



Causal role of temporo-parietal junction for social behavior: A meta-analysis

Alexander Soutschek^{*} , Rebekka S. Mattes 

Department for Psychology, Ludwig-Maximilians-Universität (LMU), Munich, Germany

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ABSTRACT

Objective: The temporo-parietal junction (TPJ) is thought to play a key role in human social behavior, however, there is currently no consensus on which aspects of social behavior are under TPJ control. Here, we tested the hypothesis that the TPJ causally underlies behaviors that require distinguishing between one's own and others' mental perspectives by conducting a meta-analysis of brain stimulation studies modulating TPJ activation during social cognition (94 papers with 160 effect sizes from 4073 participants).

Results: Our meta-analysis revealed that stimulation of the TPJ shows small-to-moderate effects on the ability to distinguish between one's own and others' mental states (standardized mean difference (SMD) = 0.36) as well as on norm-guided social decision making (SMD = 0.36). In contrast, we observed no significant impact of TPJ stimulation on empathy (SMD = 0.17) or joint attention (SMD = 0.05), though we note that relatively few effect sizes were available for these two categories. Moreover, transcranial magnetic stimulation showed stronger effects on social cognition than transcranial electrical stimulation.

Conclusions: Taken together, our meta-analysis informs us about the effectiveness of different brain stimulation protocols for modulating social behavior and clarifies which aspects of social behavior are causally implemented by the TPJ, improving our understanding of the neural basis of social behavior.

1. Introduction

Interactions with other people crucially rely on the capacity to infer the feelings, thoughts, and intentions of interaction partners, an ability referred to as “social cognition” [1]. Deficits in social cognition are prevalent in many clinical disorders [2–4], impairing patients' ability to interact successfully with others. For both basic and clinical research, it is therefore important to obtain a better understanding of the neural basis of human social behavior. The temporo-parietal junction (TPJ) has been ascribed a central role for social cognition and particularly for mentalizing (i.e., the ability to infer others' mental states), as evidenced by a large body of neuroimaging findings [5,6]. Dysfunctions of the TPJ also contribute to social cognition impairments in clinical disorders [7, 8], and brain maturation in the TPJ predicts the development of social skills in children [9]. However, to understand whether changes in social behavior can be explained by altered TPJ functioning, it is necessary to establish a causal link between TPJ activation and social behavior. Therefore, the goal of the current meta-analysis was to assess which aspects of human social behavior are causally related to TPJ activation.

Social cognition is a broad construct with several subcomponents, and not all of them might rely on TPJ activation in the same way. While there is no established, generally accepted classification of social cognition in the literature, we assume that social cognition comprises the following categories: (i) empathy, (ii) self-other distinction (understanding the perspectives and thoughts of others, attribution of mental states, and control of action imitation), (iii) norm-guided social behavior, and (iv) joint attention (e.g., social gaze cueing). Norm-guided social behavior can be subdivided further into evaluations of others' moral behavior (moral judgements), identifying dishonest or deceiving behavior (deception detection), and social decision making (e.g., costly sharing goods with others). Similar classifications have been assumed by past research [10–13], though commonly with fewer categories. Classifying social behaviors into several subcategories has the advantage of providing a more detailed picture of which aspects of social behavior might be influenced by TPJ stimulation. We do not claim, however, that these components are fully dissociable: Moral judgements, for example, require evaluating others' intentions, which in turn is thought to rely on perspective taking [14]. Likewise, the TPJ's contribution to prosocial

^{*} Corresponding author. Department for Psychology, LMU, Munich, Leopoldstr. 13, 80802, Munich, Germany.

E-mail address: Alexander.soutschek@psy.lmu.de (A. Soutschek).

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decision making is at least partially related to perspective taking [15–17]. While a previous meta-analysis already revealed evidence that non-invasive brain stimulation of the TPJ influences visual perspective taking [18], less is known about whether the TPJ also causally contributes to other domains of social cognition. Empathy, for example, has been related to a network comprising the anterior cingulate cortex and the insula rather than the TPJ [19,20]. This raises the question as to which domains of social behavior are influenced by TPJ activation, and which are not. Our meta-analysis aimed to comprehensively assess the effects of TPJ-targeted brain stimulation on different subcomponents of human social behavior to determine which aspects of social cognition are causally related to TPJ activation. We hypothesized that the TPJ causally influences aspects of social behavior that require distinguishing between the cognitive states of oneself and others (including perspective taking and social decision making), whereas the TPJ might show weaker influences on empathic reactions in social interactions.

A further goal of the current meta-analysis was to compare the effectiveness of different brain stimulation methods for manipulating social cognition. Neural activation can non-invasively be manipulated in humans by either transcranial magnetic stimulation (TMS) or transcranial electrical stimulation (tES). While TMS is commonly assumed to have robust effects on cognition [21,22], the reliability of tES effects is often evaluated more skeptically [23,24], despite the evidence for small-to-moderate effects on non-social cognition in recent tES meta-analyses [25–27]. A further goal of the current meta-analysis therefore was to assess and compare the influence of TMS versus tES on social cognition. We hypothesized that both tES and TMS influence social behavior, though we expected TMS to show stronger effects than tES.

A last goal was to investigate hemispheric differences in TPJ functioning. While most research focuses on the right TPJ, meta-analyses of imaging studies suggest that the left TPJ might also be involved in social behavior [5,6]. We therefore explored whether brain stimulation studies provide evidence for dissociable contributions of the right and left TPJ to social behavior.

2. Materials and methods

We conducted a meta-analysis to determine the impact of TPJ-targeted non-invasive brain stimulation on human social cognition. The meta-analysis was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [28].

2.1. Literature search and study selection criteria

A literature search was carried out using PubMed and Web of Science in June 2025 using the following search terms: (“stimulation” OR “tms” OR “TBS” OR “tacs” OR “tdcs” OR “ultrasound”) AND (“social” OR “social interaction” OR “empathy” OR “emotion recognition” OR “mentalizing” OR “theory of mind” OR “perspective taking” OR “perspective-taking” OR “prosocial” OR “generosity” OR “inequal” OR “fairness” OR “moral” OR “deception” OR “imitation”) AND (“temporoparietal junction” OR “temporo-parietal junction” OR “TPJ”).

A total of 484 records were identified in the initial search (248 from PubMed, 236 from Web of Science), which were reduced to 345 studies after the removal of duplicates. Then, we preselected relevant articles by screening the titles and abstracts of the studies, which resulted in a preselection of 116 articles. Among these preselected studies, the two authors then assessed the eligibility of the studies by a full-text analysis. The inter-rater agreement of the selection process was high (92 %), and disagreements were resolved through further discussion.

We selected studies that (i) included healthy adults as participants (age 18–60), (ii) applied non-invasive brain stimulation (TMS, tDCS, tACS, or tRNS) over right or left TPJ, (iii) reported original data, (iv) assessed the effects of TPJ stimulation on behavior in a task paradigm

measuring social behavior. We excluded articles from the meta-analysis if they met one of the following exclusion criteria: (i) the article type represented a review, meta-analysis, or commentary, (ii) the study tested stimulation effects only on children, adolescents, older adults, or clinical populations, (iii) reported only neuroimaging results, (iv) assessed stimulation effects only on physiological measures but not on behavior, or (v) applied non-invasive brain stimulation only to other brain regions than the TPJ. From the 116 studies selected for full-text analysis, we excluded 8 studies because they did not investigate social behavior, 5 studies because they stimulated other areas than the TPJ, 6 studies on patients rather than healthy individuals, and one study because it re-analyzed already published data. One study was assessed as eligible but had to be excluded from the analysis because no effect size could be computed based on the information reported in the paper, and no effect sizes or raw data were provided by the authors [29]. A further potentially eligible study was excluded due to the lack of an appropriate TMS control condition [30]. As a result of this selection procedure, 94 studies with 160 effect sizes were included in the meta-analysis (Fig. 1).

2.2. Statistical analysis

We first calculated Cohen’s *d* (standardized mean difference, SMD) for each study based on the data and statistical tests reported in the included papers. If sufficient statistics for effect size calculation were not reported, we estimated effect sizes by deriving means and standard deviations from plots using the online tool WebPlotDigitizer (<https://we.b.eecs.utk.edu/~dcostine/personal/PowerDeviceLib/DigiTest/>) or asked the authors of the studies for the required effect sizes or the data. We computed effect sizes for the primary outcome variable reported in each study (e.g., accuracy, reaction times, rating scores, or value-based choices). If a study reported results for more than one dependent variable, we selected the variable of primary interest (e.g., reaction times if the study authors considered variation in accuracy as too low for being susceptible to stimulation effects). For tDCS studies administering both anodal and cathodal tDCS, we computed separate effect sizes for anodal vs. sham tDCS and cathodal vs. sham tDCS under the assumption that anodal and cathodal stimulation increase and reduce, respectively, the excitability of the stimulated brain area.

We used the metafor package in R [31] to calculate hierarchical random-effects meta-analyses on the effect sizes from the single studies with the `rma.vlm` function, modelling study-specific random intercepts. Hierarchical random-effects models increase the generalizability of results by considering both the within-study and between-study variance [32]. Because publication bias can distort effect size estimations in meta-analyses, we examined the risk of publication bias with funnel plots and Egger’s regression tests [33], which quantifies asymmetry in the distribution of effect sizes. Finally, heterogeneity was tested using Cochran *Q* and the I^2 statistics. The *Q* statistic assesses whether heterogeneity between studies is significantly different from zero. I^2 was computed with the `dmeter` package [34] and indicates the proportion of the variance in effect size estimates that can be explained by heterogeneity between effect sizes ($I^2_{Level\ 2}$) and between studies ($I^2_{Level\ 3}$).

To test the impact of TPJ stimulation on different domains of social behavior, we classified task paradigms in the included studies according to the following categories: (1) empathy (e.g., empathy for pain), (2) self-other distinction, (3) norm-guided behavior, and (4) joint attention (e.g., social gaze cueing). Studies assessing self-other distinction were further subdivided into categories for (2a) visual perspective taking (evaluating an object from the view of another person), (2b) theory of mind (recognizing the mental or emotional state of another person), (2c) imitation control (ability to inhibit the automatic imitation of others’ behavior), and (2d) self-other discrimination (ability to discriminate between oneself and another person, e.g. when evaluating faces). Norm-guided behavior was subclassified into (3a) moral judgements (evaluating whether actions are morally legitimate), (3b) deception (recognizing others’ deception or deceiving others), (3c) proactive fairness

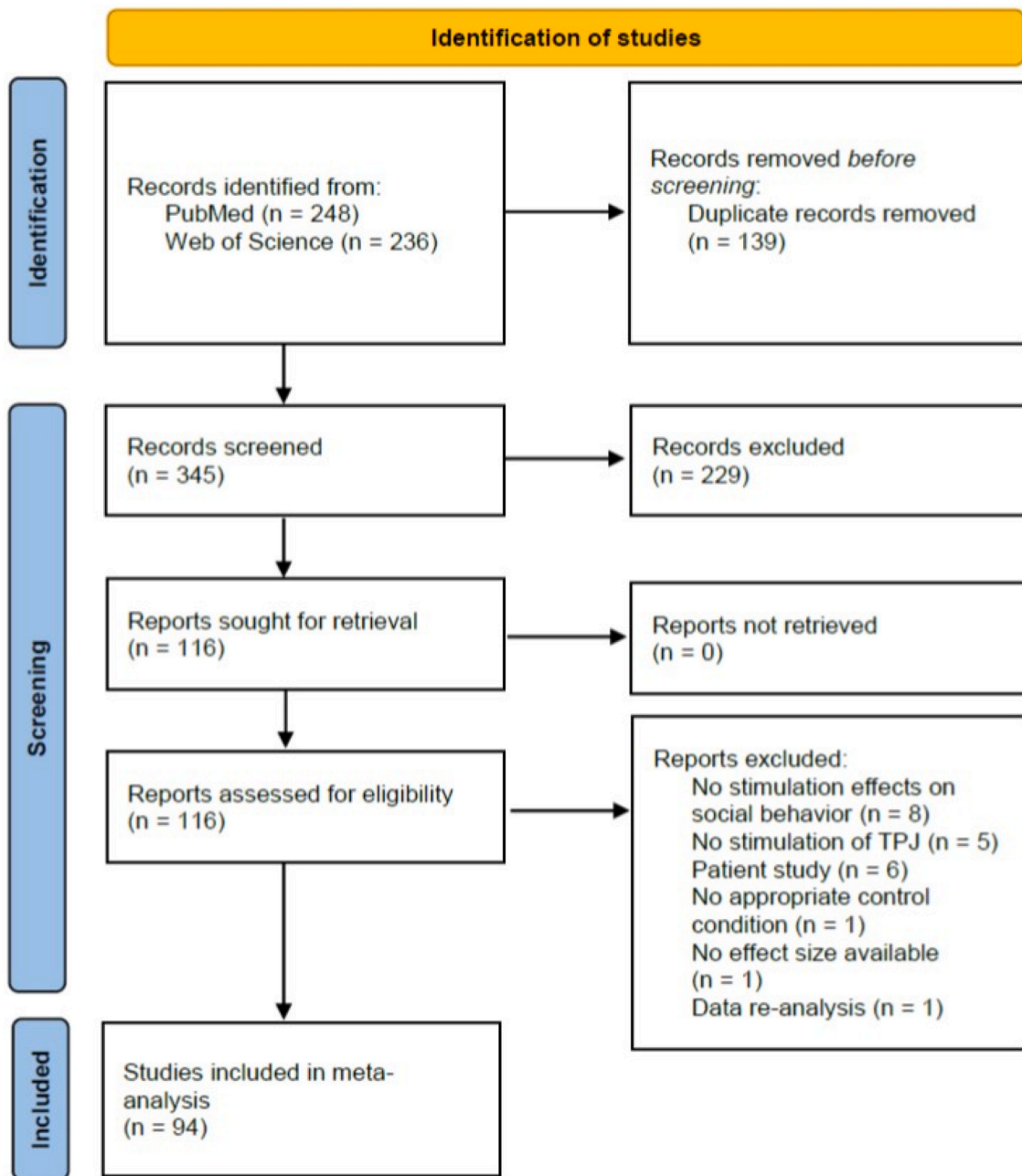


Fig. 1. Flow diagram of each step of the literature search and selection process following the PRISMA guidelines.

Table 1
Overview over studies on empathy.

Study	Protocol	Active	Control	Intensity	Duration	Electrodes/Coil	Design	Hemi.	Timing	N
Bowling et al. (2017) [68]	tDCS	tRNS	sham	1.5 mA	20 min	5 × 5 cm ²	Within	R	Online	24
Coll et al. (2017) [69]	tDCS	anodal, cathodal	sham	2 mA	20 min	7 × 5 cm ²	Between	R	Offline	48
Repetti et al. (2022) [70]	tDCS	cathodal	Sham	2 mA	20 min	7 × 5 cm ²	Between	R	Online	110
Vandenbrouke et al. (2016) [71]	tDCS	anodal, cathodal	Sham	1.5 mA	20 min	7 × 5, 10 × 10 cm ²	Within	R	Online	22
Bukowski et al. (2019) [72]	TMS	cTBS	vertex	80 % aMT	40 s	Figure-8	Within	R	Offline	31
Hartmann et al. (2024) [73]	TMS	rTMS	vertex	90 % rMT	2 s	Figure-8	Within	R	Online	14
Miller et al. (2020) [74]	TMS	rTMS	vertex	100 % rMT	20 min	Figure-8	Within	R	Offline	34
Paracampo et al. (2018) [75]	TMS	rTMS	Sham	90 % rMT	2 s	Figure-8	Within	R	Online	16
Silani et al. (2013) [48]	TMS	rTMS	vertex	110 % rMT	15 min	Figure-8	Between	R	Offline	45

Table 2
Overview over studies on self-other distinction.

Study	Protocol	Active	Control	Intensity	Duration	Electrodes/coils	Design	Hemi.	Timing	N
<i>Visual perspective taking</i>										
Christian et al. (2023) [15]	tDCS	tACS	sham	1.5 mA	30 min	5 × 5, 10 × 10 cm ²	Within	R	online	30
Martin, Huang et al. (2019) [76]	tDCS	Anodal	sham	1 mA	20 min	2.5 cm diameter	Within	R	online	25
Martin, Su et al. (2019) [77]	tDCS	Anodal	sham	1 mA	20 min	2.5 cm diameter	Within	R	online	52
Martin et al. (2020) [78]	tDCS	Anodal	sham	1 mA	20 min	2.5 cm diameter	Within	R	online	44
Nobusako et al. (2017) [79]	tDCS	Anodal	sham	1 mA	20 min	5 × 7 cm ²	between	R	offline	20
Santiesteban et al. (2012) [80]	tDCS	anodal, cathodal	Sham	1 mA	20 min	5 × 7 cm ²	between	R	online	49
Santiesteban et al. (2015) [55]	tDCS	Anodal	Sham	1 mA	20 min	5 × 7 cm ²	between	R, L	offline	45
Soutschek et al. (2024) [16]	tDCS	anodal, cathodal	Sham	1.5 mA	30 min	2 cm diameter	Within	R	online	47
van Elk et al. (2017) [81]	tDCS	anodal, cathodal	Sham	1 mA	20 min	5 × 7 cm ²	between	R	online	45
Yang et al. (2020) [56]	tDCS	Anodal	Sham	2 mA	30 min	5 × 7 cm ²	Within	R, L	online	45
Gaesser et al. (2019) [82]	TMS	rTMS	occipital	60 % MSO	17 min	Figure-8	Within	R	offline	23
Santiesteban et al. (2017) [83]	TMS	rTMS	occipital	110 % rMT	0.5 s	Figure-8	within	R	online	19
Soutschek et al. (2016) [84]	TMS	cTBS	vertex	80 % aMT	40 s	Figure-8	between	L	offline	38
Wang et al. (2016) [85]	TMS	rTMS	no TMS	110 % rMT	0.1 s	Figure-8	within	R	online	15
<i>Imitation inhibition</i>										
Bardi et al. (2017) [94]	tDCS	anodal, cathodal	Sham	75 % MSO	0.5 s	Figure-8	within	R	online	16
Hogeven et al. (2015) [86]	tDCS	Anodal	Sham	1 mA	20 min	5 × 7 cm ²	between	R	offline	33
Nobusako et al. (2017) [79]	tDCS	Anodal	Sham	1 mA	20 min	5 × 7 cm ²	between	R	offline	20
Santiesteban et al. (2012) [80]	tDCS	anodal, cathodal	Sham	1 mA	20 min	5 × 7 cm ²	between	R	online	49
Santiesteban et al. (2015) [55]	tDCS	Anodal	Sham	1 mA	20 min	5 × 7 cm ²	between	R, L	offline	45
Yang et al. (2020) [56]	tDCS	Anodal	Sham	2 mA	30 min	5 × 7 cm ²	within	R, L	offline	45
Duffy et al. (2019) [87]	TMS	iTBS	Sham	80 % aMT	192 s	Figure-8	between	R	offline	47
Era et al. (2020) [88]	TMS	cTBS	Sham	80 % aMT	20 s	Figure-8	within	R	offline	18
Giardina et al. (2015) [89]	TMS	rTMS	Sham	90 % rMT	10 min	Figure-8	between	R	offline	20
Sowden & Catmur (2015) [90]	TMS	rTMS	occipital	110 % rMT	0.5s	Figure-8	within	R	online	16
<i>Theory of mind</i>										
Filmer et al. (2019) [91]	tDCS	anodal, cathodal	Sham	1 mA	20 min	5 × 5 cm ²	between	R	offline	77
Mai et al. (2016) [92]	tDCS	anodal, cathodal	Sham	1.5 mA	20 min	5 × 7 cm ²	between	R	offline	68
Manfredi et al. (2020) [93]	tDCS	anodal	Sham	1 mA	11 min	4 × 4 cm ²	within	R	online	36
Bardi et al. (2017) [94]	TMS	rTMS	vertex	75 % MSO	0.5 s	Figure-8	within	R	online	19
Boux et al. (2023) [95]	TMS	rTMS	Sham	90 % rMT	25 min	Figure-8	within	R	offline	26
Costa et al. (2008) [54]	TMS	rTMS	vertex	90 % rMT	15 min	Figure-8	within	R, L	offline	11
Donaldson et al. (2019) [96]	tDCS	anodal, cathodal	Sham	2 mA	20 min	2 cm diameter	between	R	offline	53
Ge et al. (2022) [97]	tDCS	anodal	Sham	1.5 mA	20 min	5 × 7 cm ²	between	R	offline	58
Martin et al. (2017) [98]	tDCS	anodal	Sham	1 mA	20 min	2.5 cm diameter	within	R	online	20
Martin et al. (2021) [99]	tDCS	anodal	Sham	1 mA	20 min	2.5 cm diameter	within	R	online	25
Nejati et al. (2024) [100]	tDCS	anodal	Sham	1.5 mA	20 min	5 × 5 cm ²	within	R	online	26
Pereira et al. (2021) [145]	tDCS	anodal	Sham	1 mA	20 min	12 mm diameter	within	R	offline	20
Santiesteban et al. (2012) [80]	tDCS	anodal, cathodal	Sham	1 mA	20 min	5 × 7 cm ²	between	R	online	49
Santiesteban et al. (2015) [55]	tDCS	Anodal	Sham	1 mA	20 min	5 × 7 cm ²	between	R, L	offline	45
Zhang et al. (2023) [101]	tDCS	anodal, cathodal	Sham	2 mA	20 min	5 × 7 cm ²	between	R	offline	62
Gamond et al. (2016) [102]	TMS	rTMS	vertex	60 % MSO	0.2 s	Figure-8	within	R	online	20
Gooding-Williams et al. (2017) [103]	TMS	6 Hz rTMS	10 Hz	90 rMT	2.5 s	Figure-8	within	R	online	15
Krall et al. (2018) [104]	TMS	cTBS	vertex	30 % MSO	40 s	Figure-8	within	R	offline	20
Paracampo et al. (2017) [105]	TMS	rTMS	Sham	90 % rMT	2 s	Figure-8	within	R	Online	16
<i>Self-other discrimination</i>										
Nejati et al. (2023) [106]	tDCS	Anodal	Sham	2 mA	20 min	5 × 5 cm ²	within	R	online	20
Payne et al. (2017) [107]	tDCS	anodal, cathodal	Sham	1 mA	20 min	2 cm diameter	between	R	offline	60
Heinisch et al. (2011) [108]	TMS	rTMS	Sham	100 % rMT	20 min	Figure-8	within	R, L	offline	10
Sun et al. (2023) [109]	TMS	cTBS	Sham	80 % aMT	40 s	Figure-8	within	L	offline	30

(prosociality and costly giving), (3d) reactive fairness (e.g., costly punishing others for their unfairness), and (3e) strategic social interactions (repeated competitive interactions with others). We performed separate analyses for these different categories to test which aspects of social behavior are altered by TPJ stimulation. An overview of the classification of the effect sizes from different studies is provided by Tables 1–4. Note that several studies employed two or more experimental tasks belonging to different (sub-) categories.

3. Results

The meta-analysis included a total of 94 papers with 160 effect sizes from 4073 participants. 12 effect sizes (from 344 participants) were categorized as measuring empathy, 72 effect sizes measured self-other distinction (from 1415 participants), 72 effect sizes (from 2379 participants) measured norm-guided behavior, and 4 effect sizes (107 participants) measured joint attention. Across all domains of social behavior, we observed evidence for a significant influence of TPJ stimulation, SMD = 0.33, 95 % CI = [0.27, 0.39], $p < 0.001$, though

with substantial heterogeneity between studies, $I^2_{level 2} = 49.0\%$, $I^2_{level 3} = 5.0\%$, $Q(159) = 340.76$, $p < 0.001$. This heterogeneity might stem from different factors: First, there were remarkable differences in stimulation protocols between studies. 31 (33 %) and 63 (67 %) studies employed TMS and tDCS, respectively. Among the TMS studies, 39 % used online (single-pulse and repetitive (r)TMS) and 61 % offline (theta-burst and rTMS) designs, whereas among the tDCS studies 30 (48 %) employed online and 33 (52 %) offline designs. Administered stimulation intensities also substantially varied for TMS (ranging from 80 % active motor threshold (MT) to 110 % resting MT) and tDCS studies (from 0.8 to 2 mA, with the effective current density depending additionally on electrode size). As a second source of heterogeneity, we assume that TPJ stimulation effects might vary between different domains of social cognition. In the next step, we therefore separately assessed the impact of TPJ stimulation on different domains of social cognition.

3.1. Empathy

There was no significant evidence that TPJ stimulation affected

Table 3
Overview over studies on norm-guided behavior.

Study	Protocol	Active	Control	Intensity	Duration	Electrode/coil	Design	Hemi.	Timing	N
<i>Deception</i>										
Noguchi et al. (2018) [110]	tDCS	anodal	sham	1 mA	20 min	5 × 7 cm ²	within	R	Offline	6
Sowden et al. (2015) [90]	tDCS	anodal	occipital	1 mA	20 min	5 × 7 cm ²	between	R	Offline	34
Tang et al. (2017) [111]	tDCS	anodal, cathodal	sham	1.5 mA	20 min	5 × 7 cm ²	between	R	Offline	92
Cristiano et al. (2023) [112]	TMS	sp TMS	sham	110 % rMT	spTMS	Figure-8	within	R	Online	19
Tidoni et al. (2013) [113]	TMS	rTMS	sham	90 % rMT	2 s	Figure-8	within	L	Online	15
<i>Moral judgements</i>										
Cui et al. (2023) [114]	tDCS	anodal, cathodal	sham	2 mA	task durat.	5 × 5 cm ²	within	L	Online	26
LeLoup et al. (2016) [115]	tDCS	anodal, cathodal	sham	0.8 mA 1.5 mA	20 min	5 × 5 cm ²	between	R	Online	Exp 1: 48 Exp 2: 75
Sellaro et al. (2015) [116]	tDCS	anodal, cathodal	sham	1 mA	20 min	5 × 7 cm ²	between	R	Offline	60
Ye et al. (2015) [117]	tDCS	anodal, cathodal	sham	2 mA	15 min	5 × 7 cm ²	between	R/L	Offline	36
Chou et al. (2021) [118]	TMS	spTMS	no TMS	110 % rMT	spTMS	Figure-8	within	R	Online	16
Young et al. (2010) [41]	TMS	rTMS	occipital	70 % MSO 60 % MSO	25 min 0.5 s	Figure-8 Figure-8	within	R	Offline Online	Exp 1: 8 Exp 2: 12
Zheng et al. (2018) [119]	tDCS	anodal, cathodal	sham	2 mA	20 min	5 × 7 cm ²	between	R/L	Offline	60
<i>Proactive fairness</i>										
Christian et al. (2023) [15]	tDCS	tACS	sham	1.5 mA	30 min	5 × 5, 10 × 10 cm ²	within	R	Online	30
Langenbach et al. (2022) [120]	tDCS	anodal, cathodal	sham	2 mA	20 min	2 cm diameter	within	R	Online	Exp 1: 29 Exp 2: 30
Li et al. (2020) [121]	tDCS	anodal, cathodal	sham	2 mA	12 min	2 cm diameter	between	R	Online	102
Liu et al. (2020) [122]	tDCS	anodal, cathodal	sham	2 mA	Task durat.	5 × 5 cm ²	within	R	Online	30
Luo et al. (2017) [123]	tDCS	anodal, cathodal	sham	2 mA	20 min	5 × 7 cm ²	between	R/L	Offline	78
Soutschek et al. (2024) [16]	tDCS	anodal, cathodal	sham	1.5 m	30 min	2 cm diameter	within	R	Online	50
Wu, Cai, Dong et al. (2023) [124]	tDCS	anodal	occipital	1.5 mA	20 min	5 × 7 cm ²	between	R	Offline	71
Wu, Cai, Li et al. (2023) [125]	tDCS	anodal	sham	1.5 mA	20 min	5 × 7 cm ²	between	R	Offline	72
Yang et al. (2021) [126]	tDCS	anodal, cathodal	sham	1.5 mA	20 min	5 × 7 cm ²	between	R	Offline	96
Zhang et al. (2019) [127]	tDCS	anodal, cathodal	sham	1.5 mA	20 min	5 × 7 cm ²	between	R	Offline	75
Zhang et al. (2022) [128]	tDCS	anodal	sham	1.5 mA	20 min	5 × 7 cm ²	between	R	Offline	68
Zhang et al. (2024) [129]	tDCS	anodal	sham	1.5 mA	20 min	5 × 7 cm ²	between	R	Online	75
Brethel-Haurwitz et al. (2022) [130]	TMS	cTBS	vertex	70 % rMT	40 s	Figure-8	within	R	Offline	27
Gaesser et al. (2019) [82]	TMS	rTMS	occipital	60 % MSO	17 min	Figure-8	within	R	Offline	23
Obeso et al. (2018) [131]	TMS	cTBS	vertex	80 % aMT	40 s	Figure-8	between	R	Offline	58
Soutschek et al. (2016) [84]	TMS	cTBS	vertex	80 % aMT	40 s	Figure-8	between	R	Offline	Exp 1: 43 Exp 2: 58
Xu et al. (2025) [132]	TMS	cTBS	sham	80 % rMT	40 s	Figure-8	within	R	Offline	50
<i>Reactive fairness</i>										
Blair-West et al. (2018) [133]	tDCS	anodal	sham	1 mA	20 min	5 × 7 cm ²	within	R	Offline	20
Cheng et al. (2022) [134]	tDCS	anodal, cathodal	sham	1 mA	20 min	5 × 7 cm ²	within	R	Offline	41
Lo Gerfo et al. (2019) [135]	tDCS	anodal	sham	1 mA	20 min	5 × 5, 5 × 10 cm ²	between	R	Offline	40
Speitel et al. (2019) [136]	tDCS	anodal, cathodal	sham	1 mA	25 min	20, 60 cm ²	between	R	Online	67
Zinchenko et al. (2019) [137]	tDCS	anodal	sham	1.5 mA	15 min	5 × 5 cm ²	within	R	Offline	20
Baumgartner et al. (2014) [17]	TMS	rTMS	vertex	110 % rMT	20 min	Figure-8	between	R, L	Offline	36
Fujino et al. (2020) [138]	TMS	cTBS	sham	80 % aMT	40 s	Figure-8	within	R	Offline	21
Ogawa et al. (2023) [139]	TMS	cTBS	sham	80 % aMT	40 s	Figure-8	within	R	Offline	20
Panico et al. (2024) [140]	TMS	cTBS	vertex	100 % rMT	0.5 s	Figure-8	within	R	Online	19
<i>Strategic social decisions</i>										
Hao et al. (2022) [141]	tDCS	anodal, cathodal	sham	1.5 mA	20 min	5 × 7 cm ²	between	L	Offline	90
Hao et al. (2023) [142]	tDCS	anodal	sham	1.5 mA	20 min	5 × 7 cm ²	between	R, L	Offline	90
Hao et al. (2021) [143]	tDCS	anodal, cathodal	sham	1.5 mA	20 min	5 × 7 cm ²	between	R	Offline	72
Su et al. (2021) [144]	tDCS	anodal, cathodal	sham	1.5 mA	20 min	5 × 7 cm ²	between	R	Offline	90
Wang et al. (2019) [145]	tDCS	anodal, cathodal	sham	1 mA	20 min	5 × 7 cm ²	between	R	Offline	90
Zhang et al. (2024) [129]	tDCS	anodal	sham	1.5 mA	20 min	5 × 7 cm ²	between	R	Online	71
Hill et al. (2017) [146]	TMS	cTBS	vertex	80 % aMT	40 s	Figure-8	between	R	Offline	60

Table 4
Overview over studies on joint attention.

Study	Protocol	Active	Control	Intensity	Duration	Electrodes/Coil	Design	Hemi.	Timing	N
Pereira et al. (2021) [147]	tDCS	anodal	Sham	1 mA	20 min	12 mm diameter	within	R	Online	20
Wiese et al. (2019) [148]	tDCS	anodal	baseline	2 mA	20 min	5 × 5 cm ²	within	L	Online	36
Abubshait et al. (2023) [149]	TMS	cTBS	vertex	80 % aMT	80 s	Figure-8	within	R	Offline	27
Schuerk et al. (2021) [150]	TMS	rTMS	Somatosensory	100 % aMT	0.5 s	Figure-8	within	R	Online	24

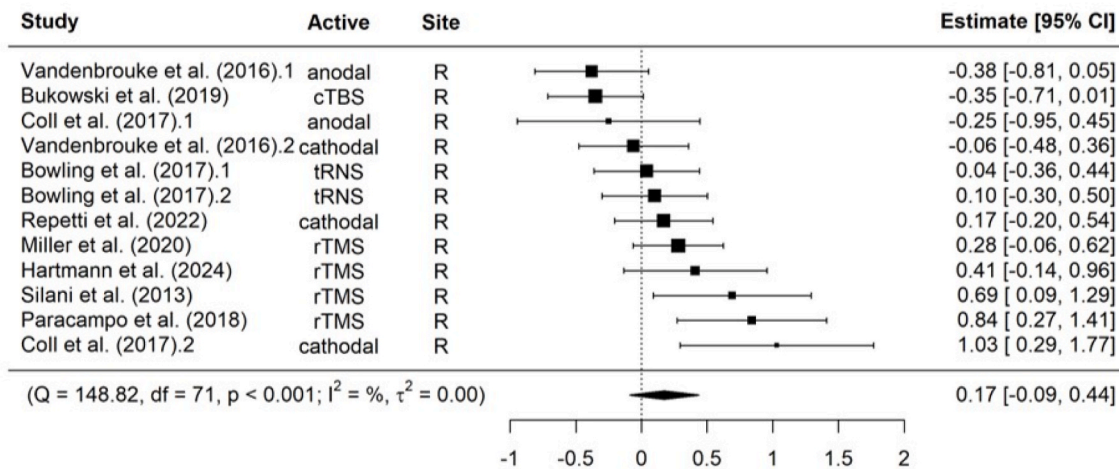


Fig. 2. Forest plot illustrating the influence of TPJ stimulation on empathy (standardized mean difference = 0.17, 344 participants). The center of the diamond represents the pooled estimate of standardized mean difference.

empathic responses, SMD = 0.17, 95 % CI = [-0.09, 0.44], $p = 0.18$, but heterogeneity between studies was again substantial, $I^2_{Level 2} = 57.2\%$, $I^2_{Level 3} = 9.4\%$, $Q(11) = 30.95$, $p = 0.001$ (Fig. 2 and Table 1). Empathy was not affected differently by TMS versus tES, $F(1, 10) = 1.20$, $p = 0.30$, and separate analyses suggest that both TPJ TMS and tES showed no significant effects on empathy, both SMD < 0.34, both $p > 0.19$. All studies on empathy targeted the right TPJ; therefore, we could not assess whether effect sizes differed between left and right TPJ stimulation. Visual inspection of funnel plots provided no clear indication of potential publication bias (Fig. 3A), which was further supported by the non-significant result of the Egger’s regression test, Bias = 3.48, $t(10) = 1.55$, $p = 0.15$. Together, our meta-analysis provided no evidence that TPJ stimulation affected empathy.

3.2. Self-other distinction

An analysis of studies measuring self-other distinction yielded a small-to-moderate influence of TPJ stimulation, SMD = 0.36, 95 % CI = [0.27, 0.45], $p < 0.001$, again with significant variability between studies, $I^2_{Level 2} = 52.9\%$, $I^2_{Level 3} = 0.0\%$, $Q(71) = 148.82$, $p < 0.001$. This effect occurred in both TMS, SMD = 0.52, 95 % CI = [0.37, 0.67], $p < 0.001$, and tES studies, SMD = 0.29, 95 % CI = [0.19, 0.40], $p < 0.001$, though the mean effect size was stronger in TMS than in tES studies, $F(1, 70) = 6.56$, $p = 0.01$. To better understand how tES affects self-other distinction, we ran additional analyses comparing anodal versus cathodal tDCS: Only anodal tDCS, SMD = 0.32, 95 % CI = [0.17, 0.47], $p < 0.001$, but not cathodal tDCS, SMD = 0.09, 95 % CI = [-0.19, 0.36], $p = 0.50$, showed significant effects on self-other distinction, though the difference between anodal and cathodal tDCS was only at trend-level, $F(1, 48) = 3.41$, $p = 0.07$. This is consistent with a previous review on non-social cognition, according to which anodal tDCS shows more reliable effects than cathodal tDCS [35]. In contrast, we found no evidence that the strength of stimulation effects differed between studies targeting the left (SMD = 0.31) versus right TPJ (SMD = 0.37), $F(1, 70) = 0.20$, $p = 0.66$. Importantly, we observed evidence for publication

bias, as revealed by a significant Egger’s test, Bias = 1.47, $t(70) = 3.06$, $p = 0.003$, and visual inspection of a funnel plot (Fig. 3B).

Based on the significant stimulation effects on self-other distinction, we assessed the TPJ’s contribution to different subfacets of self-other distinction. Separate analyses revealed that TPJ stimulation significantly affected visual perspective taking, SMD = 0.39, 95 % CI = [0.20, 0.57], $p < 0.001$, theory of mind, SMD = 0.30, 95 % CI = [0.15, 0.46], $p < 0.001$, self-other discrimination, SMD = 0.41, 95 % CI = [0.03, 0.78], $p = 0.04$, and imitation control, SMD = 0.45, 95 % CI = [0.27, 0.63], $p < 0.001$. Taken together, the TPJ appears to be causally involved in all different facets of self-other distinction processes examined in the present study.

3.3. Norm-guided social behavior

Next, we tested whether TPJ stimulation also affected norm-guided social behavior. We found norm-guided behavior to be causally related to TPJ activation, SMD = 0.36, 95 % CI = [0.28, 0.45], $p < 0.001$, with significant heterogeneity between studies, $I^2_{Level 2} = 36.3\%$, $I^2_{Level 3} = 9.9\%$, $Q(71) = 130.07$, $p < 0.001$. As for self-other distinction, TMS showed significantly stronger effects than tES, $F(1, 70) = 5.37$, $p = 0.02$, though separate analyses for TMS and tES revealed that both methods significantly affected norm-guided behavior, TMS: SMD = 0.53, 95 % CI = [0.27, 0.79], $p < 0.001$; tES: SMD = 0.31, 95 % CI = [0.22, 0.39], $p < 0.001$. A direct comparison of anodal and cathodal tDCS revealed that, contrary to the findings for self-other distinction, both anodal tDCS, SMD = 0.33, 95 % CI = [0.22, 0.44], $p < 0.001$, and cathodal tDCS, SMD = 0.24, 95 % CI = [0.11, 0.37], $p = 0.001$, significantly influenced norm-guided behavior, with no significant differences between anodal and cathodal tDCS, $F(1, 48) = 1.02$, $p = 0.32$. Again, we found no significant differences between left (SMD = 0.25) and right (SMD = 0.37) TPJ stimulation, $F(1, 66) = 0.78$, $p = 0.38$, and there was no evidence for publication bias, Egger’s test: Bias = 0.49, $t(70) = 0.68$, $p = 0.50$ (for a funnel plot, see Fig. 3C).

When assessing stimulation effects in the different subgroups of

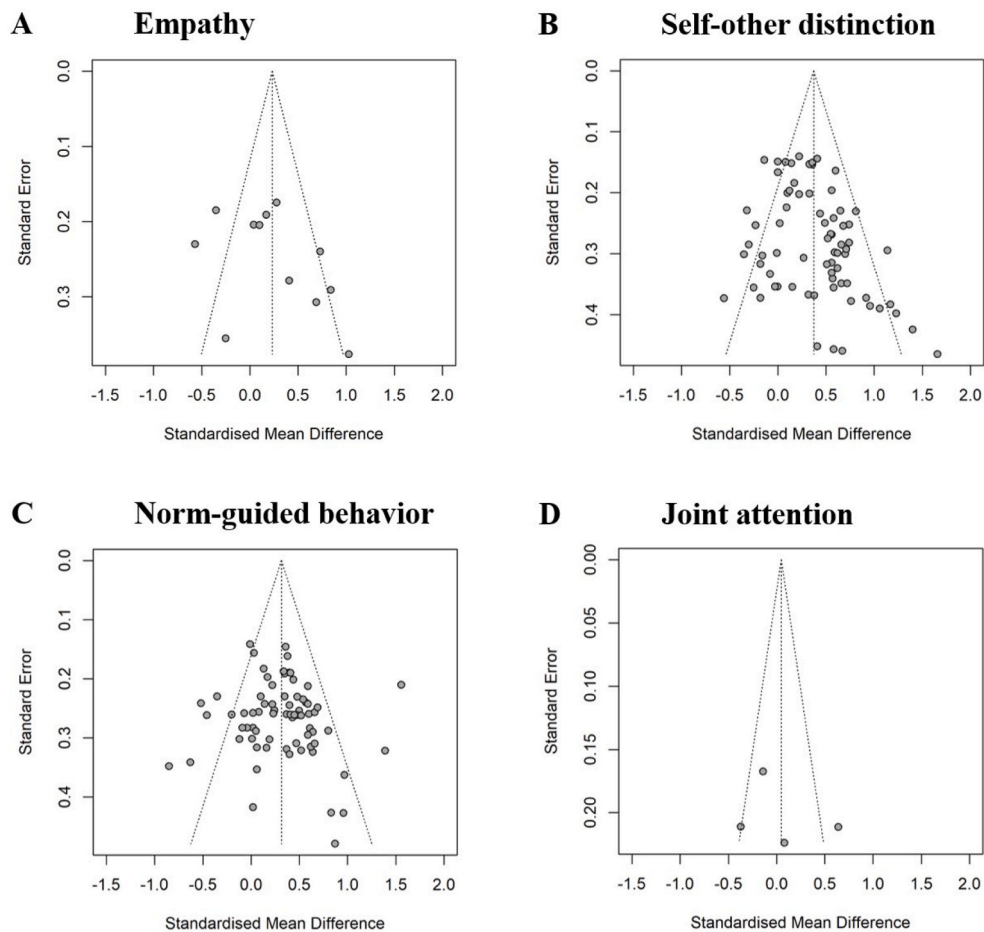


Fig. 3. Funnel plots as indicators of potential publication bias, separately for (A) empathy, (B) self-other distinction, (C) norm-guided social behavior, and (D) joint attention.

norm-guided behavior, we observed no evidence for significant TPJ involvement in deception, $SMD = 0.33$, 95 % CI = $[-0.14, 0.79]$, $p = 0.13$. In contrast, TPJ stimulation modulated moral judgements, $SMD = 0.35$, 95 % CI = $[0.14, 0.57]$, $p = 0.004$, proactive fairness, $SMD = 0.44$, 95 % CI = $[0.29, 0.60]$, $p < 0.001$, reactive fairness, $SMD = 0.34$, 95 % CI = $[0.09, 0.58]$, $p = 0.01$, and strategic social decision making, $SMD = 0.27$, 95 % CI = $[0.06, 0.47]$, $p = 0.02$ (Fig. 4). Together, this suggests that not all subfacets of norm-guided social behavior are related to TPJ activation (see Fig. 5).

3.4. Joint attention

Lastly, we observed no significant impact of TPJ stimulation on joint attention, $SMD = 0.05$, 95 % CI = $[-0.63, 0.73]$, $p = 0.84$, though there was substantial heterogeneity between studies, $I^2_{Level 2} = 38.9\%$, $I^2_{Level 3} = 38.9\%$, $Q(3) = 13.01$, $p = 0.005$ (Fig. 6). Due to the low number of effect sizes, we did not compute separate analyses for TMS versus tES effects on joint attention, and no Egger's test for publication bias could be calculated (see Fig. 3D for a funnel plot). Thus, no evidence emerged that TPJ stimulation changes processes related to joint attention; nevertheless, this result should be interpreted with caution due to the limited number of available effect sizes.

4. Discussion

The TPJ has been ascribed a key role for human social behavior, but so far, it has remained unclear which aspects of social behavior are under TPJ control. The current meta-analysis provides insights into

which facets of social cognition and behavior are causally implemented by the TPJ. We found that non-invasive stimulation of the TPJ influences the ability to distinguish between oneself and others, moral judgements, social decisions involving conflicts between fairness norms and selfish interests, as well as strategic social interactions, all with small-to-moderate effect sizes. In contrast, there was no meta-analytical evidence for stimulation effects on empathy, deception, or joint attention. This leads to a more nuanced understanding of which domains of human social behavior are controlled by TPJ activation. In the following, we discuss our findings separately for each domain.

The robust impact of TPJ stimulation on processes related to self-other distinction provides evidence for the hypothesized role of the TPJ for mentalizing and overcoming one's egocentric bias. A previous meta-analysis of brain stimulation studies already suggested a causal contribution of the TPJ to visual perspective taking [18]. Our findings extend these previous results by demonstrating that – besides visual perspective taking – the TPJ also plays a causal role in theory of mind (recognizing others' thoughts, intentions, or emotional states), self-other recognition (e.g., discriminating between one's own and another person's face), and imitation control (inhibition of automatic imitation of others' behavior). In these subfacets of self-other distinction, enhancing TPJ functioning inhibited the bias towards the own perspective and enabled individuals to better understand other persons' views or mental states, whereas inhibiting TPJ functioning (at least with TMS, though not with cathodal tDCS) showed the opposite effects. Putting ourselves into the shoes of others is considered the central function of the TPJ in social cognition and may underlie its role in other domains of social behavior [36,37]. The evidence for publication bias in

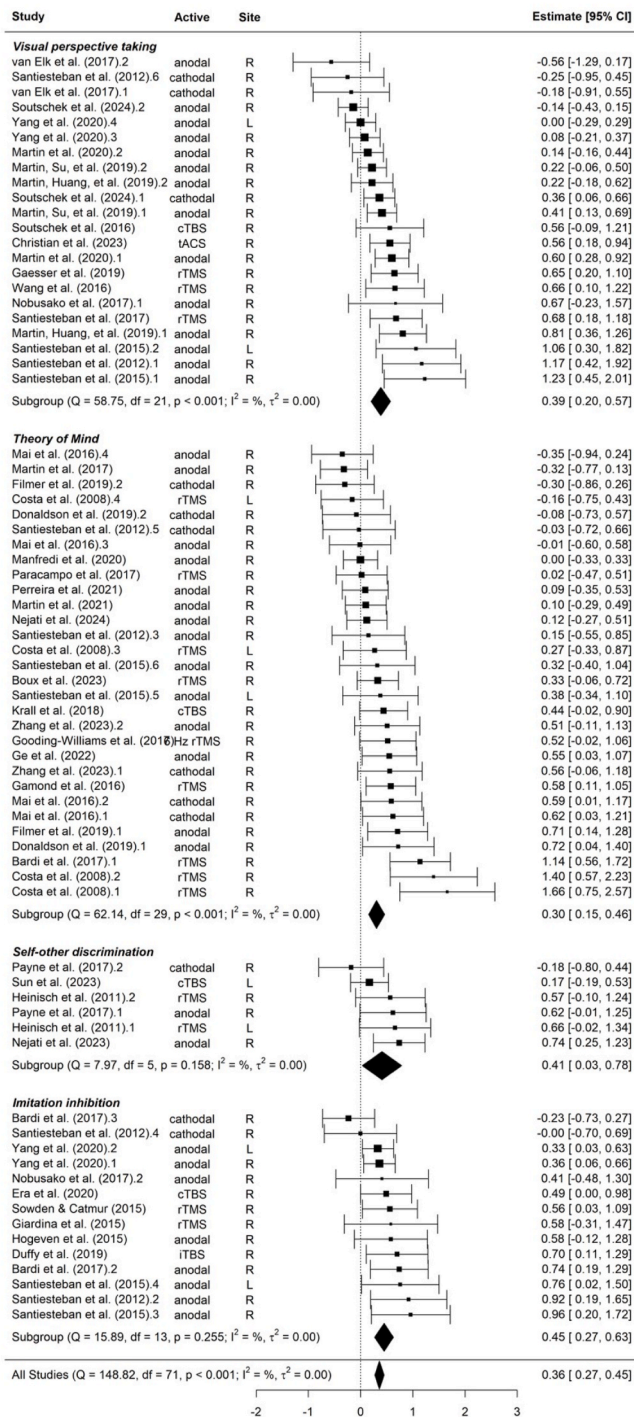


Fig. 4. Forest plot illustrating the influence of TPJ stimulation on processes related to self-other distinction, separately for visual perspective taking (standardized mean difference (SMD) = 0.39, 497 participants), theory of mind (SMD = 0.30, 665 participants), self-other discrimination (SMD = 0.41, 130 participants), and imitation inhibition (SMD = 0.45, 309 participants). The center of the diamond represents the pooled estimate of SMD.

this domain, however, suggests that the true effect of TPJ stimulation might be smaller than the observed effect size of SMD = 0.36.

In line with this assumption, we observed that TPJ stimulation altered norm-guided social decision making as well: strengthening TPJ activation increased the willingness to costly share goods with others (proactive fairness), to punish others for intentional violations of fairness norms (reactive fairness), as well as the ability to successfully

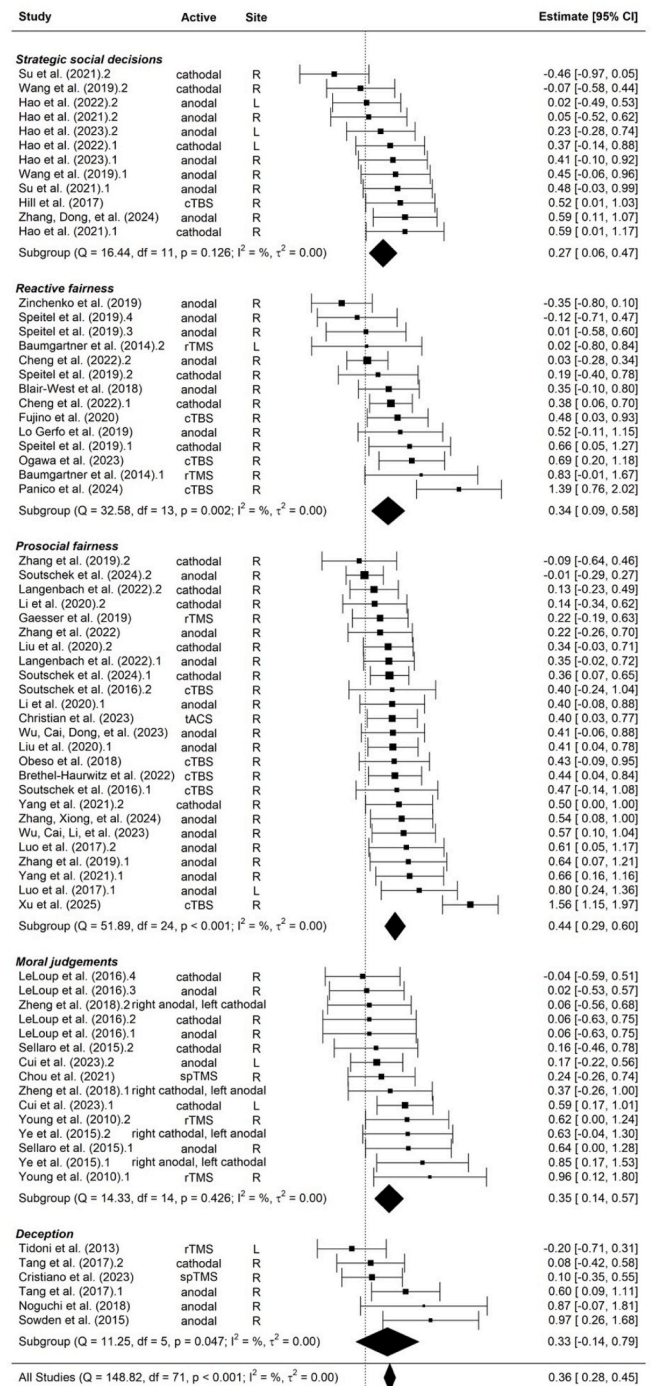


Fig. 5. Forest plot illustrating the influence of TPJ stimulation on norm-guided behavior, separately for strategic social decisions (standardized mean difference (SMD) = 0.27, 533 participants), reactive fairness (SMD = 0.34, 284 participants), proactive fairness (SMD = 0.44, 1015 participants), moral judgements (SMD = 0.35, 381 participants), and deception (SMD = 0.33, 166 participants). The center of the diamond represents the pooled estimate of SMD.

interact with others in iterative social interactions; again, perturbing TPJ functioning showed the opposite result pattern. Such social decisions are thought to rely on perspective taking [38–40], and mediation analyses indeed suggest that the TPJ's influence on social decisions can partially be explained by its role for perspective taking [15–17]. Likewise, TPJ stimulation influenced evaluations of whether actions are morally legitimate. Moral judgements depend on beliefs about whether

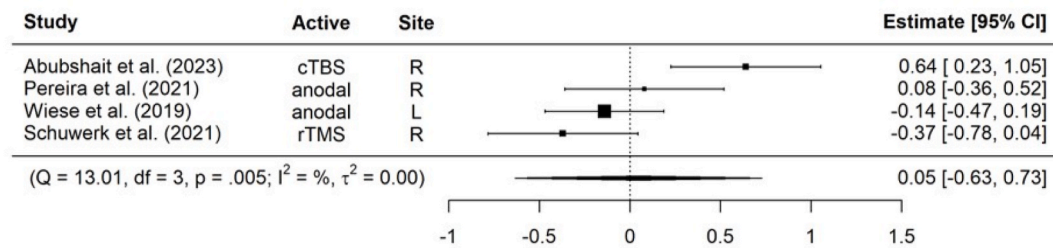


Fig. 6. Forest plot illustrating the influence of TPJ stimulation on joint attention (standardized mean difference = 0.05, 107 participants). The center of the diamond represents the pooled estimate of standardized mean difference.

a norm violation was intended or not, and the TPJ may be necessary for deciphering the intention of the acting person [41]. However, further processes like representing moral norms or affective evaluations of norm violations might also contribute to moral judgements [42], with the influence of affective components potentially dominating over cognitive ones [43,44]. Moral judgements that rely less on intention recognition (for example, in the trolley dilemma) may therefore depend on brain regions involved in representing moral norms or emotional reactions rather than the TPJ [45,46]. The assumption that the TPJ's involvement in moral judgements and social decisions can be explained by its causal role for self-other processing indicates that the categories for social cognition in our meta-analysis were not fully independent. While defining social cognition as a broad construct (that includes many different subtypes of behaviors) had the advantage of facilitating a nuanced understanding of the TPJ's role, the proposed links between these subcategories remain speculative and cannot be tested with the current meta-analytical approach.

Further, we observed no significant influence of TPJ stimulation on empathy or joint attention. In contrast to the cognitive demands of distinguishing between competing perspectives, empathy represents an affective process and requires understanding and sharing the feelings of others. Despite some correlational evidence that empathy is associated with TPJ activation [20], it seems to rely more strongly on areas involved in affective processing like the insula and anterior cingulate cortex [19,47]. Alternatively, it has been suggested that empathy is related to more anterior parts of the TPJ than perspective taking, particularly the supramarginal gyrus [48,49], which also shows functional connections to areas involved in emotional processing [50]. The strong heterogeneity in effect sizes observed in TPJ stimulation studies on empathy might therefore at least partially stem from variability in whether stimulation studies affected neural processing in the more anterior supramarginal gyrus rather than the posterior parts of the TPJ. Similarly, control over visual attention as required in joint attention tasks might be related to more anterior subregions of the TPJ, which is functionally coupled to a domain-general attention network [51,52]. Here, the lack of consistent TPJ stimulation effects might suggest that gaze cueing more strongly involves domain-general attention networks than neural mechanisms related to self-other processing. As a caveat, we note that the number of included effect sizes for empathy and joint attention was relatively small, limiting the inferences we can draw from these analyses.

Our meta-analysis provided no evidence for hemispheric specialization within the TPJ, as we observed no significant differences between right and left TPJ stimulation. While the focus of past research in social neuroscience has often been on the right rather than the left TPJ (which is also reflected by the larger number of effect sizes available for the right compared to the left TPJ), our results show no evidence that the right TPJ more strongly affects social behavior than the left TPJ. However, we note that these results do not allow for the conclusion that there are no hemispheric differences in TPJ functioning at all, as some meta-analyses of imaging studies provided evidence for (albeit weak) hemispheric lateralization of the TPJ for social cognition and attention [51,

53]. It is also worth noting that existing evidence suggests a functional specialization within the TPJ, with the posterior TPJ being linked to social cognition and the anterior TPJ to visual attention [51,53]; however, the spatial resolution of many brain stimulation protocols, particularly in the case of tES, might not be sufficient to distinguish between the anterior and posterior TPJ in this meta-analysis. We emphasize that the number of available effect sizes for the left TPJ was considerably lower than for the right TPJ, such that the lack of significant hemispheric differences may also represent a power issue. We recommend future research to directly compare the causal roles of right and left TPJ in social behavior, as was done in some past studies [17, 54–56]. The functional specialization of different TPJ subregions for cognition, as well as functional differences between the right and left hemisphere, therefore needs to be addressed by future research.

A further methodological goal of our meta-analysis was to compare the effectiveness of TMS versus tES for modulating social behavior. In domains showing an overall effect of TPJ stimulation on social behavior (self-other distinction and norm-guided behavior), we found that separate analyses for TMS and tES studies yielded significant results as well. This informs debates about the effectiveness of tES for modulating cognition [23,57] and suggests that not only TMS but also tES allows for influencing social behavior, in line with recent meta-analyses on the impact of tES on non-social cognition [25–27]. Nevertheless, in domains with significant stimulation effects, we found that effect sizes were significantly stronger for TMS than for tES. Interestingly, in the domain of self-other processing, the reduced effectiveness of tES relative to TMS could be explained by the weaker (and, in fact, non-significant) effects of cathodal relative to anodal tDCS, supporting the assumption that inhibitory cathodal tDCS is less reliable than excitatory anodal tDCS [35]. Our findings therefore support the view that, at least in the domain of social cognition in healthy individuals, TMS is a more robust and reliable neuromodulation tool than tES, and particularly cathodal tDCS. The weaker effects of tES might be related to the lower spatial precision of most electrode setups compared to TMS. Moreover, the field of tDCS research is also characterized by a large variability in electrode montage strategies (electrode size and position), stimulation parameters (current strength), and experimental designs (online versus offline stimulation). Concerns regarding variation in study designs also hold for TMS research, though to a lesser extent than for tDCS, which leaves more degrees of freedom regarding electrode montage strategies. This variability in study designs might also have contributed to the substantial heterogeneity in effect sizes that we observed for all subgroups, besides differences in the administered task designs (i.e., not all experimental paradigms in a given subdomain might be equally susceptible to stimulation effects). Therefore, a recommendation for future tES research is to (i) employ anodal rather than cathodal tES protocols and (ii) use focal high-definition electrode setups to improve spatial precision.

Taken together, the current meta-analysis provides evidence that the TPJ plays a key role in social cognition, particularly for adopting the perspective of another person and for resolving conflicts between self- and other-related interests. This supports theoretical accounts ascribing the TPJ a central function for human social cognition [58,59]. We note

that the magnitudes of the observed mean effect sizes should be considered as preliminary, given the large variability in study designs and the evidence for publication bias in some domains. The TPJ is thought to influence social behavior not in isolation but in interaction with larger brain networks: the TPJ has been shown to be functionally coupled with the dorsomedial prefrontal cortex during mentalizing processes [60], a region involved in updating mental models about others' behavior during social interactions [61,62]. The TPJ is furthermore connected to the dorsolateral prefrontal cortex (DLPFC) [63,64], which encodes abstract task goals or social norms [65,66]. The DLPFC may thus be involved in translating the results of perspective taking processes into actions in accordance with relevant goals.

Deficits in social cognition are prevalent in several clinical disorders [2–4], many of which also show abnormal TPJ functioning [7,8,67]. Our findings contribute to an improved understanding of the neural origins of impairments in social cognition and can inform ongoing research on how brain maturation in the TPJ influences the development of social skills in childhood. Given that our findings are based on studies involving healthy participants only, we note that caution is warranted with applying the current conclusions to the clinical domain. Abnormal TPJ functioning might affect the optimal intensity for TPJ-targeted stimulation protocols, and the single-session protocols employed in most studies of this meta-analysis allow no inferences regarding the potential long-term effects of repeated stimulation sessions, as required for clinical interventions. Nevertheless, the current findings suggest that TPJ-targeted neural interventions might be most beneficial for patients with deficits in processes related to self-other distinction. This meta-analysis should therefore be understood as a further step towards a better understanding of the TPJ's role in social behavior, which in the long run may promote the development of neural interventions targeting the TPJ in clinical disorders characterized by difficulties in social behavior.

CRedit authorship contribution statement

Alexander Soutschek: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Visualization, Writing – original draft. **Rebekka S. Mattes:** Investigation, Writing – review & editing.

Declaration of competing interest

The authors declare to have no conflicts of interest.

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