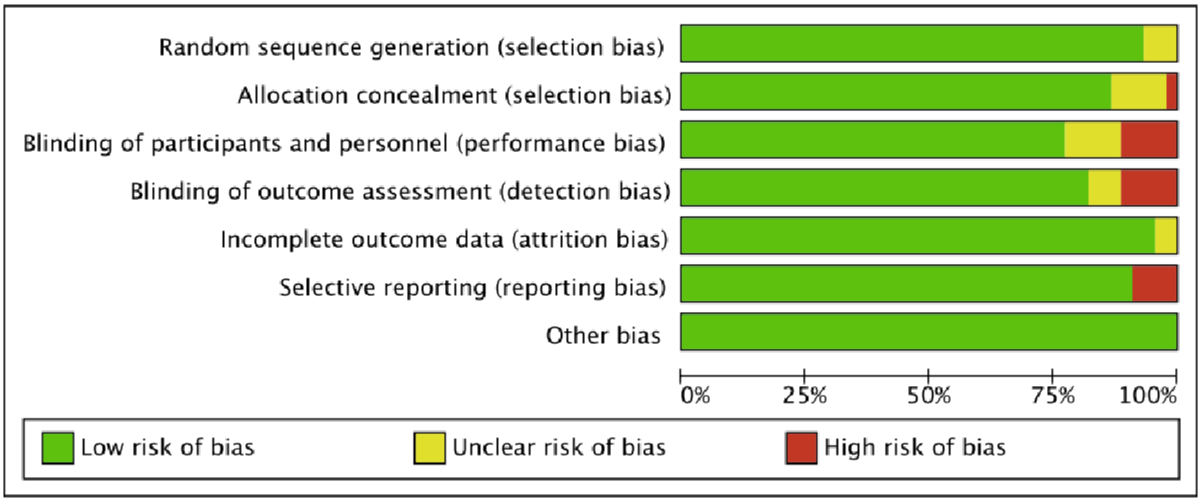


Figure 2. Risk of bias graph showing a review of the authors’ judgments across each risk criterion presented as percentages for all included studies.

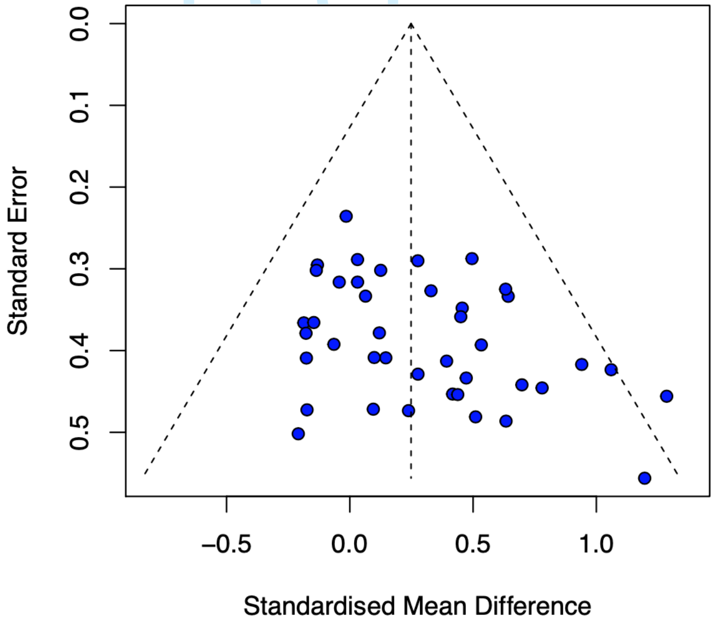


Figure 3. Funnel plot of studies included in the meta-analysis showing effect estimates (SMD) from individual studies against standard error. The effect sizes and precisions are fairly well spread within the funnel but might indicate some studies with negative effects are missing.

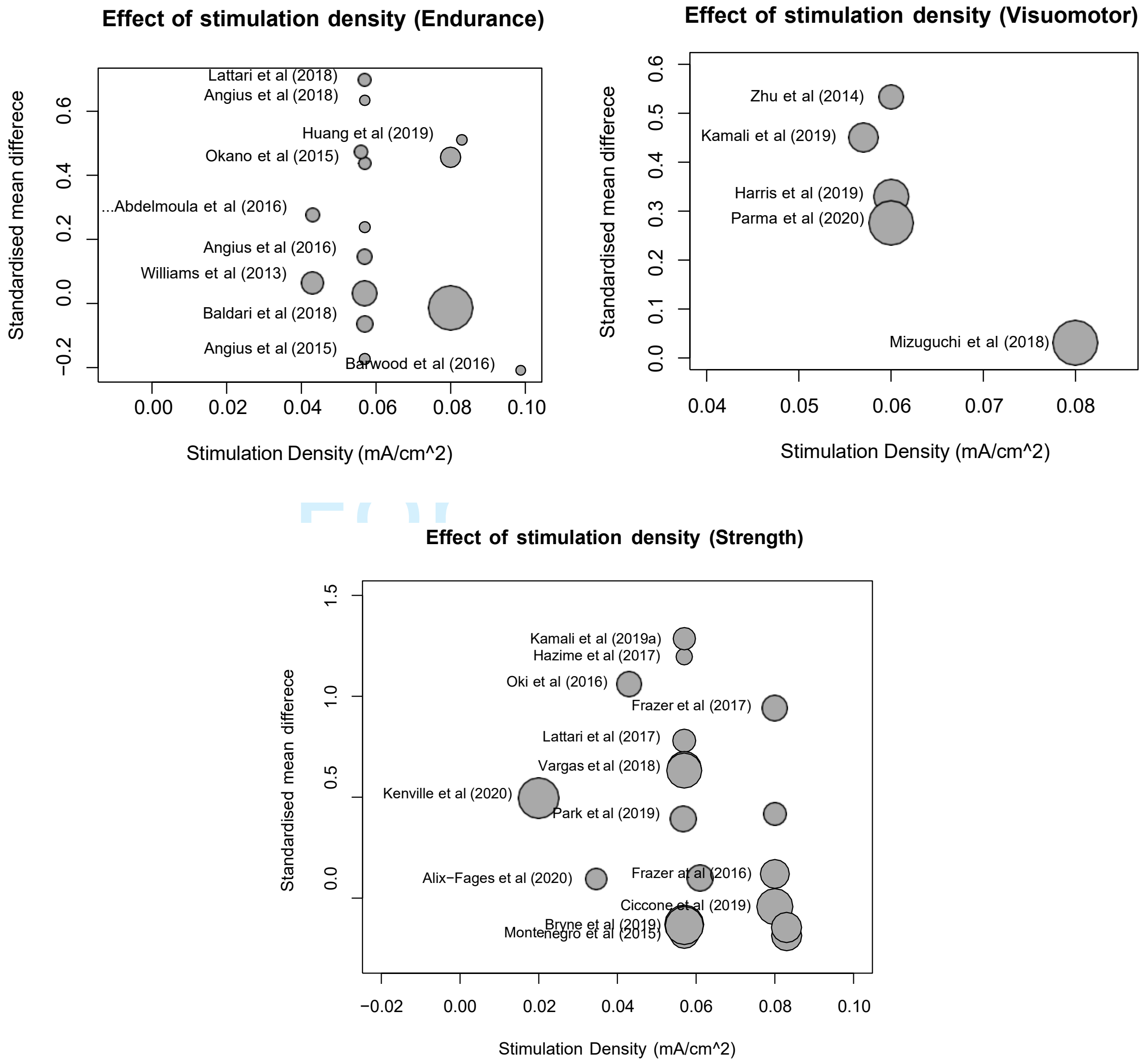
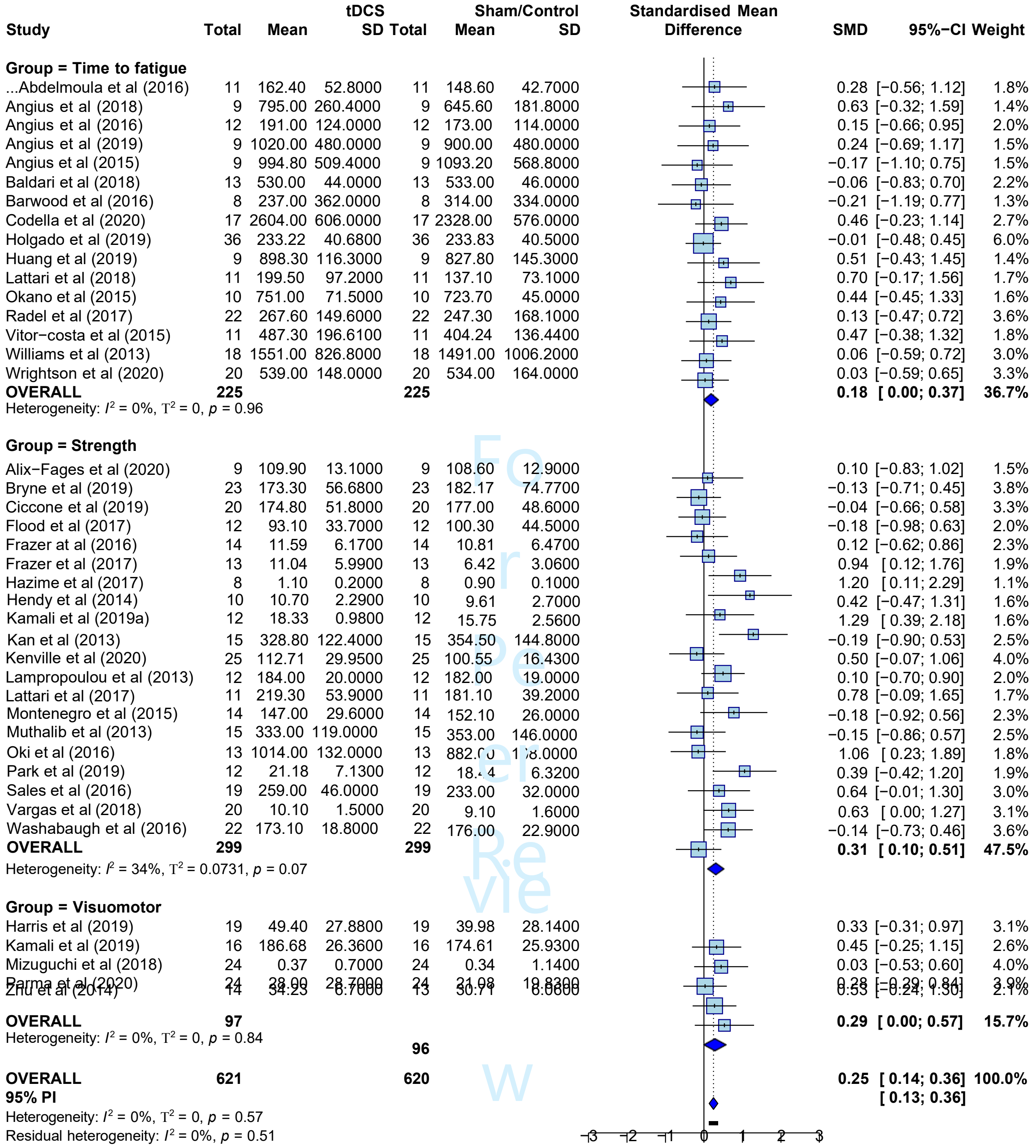


Figure 4. Bubble plots showing the relationship between stimulation density on the x-axis and SMD on the y-axis for each study in each of the three domains. The size of the plottingsymbol is inversely proportional to the variance of the reported treatment effect.



Study	tDCS Total	Mean	SD	Total	Sham/Control Mean	SD	SMD	95%−CI	Weight
Group = Time to fatigue									
...Abdelmoula et al (2016)	11	162.40	52.8000	11	148.60	42.7000	0.28	[−0.56; 1.12]	1.8%
Angius et al (2018)	9	795.00	260.4000	9	645.60	181.8000	0.63	[−0.32; 1.59]	1.4%
Angius et al (2016)	12	191.00	124.0000	12	173.00	114.0000	0.15	[−0.66; 0.95]	2.0%
Angius et al (2019)	9	1020.00	480.0000	9	900.00	480.0000	0.24	[−0.69; 1.17]	1.5%
Angius et al (2015)	9	994.80	509.4000	9	1093.20	568.8000	−0.17	[−1.10; 0.75]	1.5%
Baldari et al (2018)	13	530.00	44.0000	13	533.00	46.0000	−0.06	[−0.83; 0.70]	2.2%
Barwood et al (2016)	8	237.00	362.0000	8	314.00	334.0000	−0.21	[−1.19; 0.77]	1.3%
Codella et al (2020)	17	2604.00	606.0000	17	2328.00	576.0000	0.46	[−0.23; 1.14]	2.7%
Holgado et al (2019)	36	233.22	40.6800	36	233.83	40.5000	−0.01	[−0.48; 0.45]	6.0%
Huang et al (2019)	9	898.30	116.3000	9	827.80	145.3000	0.51	[−0.43; 1.45]	1.4%
Lattari et al (2018)	11	199.50	97.2000	11	137.10	73.1000	0.70	[−0.17; 1.56]	1.7%
Okano et al (2015)	10	751.00	71.5000	10	723.70	45.0000	0.44	[−0.45; 1.33]	1.6%
Radel et al (2017)	22	267.60	149.6000	22	247.30	168.1000	0.13	[−0.47; 0.72]	3.6%
Vitor−costa et al (2015)	11	487.30	196.6100	11	404.24	136.4400	0.47	[−0.38; 1.32]	1.8%
Williams et al (2013)	18	1551.00	826.8000	18	1491.00	1006.2000	0.06	[−0.59; 0.72]	3.0%
Wrightson et al (2020)	20	539.00	148.0000	20	534.00	164.0000	0.03	[−0.59; 0.65]	3.3%
OVERALL	**225**			**225**			**0.18**	**[0.00; 0.37]**	**36.7%**
Heterogeneity: $I^2 = 0\%$, $\mathrm{T}^2 = 0$, $p = 0.96$									
Group = Strength									
Alix−Fages et al (2020)	9	109.90	13.1000	9	108.60	12.9000	0.10	[−0.83; 1.02]	1.5%
Bryne et al (2019)	23	173.30	56.6800	23	182.17	74.7700	−0.13	[−0.71; 0.45]	3.8%
Ciccone et al (2019)	20	174.80	51.8000	20	177.00	48.6000	−0.04	[−0.66; 0.58]	3.3%
Flood et al (2017)	12	93.10	33.7000	12	100.30	44.5000	−0.18	[−0.98; 0.63]	2.0%
Frazer at al (2016)	14	11.59	6.1700	14	10.81	6.4700	0.12	[−0.62; 0.86]	2.3%
Frazer et al (2017)	13	11.04	5.9900	13	6.42	3.0600	0.94	[0.12; 1.76]	1.9%
Hazime et al (2017)	8	1.10	0.2000	8	0.90	0.1000	1.20	[0.11; 2.29]	1.1%
Hendy et al (2014)	10	10.70	2.2900	10	9.61	2.7000	0.42	[−0.47; 1.31]	1.6%
Kamali et al (2019a)	12	18.33	0.9800	12	15.75	2.5600	1.29	[0.39; 2.18]	1.6%
Kan et al (2013)	15	328.80	122.4000	15	354.50	144.8000	−0.19	[−0.90; 0.53]	2.5%
Kenville et al (2020)	25	112.71	29.9500	25	100.55	16.4300	0.50	[−0.07; 1.06]	4.0%
Lampropoulou et al (2013)	12	184.00	20.0000	12	182.00	19.0000	0.10	[−0.70; 0.90]	2.0%
Lattari et al (2017)	11	219.30	53.9000	11	181.10	39.2000	0.78	[−0.09; 1.65]	1.7%
Montenegro et al (2015)	14	147.00	29.6000	14	152.10	26.0000	−0.18	[−0.92; 0.56]	2.3%
Muthalib et al (2013)	15	333.00	119.0000	15	353.00	146.0000	−0.15	[−0.86; 0.57]	2.5%
Oki et al (2016)	13	1014.00	132.0000	13	882.00	178.0000	1.06	[0.23; 1.89]	1.8%
Park et al (2019)	12	21.18	7.1300	12	18.44	6.3200	0.39	[−0.42; 1.20]	1.9%
Sales et al (2016)	19	259.00	46.0000	19	233.00	32.0000	0.64	[−0.01; 1.30]	3.0%
Vargas et al (2018)	20	10.10	1.5000	20	9.10	1.6000	0.63	[0.00; 1.27]	3.1%
Washabaugh et al (2016)	22	173.10	18.8000	22	176.00	22.9000	−0.14	[−0.73; 0.46]	3.6%
OVERALL	**299**			**299**			**0.31**	**[0.10; 0.51]**	**47.5%**
Heterogeneity: $I^2 = 34\%$, $\mathrm{T}^2 = 0.0731$, $p = 0.07$									
Group = Visuomotor									
Harris et al (2019)	19	49.40	27.8800	19	39.98	28.1400	0.33	[−0.31; 0.97]	3.1%
Kamali et al (2019)	16	186.68	26.3600	16	174.61	25.9300	0.45	[−0.25; 1.15]	2.6%
Mizuguchi et al (2018)	24	0.37	0.7000	24	0.34	1.1400	0.03	[−0.53; 0.60]	4.0%
Parma et al (2020)	24	28.00	28.7000	24	21.08	19.8300	0.28	[−0.29; 0.84]	3.9%
Zhu et al (2014)	14	34.23	6.7000	13	30.71	6.0600	0.53	[−0.24; 1.30]	2.1%
OVERALL	**97**						**0.29**	**[0.00; 0.57]**	**15.7%**
Heterogeneity: $I^2 = 0\%$, $\mathrm{T}^2 = 0$, $p = 0.84$									
				96					
OVERALL	**621**			**620**			**0.25**	**[0.14; 0.36]**	**100.0%**
95% PI								**[0.13; 0.36]**	
Heterogeneity: $I^2 = 0\%$, $\mathrm{T}^2 = 0$, $p = 0.57$									
Residual heterogeneity: $I^2 = 0\%$, $p = 0.51$									

Figure 5. Forest plot of effect sizes (*SMD*) from all 41 studies included in the meta-analysis.Effects > 0 indicate results favouring the stimulation group over the control group. The combined estimate and 95% confidence interval (blue diamond) indicates a small but reliableoverall effect of tDCS stimulation over sham control. Time to fatigue (*SMD*=0.18), strength (*SMD*=0.31), and visuomotor (*SMD*=0.29) subgroups all showed effects with 95% CIs that did not cross zero. Light blue squares indicate the weight of the study in the combined analysis (based on sample size).

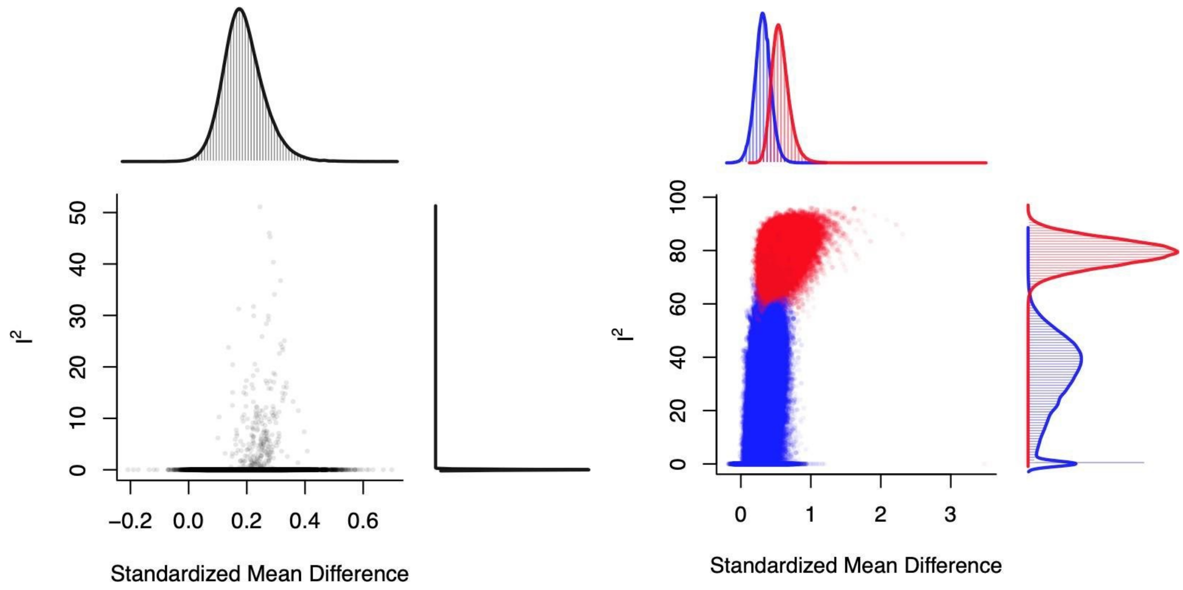


Figure 6. Graphical Display of Study Heterogeneity (GOSH) plots presenting a scatter plot of effect size estimates against heterogeneityfor all possible study combinations in each subgroup. Left: Time to fatigue studies (all). Right: Strength studies showing study combinations both with (red) and without (blue) the study of Cogiamaniam et al. (2007) which was excluded from the meta-analysis as an outlier.The plot clearly shows that the inclusion of this study would introduce additional heterogeneity as well as shift the overall point estimate. Note: the visuomotor subgroup onlyincluded five studies which was not sufficient to perform combinatorial meta-analysis.