tDCS effect on prosocial behavior: a meta-analytic review

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Abstract

Previous studies have shown that transcranial direct current stimulation (tDCS) could potentially promote prosocial behaviors. However, results from randomized controlled trials are inconsistent. The current meta-analysis aimed to assess the effects of anodal and cathodal tDCS using single-session protocols on prosocial behaviors in healthy young adults and explore potential moderators of these effects. The results showed that compared with sham stimulation, anodal (excitatory) stimulation significantly increased ($g = 0.27$, 95% CI $[0.11, 0.43]$, $Z = 3.30$, $P = 0.001$) and cathodal (inhibitory) stimulation significantly decreased prosocial behaviors ($g = −0.19$, 95% CI $[−0.39, −0.01]$, $Z = −1.95$, $P = 0.051$) using a multilevel meta-analytic model. These effects were not significantly modulated by stimulation parameters (e.g. duration, intensity and site) and types of prosocial behavior. The risk of publication bias for the included effects was minimal, and no selective reporting (e.g. P-hacking) was found in the P-curve analysis. This meta-analysis showed that both anodal and cathodal tDCS have small but significant effects on prosocial behaviors. The current study provides evidence that prosocial behaviors are linked to the activity of the ‘social brain’. Future studies are encouraged to further explore whether tDCS could effectively treat social dysfunctions in psychiatry disorders.

Key words: meta-analysis; prosocial behavior; transcranial direct current stimulation; stimulation parameters

Introduction

Among animals, Homo sapiens is unique in its capacity for widespread prosocial behavior among large and genetically heterogeneous groups of individuals. Prosocial behavior refers to a broad range of behaviors, efforts or intentions to promote or protect the well-being of other individuals, groups, organizations or societies (Penner et al., 2005; Bolino and Grant, 2016), such as helping, sharing, cooperating, trust and donating. It not only facilitates interpersonal adaptation and harmony but also enhances social welfare and social responsibility. Due to its importance and ubiquity, human prosocial behavior has received tremendous attention across scientific
Disciplines, including biology, economics, sociology and psychology (Thielmann et al., 2020).

Prosocial behavior is a composite and multidimensional construct. It can be defined as a social behavior that benefits other people or society as a whole, such as helping, donating and cooperating (Penner et al., 2005). Several classic economic games, such as the dictator game (Forsythe et al., 1994), ultimatum game (UG) (Guth et al., 1982), trust game (Berg et al., 1995), prisoner’s dilemma (Rapoport et al., 1965) and public goods game (Samuelson, 1954), have been developed to study prosocial behavior in laboratory contexts. These game paradigms were developed to model the complexity of real-life interdependent situations in a precise yet parsimonious approach that allows assessing actual prosocial behavior in standardized experimental settings (Murnighan and Wang, 2016). In essence, economic games provide a standardized substantive model of many actual encounters and therefore have good ecological validity (Baumeister et al., 2007).

Prosocial behavior involves complex cognitive and motivational processes (Coke et al., 1978; Padilla-Walker and Carlo, 2014). Acting to benefit others first requires socio-cognitive abilities (e.g. the theory of mind, ToM) to understand another person’s needs and goals (Warneken, 2015). Socio-cognitive abilities enable the helping agent to realize whether and how particular actions help others to reach their goals (Frith et al., 2003; Tomasello et al., 2005). Prosocial behavior requires the motivation to act, which may stem from empathetic processes, and the desire to reduce the misfortune of another (De Waal, 2008; Rumble et al., 2010; Xu et al., 2019). Humans exhibit empathic concerns about the welfare of others and feel committed to alleviating others’ distress and pain (De Waal, 2008; Warneken, 2015).

In addition, prosocial behavior is hypothesized to engage brain regions attributed to the mentalizing and empathy brain networks (the so-called ‘social brain’) (Chakroff and Young, 2014). The right temporoparietal junction (rTPJ) is an important hub of the mentalizing network (Preckel et al., 2018) and has been consistently shown in tasks that involve self-centered and other-regarding concerns (such as care about the harms, losses or feelings of others) (Soutschek et al., 2016; Tang et al., 2017). The rTPJ is implicated in sophisticated representations of others’ mental states and integrating them into social decisions (Lockwood et al., 2019). In addition, an agent might also need to integrate cognitive and affective signals in prosocial behaviors to prospectively evaluate actions and outcomes associated with a prosocial act (Bellucci et al., 2020). The ventromedial prefrontal cortex (vmPFC) has been posited to be a hub of processing action-outcome contingencies in goal-directed behaviors (Huang et al., 2020). The dorsolateral prefrontal cortex (dLPFC) by tDCS produced different effects on volun-
tary and sanction-based social norm compliance (Lur et al., 2017). Along the same lines, recent studies provided evidence that tDCS could also alter social behaviors such as prosocial behavior. For instance, a number of studies showed that anodal vs sham tDCS enhanced trustworthiness (Wang et al., 2016) and honesty (Maréchal et al., 2017), economic (Nihonsugi et al., 2015) and voluntary cooperation (Li et al., 2018) and empathy to others’ pain (Wang et al., 2014). Similarly, other studies reported the opposite effect of using cathodal tDCS, such as decreasing ToM, cognitive empathy (Mai et al., 2016) and emotional empathy (Coll et al., 2017).

While it is suggested that tDCS could potentially impact prosocial behaviors, its effectiveness needs to be quantitatively evaluated through a comprehensive meta-analysis. First, previous studies often yield inconsistent results regarding the overall effects of tDCS on the prosocial tendency. For example, a previous study found that stimulating right dorsolateral prefrontal cortex (rDLPFC) by tDCS produced different effects on voluntary and sanction-based social norm compliance (Ruff et al., 2013). Another study reported that the application of tDCS over the prefrontal cortex enhanced the trustee’s repayment through altruism (Zheng et al., 2016), whereas no such significant effect was reported on interpersonal trust as the trustee (Zheng et al., 2017). There is large heterogeneity in experimental prosocial tasks due to the wide range of prosocial behaviors such as trust, trustworthiness, altruism and pain empathy. The tDCS effects on prosociality may be limited to certain social behaviors, but not others. Second, similar to other research domains, tDCS research suffers from replication risk, P-hacking (file-drawer), publication bias, small sample size and hypothesizing after the results are known (problems HARKing) (Simmons et al., 2011), casting doubt on the efficacy of tDCS and the replicability of tDCS effects. A quantitative assessment of the risk of publication bias and selective reporting (e.g. P-hacking) in this field is called for. Third, substantial research design variations exist across studies in terms of stimulation parameters and protocols, leading to inconsistent research findings (Galli et al., 2019). It is well-known that a variety of factors, besides the polarity of stimulation, may modulate the magnitude of the tDCS effects, such as electrode placement and size, current density, intensity and duration of stimulation and motivational factors (Sellaro et al., 2016).
Hence, it is necessary to assess these variables’ potential moderating roles in the tDCS effects on prosocial behavior in a comprehensive meta-analysis. Finally, researchers have stimulated different parts of the ‘social brain’, including dPFC, rTPJ and vmPFC. Although these regions are involved in social cognition, it is unclear whether the tDCS effect is stronger on one site than the other, which needs to be unraveled by a meta-analysis. To the best of our knowledge, no previous meta-analysis has examined the effects of tDCS on prosocial behavior. In the present study, two meta-analyses were conducted to assess the effects of anodal and cathodal tDCS stimulations on prosocial behavior. Potential moderators of tDCS effects, such as stimulation site and types of prosocial behavior, were tested in the sub-group meta-analyses. Further meta-regression analyses were implemented to examine whether the magnitude of tDCS effects varied as a function of specific stimulation parameters (such as current density and stimulation duration). Finally, the p-curve analysis was also conducted to assess the evidential value of these effects. To sum up, the purpose of this systematic review and meta-analysis was to analyze the effect of tDCS on prosocial behaviors and explore potential moderators of such an effect in healthy adults.

Method

Literature search

We conducted searches for published and unpublished articles/reports in English language in the following databases: Web of Science, Science Direct, PubMed and Google Scholar. The search terms included ‘[Transcranial Direct Current Stimulation’ OR ‘tDCS’] AND [‘trust’ OR ‘cooperation’ OR ‘prosocial behavior’ OR ‘helping behavior’ OR ‘altruism’ OR ‘honesty’ OR ‘altruism behavior’ OR ‘empathy’]. In addition, a few review articles and their reference lists were screened (Boggio et al., 2016; Sellaro et al., 2016; Di Nuzzo et al., 2018). This work followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher et al., 2015). Two reviewers (WY and YB) independently screened the titles and abstracts of articles identified in the initial search strategy against the inclusion criteria (see below) and potentially relevant studies were retrieved for full-text screening. Discrepancies between reviewers were settled through a discussion.

Inclusion and exclusion criteria

The following inclusion criteria were implemented: (i) only manuscripts written in English and available before December 2020 were considered; (ii) only studies that involved randomized, sham–controlled trials were included; (iii) participants have to be healthy population; (iv) the main outcome of the study has to be a measure of prosocial behavior such as trust, trustworthiness, altruism, honesty, empathy and ToM; (v) only studies that provided sufficient data [e.g. M, standard deviation (s.d.), t, F] for effect size calculation were included and (vi) only studies implemented anodal and cathodal stimulation in any brain region and any type of electrode were considered.

Although both empathy and ToM are indirectly related to prosocial behaviors, we included them in our meta-analysis, because these socio-cognitive abilities are basic of prosocial behavior. In addition, we also reported the anodal and cathodal tDCS effects on prosocial behaviors after removing the empathy and ToM items.

For each study, we extracted means and standard deviations of the outcome measures of interest, along with the sample sizes. The same two reviewers independently extracted data using a data extraction form. The following variables were extracted according to a structured checklist previously elaborated by the authors: (i) metadata (i.e. authorship, publication date, journal); (ii) demographics (sample size in each group, mean age and gender); (iii) prosocial behavior types such as trust, trustworthiness, altruism (e.g. altruistic giving or help), honesty, empathy, ToM; (iv) stimulation sites such as dLPPFC, vmPFC, rTPJ, IDLPFC (left dorsolateral prefrontal cortex), rOFC (right orbitofrontal cortex) and SI (somatosensory cortex) and (v) characteristics of the tDCS technique (intensities of the current, stimulation durations and online/offline stimulation).

Wherein mean and s.d. values were not provided for anodal/cathodal and sham condition as numerical data, they were pooled out from the graphs with Plot Digitizer software (Jelicic Kadic et al., 2016). Some of the studies included in the current meta-analysis tested multiple experimental variables within-subjects or involved other types of non-independent statistical comparisons. We treated stimulated brain areas, prosocial behavior types, characteristics of the tDCS technique as independent data. We were aware that computing different effect sizes for the same or overlapping sets of participants and treating them as completely unrelated effect sizes violate the assumptions of the traditional meta-analytic method. However, the variables mentioned above were of primary interest and were included as moderators; therefore, we reasoned that data reduction would have resulted in a loss of relevant information. To address this, we also reported the results fitted a two-level model with random effects at the study level, using the rma.mv function of the ’metaphor’ package (Viechtbauer, 2010). This strategy allowed us to control for dependencies in the dataset, while preserving the information conveyed by each effect size (Galli et al., 2019).

Statistical approach and publication bias

For the main outcome, the standardized mean difference and the pooled s.d. for each comparison were calculated. The Hedges’ g was used as the measure of effect sizes, which is appropriate for studies with small sample sizes. All meta-analyses were conducted using random-effects models. Heterogeneity was evaluated with $I^2$ and $\chi^2$ tests (Higgins and Thompson, 2002). Publication bias was examined by Egger’s regression test and a funnel plot. The Duval and Tweedie ‘Trim and Fill’ procedure (Duval and Tweedie, 2000) was implemented to adjust for any suspected publication bias using a random-effects model.

Further analyses were performed to explore the potential moderators such as age, the current density of stimulation, duration of stimulation, stimulation sites and prosocial behavior types. Current density ($A/m^2$) was estimated by dividing the electric current (Amperes, A) by the electrode surface area (square meters, m$^2$).

Quality assessment

A quality assessment was conducted for each included study by using the Physiotherapy Evidence Database (PEDro scale) (Maher et al., 2003) to assess the methodological quality of included articles (Supplementary Table S1). The PEDro scale includes 11
specific criteria, graded on a ‘yes’/’no’ scale in which the first item relates to external validity and the other 10 items assess the internal validity of a clinical trial (Bastani and Jaberzadeh, 2012). The first criterion does not count toward the overall score that the article receives for the quality of its study design. The PEDro scale is marked out of 10, and a higher PEDro score represents a higher assumed ‘quality’ of the trial.

**P-Curve analysis**

Simonsohn et al. (2014) proposed a method for diagnosing P-hacking by considering the distribution of significant P-values obtained over a series of independent studies. P-curve analysis assesses the distribution of P-values among published articles to diagnose whether the findings provide evidence for a true phenomenon, or whether they likely reflect an artifact of publication bias and P-hacking. The logic is that studies demonstrating true effects (where the null is false) will be more likely to produce particularly low P values ($P < 0.025$) than those in the higher range of significance ($0.025 < P < 0.05$). The distribution of P values for a true effect should thus be right-skewed. Studies that investigate null effects produce an equal distribution of P values, resulting in a uniform P curve. This type of ‘flat’ P curve suggests that the body of literature lacks evidentiary value (Shariff et al., 2016). We conducted P-curve analyses using P values of the main effects included in the meta-analyses to assess their evidential value (Köbis et al., 2019).

**Overall meta-analysis**

Tables 1 and 2 list the anodal/cathodal tDCS effects on prosocial behaviors and the corresponding study characteristics. We found that anodal tDCS, in comparison with sham tDCS, enhanced prosocial behavior to a modest extent, $g = 0.16$, 95% CI [0.03, 0.29], $Z = 2.44$, $P = 0.015$ (Figure 2). The anodal tDCS effect was still significant when we fitted a two-level model with random effects at the study level, $g = 0.27$, 95% CI [0.11, 0.43], $Z = 3.30$, $P = 0.001$ (Figure 2). The anodal tDCS effect was still significant when we fitted a two-level model with random effects at the study level, $g = -0.24$, 95% CI $[-0.39, -0.09]$, $Z = -3.08$, $P = 0.002$ (Figure 3). This effect was still significant when we fitted a two-level model with random effects at the study level, $g = -0.19$, 95% CI $[-0.39, -0.01]$, $Z = -1.95$, $P = 0.051$.

In addition, we analyzed the anodal and cathodal tDCS effects on prosocial behaviors after removing the empathy and ToM items in the meta-analysis. Empathy and ToM are important foundations for prosocial behavior, but may not be considered as forms of prosocial acts. Nevertheless, anodal tDCS still enhanced prosocial behavior ($k = 44$) to a small extent, $g = 0.13$, 95% CI $[-0.02, 0.27]$, $Z = 1.73$, $P = 0.082$, and this effect...
| Author, year, Experiment | Age (years) | N(a) | N(c) | Active brain | Prosocial behavior | Duration (min) | Area (cm²) | Intensity (mA) | Q_Score | Hedges’ g |
|--------------------------|-------------|------|------|--------------|-------------------|----------------|------------|----------------|---------|-----------|
| Adenzato et al. (2017)   | 23.50       | 16   | 16   | vmPFC        | ToM               | 6              | 35         | 1.00           | 6       | 0.85      |
| Adenzato et al. (2017)   | 23.50       | 16   | 16   | vmPFC        | ToM               | 6              | 35         | 1.00           | 6       | −0.16     |
| Adenzato et al. (2019)   | 68.3        | 15   | 15   | vmPFC        | ToM               | 6              | 35         | 1.5            | 8       | −0.06     |
| Adenzato et al. (2019)   | 68.3        | 15   | 15   | vmPFC        | ToM               | 6              | 35         | 1.5            | 8       | −0.09     |
| Adenzato et al. (2019)   | 67.5        | 15   | 15   | vmPFC        | ToM               | 6              | 35         | 1.5            | 8       | −0.36     |
| Adenzato et al. (2019)   | 67.5        | 15   | 15   | vmPFC        | ToM               | 6              | 35         | 1.5            | 8       | −0.56     |
| Chen et al. (2019)       | 20.5        | 25   | 25   | rDLPFC       | Altruism          | 30             | 35         | 1.5            | 7       | −0.44     |
| Chen et al. (2019)       | 20.5        | 25   | 25   | rDLPFC       | Altruism          | 30             | 35         | 1.5            | 7       | 0.16      |
| Chen et al. (2019)       | 20.5        | 25   | 25   | rDLPFC       | Altruism          | 30             | 35         | 1.5            | 7       | −0.5      |
| Chen et al. (2019)       | 20.5        | 25   | 25   | rDLPFC       | Altruism          | 30             | 35         | 1.5            | 7       | 0.36      |
| Chen et al. (2019)       | 20.5        | 25   | 25   | rDLPFC       | Altruism          | 30             | 35         | 1.5            | 7       | 0.05      |
| Chen et al. (2019)       | 20.5        | 25   | 25   | rDLPFC       | Altruism          | 30             | 35         | 1.5            | 7       | 0.1       |
| Coll et al. (2017)       | 26.54       | 16   | 16   | rTPJ         | Empathy           | 20             | 35         | 2.0            | 7       | −0.51     |
| Coll et al. (2017)       | 25.69       | 16   | 16   | rTPJ         | Empathy           | 20             | 35         | 2.0            | 7       | 0.02      |
| Colzato et al. (2015)    | 21.00       | 20   | 20   | vmPFC        | Trust            | 20             | 35         | 1.0            | 9       | −0.03     |
| Gallo et al. (2018)      | 24.50       | 25   | 25   | SI           | Empathy           | 18             | 35         | 1.5            | 7       | 0.49      |
| Gallo et al. (2018)      | 24.50       | 25   | 25   | SI           | Empathy           | 18             | 35         | 1.5            | 7       | −0.49     |
| Gross et al. (2018)      | 21.40       | 35   | 36   | rDLPFC       | Altruism          | 30             | 35         | 2.0            | 9       | −0.10     |
| Jospe et al. (2020)      | 23.94       | 26   | 26   | rIFG         | Empathy           | 15             | 16         | 1.25           | 7       | −0.06     |
| Jospe et al. (2020)      | 23.94       | 26   | 26   | rIFG         | Empathy           | 15             | 16         | 1.25           | 7       | 1.46      |
| Li et al. (2018)         | 24.04       | 27   | 28   | rDLPFC       | Altruism          | 15             | 35         | 1.0            | 8       | 0.97      |
| Li et al. (2018)         | 24.04       | 27   | 28   | rDLPFC       | Altruism          | 15             | 35         | 1.0            | 8       | 0.25      |
| Liao et al. (2018)       | 20.80       | 20   | 20   | vmPFC        | Altruism          | 20             | 25         | 2.0            | 6       | 0.48      |
| Liu et al. (2019)        | 25.6        | 27   | 28   | rDLPFC       | Altruism          | 15             | 35         | 1.5            | 7       | 0.97      |
(continued)
Table 1. (Continued)

| Author, year, Experiment | Age (years) | N(a) | N(c) | Active brain | Prosocial behavior | Duration (min) | Area (cm²) | Intensity (mA) | Q_Score | Hedges’ g |
|--------------------------|-------------|------|------|--------------|--------------------|----------------|------------|----------------|---------|-----------|
| Liu et al. (2019)        | 25.6        | 27   | 28   | rDLPFC       | Altruism           | 15             | 35         | 1.5            | 7       | 0.25      |
| Liu et al. (2019)        | 25.6        | 27   | 28   | rDLPFC       | Altruism           | 15             | 35         | 1.5            | 7       | 0.97      |
| Liu et al. (2019)        | 25.6        | 27   | 28   | rDLPFC       | Altruism           | 15             | 35         | 1.5            | 7       | 0.25      |
| Luo et al. (2017)        | 19.80       | 25   | 25   | rDLPFC       | Altruism           | 20             | 35         | 2.00           | 8       | 0.32      |
| Mai et al. (2016)        | 22.80       | 21   | 24   | rTPJ         | Empathy            | 20             | 35         | 1.50           | 8       | −0.47     |
| Mai et al. (2016)        | 22.80       | 21   | 24   | rTPJ         | Empathy            | 20             | 35         | 1.50           | 8       | −0.10     |
| Mai et al. (2016)        | 22.80       | 21   | 24   | rTPJ         | Empathy            | 20             | 35         | 1.50           | 8       | −0.04     |
| Mai et al. (2016)        | 22.80       | 21   | 24   | rTPJ         | Empathy            | 20             | 35         | 1.50           | 8       | −0.17     |
| Maréchal et al. (2017)   | 23.00       | 49   | 47   | rDLPFC       | Honesty            | 30             | 35         | 1.50           | 7       | 0.53      |
| Maréchal et al. (2017)   | 23.00       | 78   | 78   | rDLPFC       | Altruism           | 30             | 35         | 1.50           | 7       | −0.16     |
| Nihonsugi et al. (2015)  | 20.50       | 22   | 22   | rDLPFC       | Trust              | 9              | 35         | 2.00           | 6       | 0.45      |
| Peled-Avron et al. (2019)| 25.2        | 17   | 17   | rIFG         | Empathy            | 15             | 25         | 1.5            | 7       | −0.07     |
| Peled-Avron et al. (2019)| 25.2        | 18   | 18   | rIFG         | Empathy            | 15             | 25         | 1.5            | 7       | 1.56      |
| Rêgo et al. (2015)       | 24.00       | 12   | 12   | rDLPFC       | Empathy            | 15             | 35         | 2.00           | 8       | 0.70      |
| Ruff et al. (2013)       | 22.00       | 19   | 20   | rDLPFC       | Altruism           | 12             | 35         | 1.00           | 8       | 1.64      |
| Ruff et al. (2013)       | 22.00       | 19   | 20   | rDLPFC       | Altruism           | 12             | 35         | 1.00           | 8       | −1.10     |
| Santiesteban et al. (2012)| 26.50       | 17   | 15   | rTPJ         | ToM                | 20             | 35         | 1.00           | 5       | 1.15      |
| Snowdon et al. (2016)    | 23.07       | 33   | 33   | rDLPFC       | Empathy            | 20             | 35         | 1.50           | 8       | 0.10      |
| Snowdon et al. (2016)    | 23.07       | 33   | 33   | rDLPFC       | Altruism           | 20             | 35         | 1.50           | 8       | 0.17      |
| Tang et al. (2017)       | 22.36       | 32   | 34   | rTPJ         | Altruism           | 20             | 35         | 1.50           | 8       | 0.29      |
| Wang et al. (2014)       | 23.60       | 8    | 10   | IDLPFC       | Empathy            | 5              | 35         | 2.00           | 7       | 1.41      |
| Wang et al. (2016)       | 22.37       | 30   | 30   | rOFC         | Trust              | 15             | 9          | 2.00           | 7       | 1.13      |
| Wang et al. (2020)       | 22.35       | 30   | 30   | vmPFC        | Altruism           | 20             | 35         | 1              | 7       | −0.51     |

(continued)
Table 1. (Continued)

| Author, year, Experiment | Age (years) | N(a) | N(c) | Active brain | Prosocial behavior | Duration (min) | Area (cm²) | Intensity (mA) | Q_Score | Hedges’ g |
|--------------------------|-------------|------|------|--------------|-------------------|----------------|------------|---------------|---------|----------|
| Wang et al. (2020)       | 22.35       | 30   | 30   | vmPFC        | Altruism          | 20             | 35         | 1             | 7       | -0.52    |
| Wang et al. (2020)       | 22.35       | 30   | 30   | vmPFC        | Altruism          | 20             | 35         | 1             | 7       | -0.48    |
| Wang et al. (2020)       | 23.35       | 30   | 30   | vmPFC        | Altruism          | 20             | 35         | 1             | 7       | -0.44    |
| Wang et al. (2020)       | 23.35       | 30   | 30   | vmPFC        | Altruism          | 20             | 35         | 1             | 7       | -0.46    |
| Wang et al. (2020)       | 23.35       | 30   | 30   | vmPFC        | Altruism          | 20             | 35         | 1             | 7       | -0.42    |
| Wu et al. (2018)         | 24.39       | 23   | 23   | rIFG         | Empathy           | 20             | 35         | 1.5           | 7       | 0.31     |
| Wu et al. (2018)         | 24.39       | 23   | 23   | rIFG         | Empathy           | 20             | 35         | 1.5           | 7       | -0.05    |
| Wu et al. (2018)         | 23.57       | 32   | 32   | vmPFC        | Empathy           | 30             | 35         | 1.50          | 8       | -0.08    |
| Yuan et al. (2017)       | 21.50       | 20   | 20   | vmPFC        | Trust             | 20             | 35         | 2.00          | 8       | 1.31     |
| Zheng et al. (2016), exp1| 21.50       | 20   | 20   | vmPFC        | Trustworthiness   | 20             | 35         | 2.00          | 8       | 0.75     |
| Zheng et al. (2016), exp1| 21.50       | 20   | 20   | vmPFC        | Altruism          | 20             | 35         | 2.00          | 8       | 0.69     |
| Zheng et al. (2016), exp2| 21.50       | 20   | 20   | rDLPFC       | Trustworthiness   | 20             | 35         | 2.00          | 8       | 0.16     |
| Zheng et al. (2016), exp2| 21.50       | 20   | 20   | rDLPFC       | Altruism          | 20             | 35         | 2.00          | 8       | 0.14     |
| Zheng et al. (2017), exp1| 21.00       | 30   | 30   | rDLPFC       | Trust             | 20             | 35         | 2.00          | 8       | 0.08     |
| Zheng et al. (2017), exp2| 21.00       | 30   | 30   | rDLPFC       | Trust             | 20             | 35         | 2.00          | 8       | 0.03     |
| Zinchenko et al. (2019)  | 21.5        | 20   | 20   | rTPJ         | Altruism          | 15             | 25         | 1.5           | 7       | -0.19    |
| Zinchenko et al. (2019)  | 21.5        | 20   | 20   | rDLPFC       | Altruism          | 15             | 25         | 1.5           | 7       | -0.05    |
| Zinchenko et al. (2019)  | 21.5        | 20   | 20   | rTPJ         | Altruism          | 15             | 25         | 1.5           | 7       | -0.09    |
| Zinchenko et al. (2019)  | 21.5        | 20   | 20   | rDLPFC       | Altruism          | 15             | 25         | 1.5           | 7       | 0.07     |
| Zinchenko et al. (2019)  | 21.5        | 20   | 20   | rTPJ         | Altruism          | 15             | 25         | 1.5           | 7       | -0.17    |
| Zinchenko et al. (2019)  | 21.5        | 20   | 20   | rDLPFC       | Altruism          | 15             | 25         | 1.5           | 7       | -0.02    |

Note: Q_Score = quality score; N(a) = sample size of anodal condition; N(c) = sample size of control (sham) condition; ToM = theory of mind; vmPFC = ventromedial prefrontal cortex; rDLPFC = right dorsolateral prefrontal cortex; lDLPFC = left dorsolateral prefrontal cortex; rTPJ = right temporoparietal junction; rOFC = right orbitofrontal cortex; SI = somatosensory cortex.
| Author, year, Exp | Age (years) | N(ca) | N(c) | Deactivate brain | Prosocial behavior | Duration (min) | Area (cm²) | Intensity (mA) | Q_Score | Hedges’ g |
|------------------|------------|-------|------|------------------|--------------------|----------------|------------|----------------|---------|----------|
| Adenzato et al. (2019) | 68.3 | 15 | 15 | vmPFC | ToM | 6 | 35 | 1.5 | 8 | -0.23 |
| Adenzato et al. (2019) | 68.3 | 15 | 15 | vmPFC | ToM | 6 | 35 | 1.5 | 8 | 0.1 |
| Adenzato et al. (2019) | 67.5 | 15 | 15 | vmPFC | ToM | 6 | 35 | 1.5 | 8 | 0.06 |
| Adenzato et al. (2019) | 67.5 | 15 | 15 | vmPFC | ToM | 6 | 35 | 1.5 | 8 | -0.1 |
| Coll et al. (2017) | 26.54 | 16 | 16 | rTPJ | Empathy | 20 | 35 | 2.00 | 7 | -1.49 |
| Coll et al. (2017) | 25.69 | 16 | 16 | rTPJ | Empathy | 20 | 35 | 2.00 | 7 | 0.03 |
| Colzato et al. (2015) | 21.00 | 20 | 20 | vmPFC | Trust | 20 | 35 | 1.00 | 9 | -0.11 |
| Gross et al. (2018) | 21.40 | 32 | 32 | rDLPFC | Altruism | 30 | 35 | 2.00 | 9 | -0.10 |
| Li et al. (2018) | 24.04 | 28 | 28 | rDLPFC | Altruism | 15 | 35 | 1.00 | 8 | -0.77 |
| Li et al. (2018) | 24.04 | 28 | 28 | rDLPFC | Altruism | 15 | 35 | 1.00 | 8 | -0.99 |
| Liao et al. (2018) | 20.80 | 20 | 20 | vmPFC | Altruism | 20 | 35 | 2.00 | 6 | -0.57 |
| Liu et al. (2019) | 25.6 | 28 | 28 | rDLPFC | Altruism | 15 | 35 | 1.5 | 7 | -0.77 |
| Liu et al. (2019) | 25.6 | 28 | 28 | rDLPFC | Altruism | 15 | 35 | 1.5 | 7 | -1.03 |
| Liu et al. (2019) | 25.6 | 28 | 28 | rDLPFC | Altruism | 15 | 35 | 1.5 | 7 | -0.77 |
| Liu et al. (2019) | 25.6 | 28 | 28 | rDLPFC | Altruism | 15 | 35 | 1.5 | 7 | -1.03 |
| Luo et al. (2017) | 19.80 | 25 | 25 | rDLPFC | Altruism | 20 | 35 | 2.00 | 8 | -0.43 |
| Mai et al. (2016) | 22.80 | 23 | 23 | rTPJ | Empathy | 20 | 35 | 1.50 | 8 | -0.79 |
| Mai et al. (2016) | 22.80 | 23 | 23 | rTPJ | Empathy | 20 | 35 | 1.50 | 8 | -0.67 |
| Mai et al. (2016) | 22.80 | 23 | 23 | rTPJ | Empathy | 20 | 35 | 1.50 | 8 | 0.00 |
| Mai et al. (2016) | 22.80 | 23 | 23 | rTPJ | Empathy | 20 | 35 | 1.50 | 8 | 0.03 |
| Maréchal et al. (2017) | 23.00 | 49 | 49 | rDLPFC | Honesty | 30 | 35 | 1.50 | 7 | 0.05 |
| Maréchal et al. (2017) | 23.00 | 49 | 49 | rDLPFC | Altruism | 30 | 35 | 1.50 | 7 | -0.07 |
| Rêgo et al. (2015) | 24.00 | 12 | 12 | rDLPFC | Empathy | 15 | 35 | 2.00 | 8 | -0.14 |
| Ruff et al. (2013) | 22.00 | 24 | 24 | rDLPFC | Altruism | 12 | 35 | 1.00 | 8 | -0.97 |
| Ruff et al. (2013) | 22.00 | 24 | 24 | rDLPFC | Altruism | 12 | 35 | 1.00 | 8 | 0.52 |
Table 2. (Continued)

| Author, year, Exp | Age (years) | N(ca) | N(c) | Deactivate brain | Prosocial behavior | Duration (min) | Area (cm²) | Intensity (mA) | Q_Score | Hedges’ g |
|-------------------|-------------|-------|------|------------------|--------------------|----------------|-------------|---------------|---------|-----------|
| Santiesteban et al. (2012) | 26.50 | 17 | 15 | rTPJ | ToM | 20 | 35 | 1.00 | 5 | 0.24 |
| Tang et al. (2017) | 22.36 | 30 | 34 | rTPJ | Altruism | 20 | 35 | 1.50 | 8 | 0.39 |
| Wang et al. (2014) | 23.60 | 9 | 10 | lDLPFC | Empathy | 5 | 35 | 2.00 | 7 | 0.50 |
| Wang et al. (2020) | 22.35 | 30 | 30 | vmPFC | Altruism | 20 | 35 | 1 | 7 | −0.04 |
| Wang et al. (2020) | 22.35 | 30 | 30 | vmPFC | Altruism | 20 | 35 | 1 | 7 | 0.04 |
| Wang et al. (2020) | 22.35 | 30 | 30 | vmPFC | Altruism | 20 | 35 | 1 | 7 | 0.07 |
| Wang et al. (2020) | 23.35 | 30 | 30 | vmPFC | Altruism | 20 | 35 | 1 | 7 | −0.03 |
| Wang et al. (2020) | 23.35 | 30 | 30 | vmPFC | Altruism | 20 | 35 | 1 | 7 | 0.05 |
| Wang et al. (2020) | 23.35 | 30 | 30 | vmPFC | Altruism | 20 | 35 | 1 | 7 | 0.07 |
| Wu et al. (2018)  | 24.39 | 23 | 23 | rIFG | Empathy | 20 | 35 | 1.5 | 7 | −0.4 |
| Wu et al. (2018)  | 24.39 | 23 | 23 | rIFG | Empathy | 20 | 35 | 1.5 | 7 | −0.14 |
| Wu et al. (2018)  | 24.39 | 23 | 23 | rIFG | Empathy | 20 | 35 | 1.5 | 7 | −0.11 |
| Zheng et al. (2016), exp1 | 21.50 | 20 | 20 | vmPFC | Trustworthiness | 20 | 35 | 2.00 | 8 | 0.63 |

Note: Q_Score = quality score; N(ca) = sample size of cathodal condition; N(c) = sample size of control (sham) condition; ToM = theory of mind; vmPFC = ventromedial prefrontal cortex; rDLPFC = right dorsolateral prefrontal cortex; lDLPFC = left dorsolateral prefrontal cortex; rTPJ = right temporoparietal junction.
was significant when we fitted a two-level model with random effects at the study level, \( g = 0.21 \), 95% CI [0.03, 0.39], \( Z = 2.33, P = 0.020 \). In addition, cathodal tDCS significantly decreased prosocial behaviors after removing empathy and ToM effects (\( k = 22 \)), \( g = -0.26 \), 95% CI [−0.47, −0.05], \( Z = -2.42, P = 0.015 \). However, the effect was not significant using two-level model with random effects: \( g = -0.21 \), 95% CI [−0.49, 0.07], \( Z = -1.48, P = 0.140 \).

### Heterogeneity test and publication bias detection

The Q test for heterogeneity was significant in our two meta-analysis \( Q(69) = 232.17, P < 0.001, I^2 = 72.00\% \), \( Q(37) = 96.23, P < 0.001, I^2 = 62.38\% \), indicating the necessity for exploring potential moderators of these effects (Borenstein et al., 2011). To assess the potential publication bias, we first examined the adjusted effect size estimates following Duval and
Fig. 3. Forest plot of cathodal tDCS effect sizes (Hedges’ $g$) and 95% CI for each study and the overall effect size.

Tweedie’s (2000) Trim-and-Fill procedure. No missing effects were detected by the Trim-and-Fill method (Figure 4). Similarly, the Egger’s regression tests indicate that the risk of publication bias in both meta-analyses was little (the anodal effects: $Z = 1.29$, $P = 0.194$; the cathodal effects: $Z = -1.22$, $P = 0.222$).

**Moderator analyses**

Categorical variables. For the anodal tDCS effects, moderator analyses (sub-group analyses) revealed no main effects of the types of prosocial behavior ($Q_B (3) = 3.56$, $P = 0.313$), active brain areas ($Q_B (2) = 3.31$, $P = 0.191$) as well as online/offline stimulation ($Q_B (1) < 0.001$, $P = 0.976$). Along the same lines, the types of social behavior ($Q_B (2) = 1.83$, $P = 0.400$), active brain areas ($Q_B (1) = 0.89$, $P = 0.347$) and online/offline stimulation ($Q_B (1) = 1.38$, $P = 0.241$) did not significantly moderate the cathodal tDCS effects. Note that those levels with the number of effects ($k$) less than 5 were excluded in the above moderator analyses, given that a small number of effects ($k < 5$) might result in low statistical power and be unable to produce reliable results.

Continuous variables. Meta-regression analyses evidenced that only current density significantly moderated the anodal effects tDCS on prosocial behaviors ($Q_B (1) = 3.39$, $P = 0.047$). No modulating roles of other various continuous variables in the anodal effects tDCS on prosocial behaviors such as stimulating duration ($Q_B (1) = 0.80$, $P = 0.371$), age ($Q_B (1) = 1.40$, $P = 0.237$) and
Fig. 4. Funnel plots representative of publishing bias of two meta-analyses.

Fig. 5. Meta-regression of anodal tDCS effect.

These factors also did not significantly moderate the cathodal tDCS effects: current density, \( Q_B(1) = 0.25, P = 0.617 \); stimulate duration, \( Q_B(1) = 0.38, P = 0.538 \); age, \( Q_B(1) = 0.25, P = 0.615 \) and quality score, \( Q_B(1) = 0.02, P = 0.889 \) (Figure 6).

P-Curve analysis. P-curve analysis combines the half and full P-curve to make inferences about evidential value. In particular, if the half P-curve test is right-skewed with \( P < 0.05 \) or both the half and full tests are right-skewed with \( P < 0.1 \), then P-curve analysis indicates the presence of evidential value (Simonsohn et al., 2015). Our P-curve analysis revealed that it was significantly right-skewed for the anodal tDCS effects, Full P-curve: \( z = -6.88, P < 0.001 \); Half P-curve: \( z = -6.88, P < 0.001 \) (Figure 7); and the cathodal tDCS effects, Full P-curve: \( z = -4.68, P < 0.001 \); Half P-curve: \( z = -3.90, P < 0.001 \), suggesting sufficient evidence for justifying the existence of the anodal and cathodal effects on prosocial behaviors.

Similarly, P-curve analysis indicates that evidential value is inadequate or absent if the 33% power test is \( P < 0.05 \) for the full P-curve or both the half P-curve and binomial 33% power test are \( P < 0.1 \). The flatter than 33% power test in the current meta-analysis is non-significant binomial test: \( P_{Binomial} = 0.903 \), Full P-curve: \( z = 3.54, P > 0.999 \); Half P-curve: \( z = 6.774, P > 0.999 \) in the anodal tDCS effects (\( P_{Binomial} = 0.97 \), Full P-curve: \( z = 2.13, P = 0.983 \); Half P-curve: \( z = 4.430, P > 0.999 \) in the cathodal tDCS effects), indicating that evidential value is adequate to support the existence of the effects. These results suggest that the included studies reflect a real effect of the relationship
Fig. 6. Meta-regression of cathodal tDCS effect.

Fig. 7. Observed P-curve for anodal tDCS effects on prosocial behavior in the meta-analysis. The observed P-curve includes 17 statistically significant (P < 0.05) results, of which 14 were P < 0.025. Fifty-three additional results were entered but excluded from the P-curve because they were P > 0.05. The blue line shows the observed P-curve, the dashed red line shows the uniform distribution of the P-values and the green line plots the right-skewed distribution for a power level of 33%.

Discussion

The current meta-analyses found that anodal tDCS promoted prosocial behaviors, whereas cathodal tDCS inhibited them. The risk of publication bias for the included effect sizes was low. These effects were not modulated by a range of factors such as stimulation site, types of prosocial behavior and stimulation parameters (e.g. stimulate duration, current intensity). The P-curve analysis showed that the P-values for anodal and cathodal tDCS effects were significantly right-skewed, indicating evidential value supporting the existence of the anodal and cathodal tDCS effects on prosocial behaviors.

tDCS technique was proved to be able to alter many aspects of cognitive processes and behaviors (such as enhancing perceptual and motor learning) among healthy adults (Falcone et al., 2012; Galli et al., 2019). However, the impact of tDCS on social decision-making is often debated (Sellaro et al., 2016). The current meta-analysis indicated that anodal tDCS increases prosocial behaviors and cathode tDCS reduces prosocial behaviors. Such anodal-excitation and cathodal-inhibition dual-polarity effect have not been consistently observed in previous tDCS studies. For example, a number of studies have reported the lack of inhibitory cathodal effects on perception and motor learning, indicating that cathodal stimulation effects are in general less reliable in modulating cognitive processes (Jacobson et al., 2012). In the social domain, several studies also reported a lack of cathodal effects, but significant anodal effects (Kuehne et al., 2015; Sellaro et al., 2015). Similarly, in the current meta-analysis, several studies reported significant anodal effects but non-significant cathodal effects (e.g. Santiesteban et al., 2012; Maréchal et al., 2017). However, lumping together these studies, we found that weighted mean effect sizes of the anodal and cathodal stimulations were generally comparable, although the cathodal effects tended to be slightly weaker than the anodal effects when we fitted a two-level model with random effects at the study level. The bidirectional effects of tDCS on prosociality

It is noteworthy that although the current density was found to significantly moderate the anodal effects tDCS on prosocial behaviors (Qa(1) = 3.39, P = 0.047), this effect was not replicated in the cathodal tDCS effects. These results suggested that the moderating effect did not exist.
may suggest that the initial neuronal activation state in the 'social brain' is subject to substantial modulation.

We also found that the risk of publication bias of the current meta-analyses was low. In addition, the P-curve analysis indicated that anodal or cathodal tDCS had a real effect on prosocial behaviors. Importantly, the effect sizes of anodal tDCS ($g = 0.27$) and cathode tDCS ($g = -0.19$) are relatively small, and the confidence interval range was relatively wide, with the lower limit close to zero. Hence, overall, the tDCS effects on prosocial behavior are relatively weak, and further RCTs with larger sample sizes are warranted. These findings also suggest that the observed tDCS effects on prosocial behaviors are unlikely to be driven by publication bias and P-hacking, as shown by the above P-curve analyses.

Although the results revealed that the included effects were substantially heterogeneous, no reliable significant moderators were found. Subgroup analyses indicated that neither the types of social behavior nor active brain areas significantly moderate the effects. In the identified literature, prosocial behavior mainly included the following categories: trust, trustworthiness, altruism, honesty, empathy and ToM. Our results showed that the tDCS effect did not significantly differ across those types of prosocial behaviors, indicating that tDCS stimulation has a general effect on prosociality independent of specific social tasks or domains. However, it is worth noting that the non-significant effects for the sub-types of social behavior may result from the small number of effect sizes in each category. Despite our results did not show significant moderate effects, several studies included in our meta-analysis reported that the application of anodal tDCS over the prefrontal cortex enhanced the trustee’s repayment through altruism (Wang et al., 2016; Zheng et al., 2016), whereas no such significant effect was reported on investment as the trustee (Zheng et al., 2017). Future studies should further explore prosocial behaviors that are most sensitive to tDCS manipulation using more rigorous procedures that consider factors known to influence tDCS.

In the included studies in our meta-analysis, the commonly used stimulation brain areas are vmPFC, rDLPFC and rTPJ. These regions are part of the 'social brain' circuits (Adolphs, 2003, 2009), which are involved in the process of metalinguistic and empathy (Chakroff and Young, 2014). It has been demonstrated that the vmPFC is associated with decisions involving trustworthiness and altruism (Waytz et al., 2012). For example, patients with lesions in the vmPFC showed less trustworthiness and altruism than control subjects (Moretto et al., 2013). In addition, clinical lesion studies reported that patients with damage to the vmPFC gave significantly less allocation in the dictator game as well as showed less trustworthiness in the trust game. The vmPFC has been posited to be a hub of processing action-outcome contingencies in goal-directed behaviors (Huang et al., 2020), which might indicate that the vmPFC is indispensable in both altruistic and trustworthy decisions (Krajbich et al., 2009).

In addition, rDLPFC has been shown to play an important role in social norm compliance. For instance, Sanfey et al. (2003) showed that dlPFC was associated with social norm compliance in the US. Similarly, Ruff et al. (2013) reported that social norm compliance was changed while the activity of rDLPFC was manipulated by tDCS. Furthermore, rTPJ is a key node within the 'social brain' for decision-making involved in self-centered and other-regarding concerns (Soutschek et al., 2016; Tang et al., 2017), which has been implicated in sophisticated representations of others’ mental states and integrating these into social decisions (Lockwood et al., 2019). We did not find any modulation effect of stimulation sites, suggesting that all these regions play an important role in prosocial behaviors. Importantly, these regions are functionally and anatomically well-connected (Kennedy and Adolphs, 2012). Stimulation any node of this 'social brain' network may activate the whole circuit and elicit comparable behavioral effects. Our results provide evidence supporting that activity in the 'social brain', comprising TPJ, dlPFC and vmPFC, is causally linked to prosocial behaviors.

In addition, meta-regression results showed no significant influence of stimulation parameters such as stimulation duration and current intensity. There are some plausible explanations for these non-significant moderating results. First, most studies used typical stimulating parameters such as 12–20 min stimulation durations and 1~2 mA intensities of the current. There may not be enough variances between studies to detect the modulation effects of these parameters. Second, the stimulating parameters (stimulation duration and current intensity) used by the investigators were both able to elicit a transient stimulating effect of tDCS. Finally, the small number of included studies may also limit our ability to detect significant moderating effects because of low statistical power.

The current study suffers from a few limitations. First, our meta-analysis only pooled together the studies that assessed the effects of one single session of tDCS, which resulted from the fact that by far no RCTs have explored the medium- or long-term outcomes of tDCS on prosocial behavior. Future studies should evaluate the long-term outcomes of tDCS. Second, the included participant samples were restricted to healthy adults. It remains unclear whether such effects are generalizable to people with psychiatric conditions such as ADHD (Young, 2005), autism (Fontes-Dutra et al., 2019), and schizophrenia (Doddell-Feder et al., 2015), etc. It should be noted that tDCS may exert stronger effects in patients with psychiatric disorders such as autism and schizophrenia (Lee et al., 2018; Kim et al., 2019). Third, due to the complexity of prosocial behavior, only a limited number of studies were included in each specific type of prosocial behavior. This might contribute to the non-significant modulation effect of behavior type, and for this reason, the moderator analysis results documented in the present study require further investigation. Last, most studies included in the current meta-analysis did not measure individual differences at baselines in emotion or trait tendencies (e.g. social value orientation), we were unable to test whether participants’ characteristics were potential modulator factors in our meta-analysis. Future studies are encouraged to systematically examine the role of participants’ characteristics in the tDCS effects on prosocial behaviors. tDCS has become increasingly recognized as a promising tool in neuroscience research for understanding the relationship between brain and behavior in both healthy humans and clinical populations (Filmer et al., 2014). Indeed, several studies have provided converging evidence showing that tDCS is suited to modulate basic cognitive (Kuo and Nitsche, 2012, 2015; Kadosh, 2015) and sensory–perceptual functioning (Costa et al., 2015) and to ameliorate symptoms of many neurological and psychiatric disorders (Brunoni et al., 2012). However, there is still some controversy regarding whether tDCS can effectively change the prosocial behaviors due to the wide range of prosocial behaviors and the heterogeneity in experimental tasks. No previous meta-analysis has systematically examined the effects of tDCS on prosocial behavior. Our meta-analytic study improved our understanding of how prosocial behaviors are linked to the activity of the 'social brain' and supported the promising potential of tDCS in modulating high-order social functioning. Our results, for the first time, showed that tDCS effects were not modulated by the types of prosocial behavior, suggesting that
tDCS stimulation can be used to improve different types of prosocial behavior and may be effective in treating psychiatric disorders that are characterized by deficits in general social functions. The convergent evidence from the meta-analysis is important to allow valid and reliable interpretation of findings in neurotypical cohorts, but also to allow tailored tDCS protocols to atypical groups with social difficulties.

Conclusion

Although tDCS has been widely used to change cognition and motor control (Miniussi et al., 2013), the application of tDCS to alter high-level social behaviors is still under development. Our findings point out that both anodal and cathodal tDCS have significant effects on prosocial behaviors, suggesting a causal role of several key nodes within the ‘social brain’ in orchestrating human social behaviors. Given the complexity of prosocial behavior, future research is encouraged to systematically vary the stimulation parameters (e.g. stimulation protocol, current intensity and electrode montage) to gain a better understanding of the beneficial effects of tDCS on social behaviors.

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Conflict of interests

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Supplementary data

Supplementary data are available at SCAN online.

Contributors

Y.B. and W.Y. recorded and analyzed the metadata; Y.B. wrote the first draft of the manuscript; Y.B., Y.C.L., S.T. and Y.R.J. revised the manuscript. All authors approved the final version of the manuscript.

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