Effects of non-invasive brain stimulation on visual perspective taking: A meta-analytic study

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Abstract

Visual perspective taking (VPT) is a critical ability required by complex social interaction. Non-invasive brain stimulation (NIBS) has been increasingly used to examine the causal relationship between brain activity and VPT, yet with heterogeneous results. In the current study, we conducted two meta-analyses to examine the effects of NIBS of the right temporoparietal junction (rTPJ) or dorsomedial prefrontal cortex (dmPFC) on VPT, respectively. We performed a comprehensive literature search to identify qualified studies, and computed the standardized effect size (ES) for each combination of VPT level (Level-1: visibility judgment; Level-2: mental rotation) and perspective (self and other). Twelve studies (rTPJ: 11 studies, 20 ESs; dmPFC: 4 studies, 18 ESs) were included in the meta-analyses. Random-effects models were used to generate the overall effects. Subgroup analyses for distinct VPT conditions were also performed. We found that stimulation of rTPJ significantly improved participants' visibility judgment from the allocentric perspective, whereas dmPFC stimulation mainly influenced Level-1 performance from the egocentric perspective. For both areas, the effects of stimulation on Level-2 performance are negligible. These findings suggest that the rTPJ and dmPFC are involved in basic allocentric and egocentric perspective-taking processes, respectively. Notably, contrary to some theoretical models, neither of them appears to be necessary for more complex VPT with a higher requirement of mental rotation. These findings may help clarify the causal roles of the rTPJ and dmPFC in VPT and emphasize the importance of specifying VPT conditions in experimental designs.

Keywords: brain stimulation, visual perspective taking, temporoparietal junction, dorsomedial prefrontal cortex, meta-analysis

1 Introduction

The ability to take another's perspective is crucial for navigating complex social environments. To view the world from the second-person standpoint requires that one distinguishes between the self and the other in relation to the environment (Kessler and Rutherford, 2010; Lieberman, 2007). One social cognitive process that is closely related to this ability is visual perspective-taking (VPT). Dysfunction related to VPT has been observed in multiple clinical disorders, including autism and schizophrenia (Eack et al., 2017). Thus, it is essential to identify cognitive and neural mechanisms underlying the VPT process, as a steppingstone to target interventions for related disorders.

Flavell and colleagues (1977; 1981), identified two levels of VPT. Level-1 VPT refers to the ability to judge an object's visibility from the perspective of both the self and other. Consider, for example, playing hide-and-seek: You need knowledge about what the other person can see to hide from them. Children around the age of 18-24 months (Flavell et al., 1981) as well as chimpanzees (Bräuer et al., 2007), dogs (Hare and Tomasello, 2005) and goats (Kaminski et al., 2005) show the ability to make such line-of-sight judgements. Level-2 VPT, on the other hand, enables humans to describe how an object looks from another's perspective and establishes a shared view of the world by creating a common reference frame for spatial localizations (Flavell, 1977; Kessler and Rutherford, 2010; Michelon and Zacks, 2006; Zacks and Michelon, 2005). For instance, imagine standing in front of a car, while your friend views it from behind: you are aware that although the car is visible to both of you, your friend has a different visual perspective on it (Pearson et al., 2013). Thus, Level-2 VPT has a higher level requirement of embodied rotation compared to its Level-1 counterpart (Martin et al., 2020).

In recent years, researchers have conducted a few neuroimaging studies to assess the neural mechanisms underlying VPT. One candidate region identified for this process is the temporoparietal junction (TPJ), as both the right and left parts of this region appear to play a critical role in multiple processes relevant to VPT, including detecting self-other incongruences, controlling self and other representations, and inhibiting the influence of the non-relevant representation via orienting attention (Bahnemann et al., 2009; Lamm et al., 2016; Quesque and Brass, 2019; Wolf et al., 2010). Indeed, the bilateral TPJ has often been reported across different VPT conditions (Bukowski, 2018; Schurz et al., 2013). Another critical region for integrating self-other processing is the dorsomedial prefrontal cortex (dmPFC). The dmPFC has also been implicated in making judgements about others (Denny et al., 2012), social information processing (Lieberman et al., 2019), and in introspection and assessment of mental states (Doré et al., 2015). In VPT tasks, the dmPFC has been reported when requiring egocentric perspective taking and suppressing the influence of the other's perspective, with a proposed process of imagining movement and suppressing the motor response to physically rotate the body (Bukowski, 2018; Mazzarella et al., 2013; Munzert et al., 2009).

While these neuroimaging studies highlight candidate brain hubs for self-other differentiation and integration in VPT, they are mostly based on correlational methods and thus causal relationships remain to be established (Bell and DeWall, 2018; Lieberman et al., 2019). Fortunately, non-invasive brain stimulation (NIBS) techniques, including transcranial direct current brain stimulation (tDCS) and transcranial magnetic stimulation (TMS), provide an approach to overcome this limitation (Donaldson et al., 2015; Polanía et al., 2018). For this reason, researchers began to use NIBS to investigate the causal role of different brain regions in VPT in the past few years. For example, anodal tDCS of the right TPJ (rTPJ) has been shown to improve participants' performance when judging an item's visibility from another's perspective (Santiesteban et al., 2012). Moreover, another study showed that such an improvement could extend to Level-2 allocentric perspective-taking (Martin et al., 2019b). However, there is also opposing evidence in which the rTPJ stimulation increased the impact of perspective discrepancy during Level-1 VPT (Martin et al., 2020). Thus, despite that much effort has been devoted to clarifying the causal relationships between brain regions and VPT, the overall findings to date paint a rather mixed and inconclusive picture.

The inconsistency may be partly due to the complexity and heterogeneity of the existing VPT paradigms (Bukowski, 2018). As mentioned above, participants may be asked to judge the visibility or location of a target

from different perspectives (e.g., self or other), in which distinct underlying cognitive mechanisms may be involved. For example, Level-2 VPT typically requires more embodied processing than Level-1 VPT (Martin et al., 2020). However, there is no consensus yet if stimulating a brain region would selectively influence any VPT conditions. Moreover, with a few exceptions (Martin et al., 2019a,b, 2020), most NIBS studies in this field only focused on one brain region, making it difficult to compare the different regions' roles in VPT.

The current study aims to clarify the causal roles of key brain regions in VPT. Based on the feasibility of the included studies, we focused on studies targeting rTPJ and dmPFC and quantitatively synthesized the effects of stimulation of these two regions on distinct VPT components.

2 Methods

The meta-analysis was conducted following the Cochrane Handbook for Systematic Reviews of Interventions (Higgins et al., 2019) and PRISMA guidelines for meta-analyses (Liberati et al., 2009). The literature search and review, as well as data extraction, were performed by two co-authors (Y.W.Y and V.C) independently. Discrepancies were resolved by discussion.

2.1 Search strategy and eligibility criteria

An online literature search was conducted in Pubmed, Web of Science, and ProQuest for full-text articles from January 2000 to June 2020 without language restrictions. The following query syntax was used: ("stimulation" OR "TMS" OR "tDCS" OR "tACS" OR "tPCS" OR "tRNS" OR "TBS") AND ("perspective taking" OR "perspective-taking" OR "VPT"). To be included in the final meta-analysis, studies had to: (1) perform NIBS, (2) include a VPT task, (3) enroll healthy participants, (4) have a control or sham condition. Studies without full-text available were excluded. Note that, although previous brain stimulation studies mainly focused on rTPJ or dmPFC, we did not explicitly include "rTPJ" OR "dmPFC" during the literature search. However, as a random-effects model requires at least 3 effect sizes (ESs), the sample size limitation did not allow us to perform a meta-analysis on studies that targeted other brain regions. The inter-rater reliability for the article selection shows a high agreement (Cohen's Kappa = 0.87, $p < 0.001$). The authors resolved their disagreement about two articles by discussion.

2.2 Quality assessment

We used the Cochrane risk of bias tool to assess the quality of studies. Ratings (low, high, or unclear risk of bias) were assigned to each study based on the following six criteria: (1) assessments for sequence generation, (2) allocation concealment, (3) blinding of participants and researchers, (4) blinding of outcome assessment, (5) incomplete outcome data, and (6) selective reporting.

2.3 Data extraction

For each included study, we extracted information regarding the sample size, age, and sex ratio. For intervention characteristics, we extracted the type of NIBS technique, stimulation region, blinding protocol, intensity, duration of active stimulation, valence (excitatory or inhibitory), and study design. For tasks, we extracted the VPT Level (1 or 2) and Perspective (Self or Other) information for each effect and focused on these four conditions in the following analyses.

As most VPT tasks had an experimental condition, where the object being judged was incongruent from the Self compared to the Other perspective, and a control condition, where the object was congruent from both perspectives, we extracted the means and standard deviation (SDs) of the congruency effect (i.e., incongruent-congruent for RT

or congruent-incongruent for accuracy) for each VPT condition whenever possible. If there was no VPT control condition, we extracted the means and SDs of RT or accuracy of the incongruent trials. If the data were only presented in figures, means and SDs were estimated using the WebPlotDigitizer (Rohatgi, 2020). If only the standard error (SE) was available, we calculated the SD with the formula: $SD = SE * \sqrt{n}$

2.4 Data analysis

Data analysis was performed using R (version 4.0.1) and the Metafor package (Viechtbauer, 2010). We used the means and SDs to calculate the standardized ESs for each of the four conditions (VPT Level: 1 or 2, Perspective: Self or Other) and each stimulation target (rTPJ, dmPFC), respectively. For between-subject studies, we calculated the standardized mean difference (i.e., Hedge's g). For within-subject studies, we calculated the standardized mean change (Morris and DeShon, 2002). As the correlation between pre- and post-stimulation measures is typically above 0.5 (Elbourne et al., 2002), we used an assumed correlation of 0.7 when this information was not available in the study. To test if this choice would influence the results of the meta-analyses, we also changed the assumed correction to 0.5 and 0.9 in the sensitivity analysis.

If a study reported both RT and accuracy, we calculated a combined ES according to Scammacca et al. 2014's recommendations. For two studies (Martin et al., 2020; Wang et al., 2016) that reported effects for different rotation angles and body postures during VPT, we also calculated a combined ES for these conditions. For one study (van Elk et al., 2017) that examined the effects of complex mental body transformation and stimulation sessions (online and offline) on VPT, to ensure its comparability with other studies, we only focused on the z-axis 180-degree condition and combined the ESs of both stimulation sessions.

For consistency, the direction of the ES was defined as positive if the excitatory stimulation increased the incongruent RT or decreased the incongruent accuracy, and negative for the inhibitory stimulation. For the tDCS studies that included both anodal and cathodal stimulation groups, only the anodal > sham contrast was used for the main meta-analysis. We first performed two separate meta-analyses to examine the overall effect of rTPJ and dmPFC stimulation on VPT, respectively. As some studies included multiple VPT conditions, we used both the two-level (first level: ES, second level: VPT condition) and three-level (third level: study) random-effects model with restricted maximum-likelihood estimator (Cheung, 2014; Konstantopoulos, 2011). A critical difference between the two models is that the former treated ESs from different VPT conditions as independent, whereas the latter accounted for potential dependence between ESs from the same study. Model comparison based on Akaike's information criteria (AIC) was conducted to test which model was better given the data. Heterogeneity among the included ESs was assessed using the Q and I2 tests. The funnel plot and Egger's test was used to assess publication bias (Egger et al., 1997). To investigate if rTPJ and dmPFC stimulation selectively influence any VPT conditions, we further conducted subgroup analyses for each of the conditions and each stimulation target (except for rTPJ stimulation on VPT Level-2 Self condition because of insufficient ESs). Q test was used to statistically compare the aggregate ESs of different subgroups.

To assess the reliability of the results, we conducted a few control analyses. First, we used a leave-one-study-out analysis to examine the influence of individual ESs. Second, we conducted a sensitivity analysis by using an assumed correlation of 0.5 and 0.9 for within-subject studies that have not reported correlation coefficients. Third, we used the anodal > cathodal contrast for tDCS studies with two active stimulation groups to examine if the results were influenced by the contrast selection.

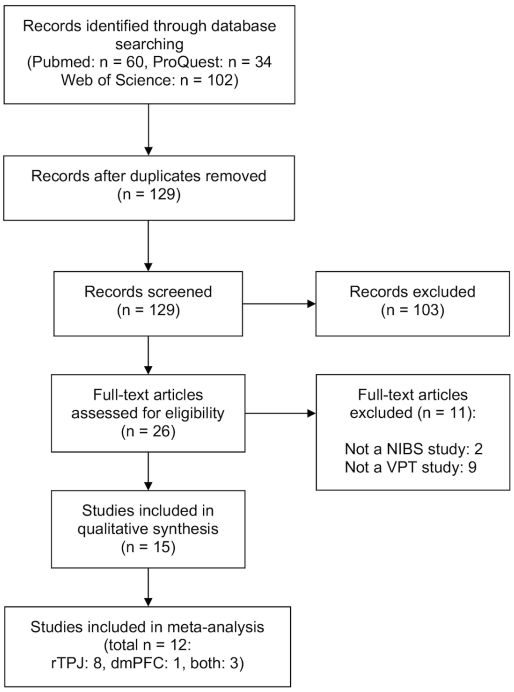

Figure 1: PRISMA flow diagram of literature search strategy

3 Results

A total of 15 studies met the inclusion criteria for the qualitative review (Fig 1). Since a random-effects model requires at least 3 effect sizes (ESs), 3 studies were excluded from the meta-analysis because they stimulated regions not tested for in other studies and thus did not provide sufficient ESs required by a meta-analysis. Among the remaining 12 studies, 8 stimulated rTPJ only, 1 stimulated dmPFC only, and 3 stimulated both regions (see Table 1 for study overview). After distinguishing 4 unique combinations of VPT Level and Perspective, we obtained 20 ESs for the rTPJ and 18 ESs for the dmPFC targets.

3.1 Quality assessment

The majority of the included studies were not associated with randomization, detection, attrition, and reporting biases (Fig 2). However, none of the studies included an explicit statement about the allocation concealment, and more than half of them were unclear on the blinding of participants and personnel, leading to a high proportion of the unclear risk of bias regarding these two criteria.

3.2 Effects of rTPJ stimulation

The two-level random-effects model showed that the overall effect of rTPJ stimulation on VPT was small (g = -0.18, 95% CI: [-0.37, -0.004], Z = -1.92, $p = 0.055$; Fig 3), with high dispersion and residual heterogeneity (I2= 81.50%, Q(19) = 91.26, $p < 0.001$). Egger's test (Z = -2.41, $p = 0.02$) suggested the possibility of larger effect sizes in studies with smaller sample sizes (Fig S1). The three-level random-effects model using study as an additional factor showed almost the same results (g = -0.18; 95% CI: [-0.37, -0.004], Z = -1.92, $p = 0.055$). Model comparison preferred

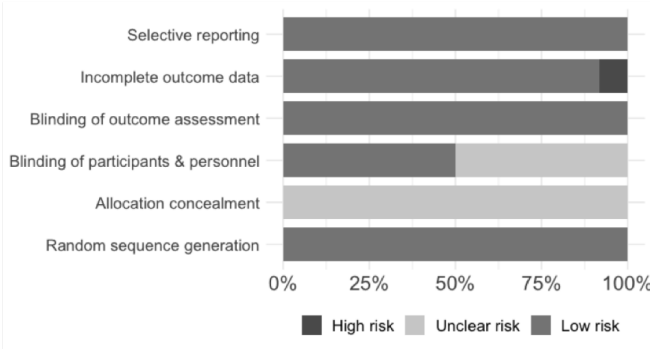

Figure 2: Risk of bias graph of included studies

two-level random-effects model (AIC = 28.20) than the three-level counterpart (AIC = 30.20), suggesting that the ESs within the same study were rather independent. Therefore, we only used the two-level random-effects model for the follow-up analyses.

To test if the rTPJ stimulation has an effect on the specific task conditions, we further ran subgroup meta-analyses for each unique combination of VPT Level and Perspective (Fig 3), except for the VPT Level-2 Self condition due to insufficient ESs. Our results showed only one significant effect of rTPJ stimulation in the VPT Level-1 Other condition (g = -0.46, 95% CI: [-0.81, -0.11], Z = -2.61, p = 0.009). We did not find a significant effect of rTPJ stimulation on VPT Level-1 Self (g = -0.01, 95% CI: [-0.34, 0.32], Z = -0.05, p = 0.96) or VPT Level-2 Other condition (g = -0.16, 95% CI: [-0.45, 0.13], Z = -1.07, p = 0.28).

3.3 Effects of dmPFC stimulation

The two-level random-effects model showed that the overall effect of dmPFC on VPT was negligible (g = -0.05, 95% CI: [-0.03, 0.14], Z = -1.20, p = 0.23; Fig 4), with moderate to high dispersion and residual heterogeneity (I2 = 44.59%, Q(17) = 30.71, p = 0.02). Egger's test (Z = 0.02, p = 0.99) suggests that the risk of the potential publication bias was low (Fig S1). The three-level model yielded similar results (g = -0.05, 95% CI: [-0.03, 0.14], Z = -1.20, p = 0.23). Model comparison preferred two-level random-effects model (AIC = -2.94) than the three-level counterpart (AIC = -0.94). We thus focused on the two-level random-effects model for the follow-up analyses.

Again, we ran subgroup meta-analyses for each condition respectively (Fig 4). We found a significant effect of dmPFC stimulation in the VPT Level-1 Self condition (g = 0.21, 95% CI: [0.07, 0.36], Z = 2.85, p = 0.004). None of the other three conditions showed a significant effect: VPT Level-1 Other (g = -0.01, 95% CI: [-0.27, 0.25], p = 0.94), VPT Level-2 Self (g = 0.08, 95% CI: [-0.11, 0.28], p = 0.41) and VPT Level-2 Other (g = -0.02, 95% CI: [-0.14, 0.09], p = 0.68).

3.4 Sensitivity analysis

We performed each meta-analysis with three levels of assumed correlation coefficient (r = 0.5, 0.7, or 0.9) with the Wald test, to check if the results were sensitive to the correlation between ESs. We did not find a significant influence on the results (see Table S1). In addition, the leave-one-study-out analyses showed that the overall effects of the main and subgroup analyses were stable. The key findings were not significantly driven by any individual studies. The detailed results were listed in Table S2.

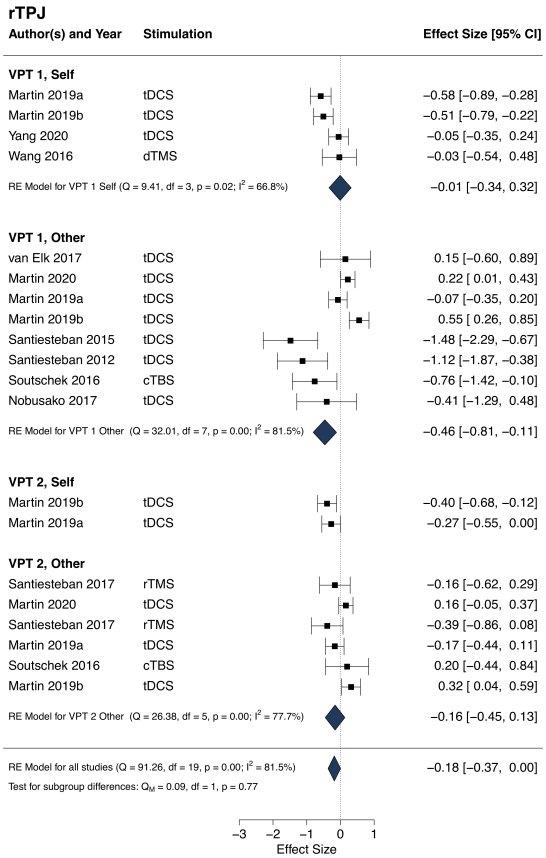

Figure 3: The effect of rTPJ stimulation on different VPT conditions. Assumed correlation between pre- and post-stimulation measures is r = 0.7

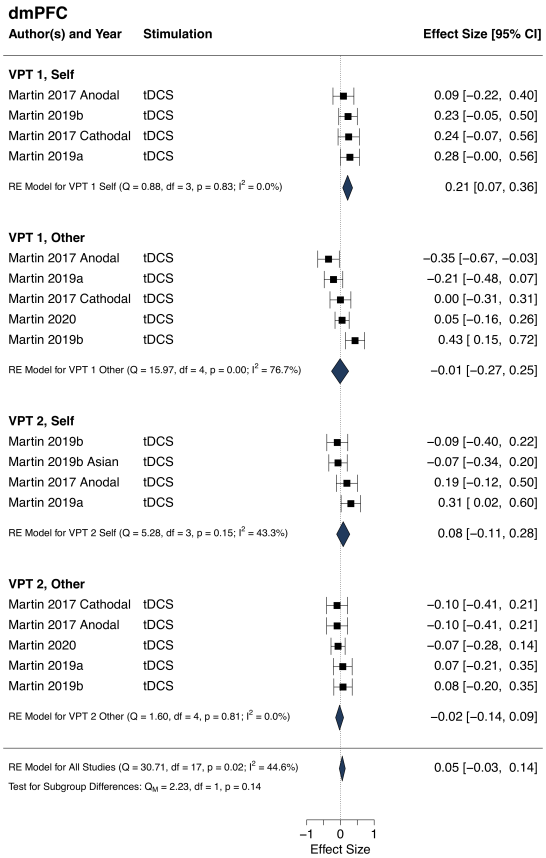

Figure 4: The effect of dmPFC stimulation on different VPT conditions. Assumed correlation between pre- and post-stimulation measures is r = 0.7

4 Discussion

This meta-analytic study examined the effects of rTPJ and dmPFC stimulation on VPT across 12 high-quality studies. The results showed a functional dissociation of these two regions during Level-1 VPT, in which the rTPJ was mainly involved in allocentric visibility judgment, whereas the dmPFC in processes related to the egocentric perspective. The involvement of these two regions in Level-2 VPT was limited. These findings further clarified the neural mechanisms underlying VPT and highlight the importance of specifying VPT conditions.

One main finding of our meta-analysis is that excitatory stimulation of the rTPJ increased performance in Level-1 VPT Other condition: Participants' error rate and reaction time decreased during line-of-sight or visibility judgements when their own perspective was incongruent with the other's perspective. Level-1 VPT does not rely on deliberate movement simulation (Kessler and Thomson, 2010) and only requires participants to trace-the-line of sight between the self and target object (Michelon and Zacks, 2006). Therefore, in contrast to prior theories that proposed a critical role of the rTPJ in embodied processes required by Level-2 VPT (Martin et al., 2020), this result suggests that this region may be more involved in suppressing the egocentric perspective when taking the other's perspective rather than generally detecting incongruencies or fostering mental self-rotation (Payne and Tsakiris, 2017; Soutschek et al., 2016). Notably, the ability to overcome one's self-centered perspective implemented in the posterior TPJ was also recruited in choosing delayed and prosocial rewards (Soutschek et al., 2016). Moreover, two subprocesses within Level-1 VPT have been proposed, in which perspective calculation is the fast, automatic and cognitively efficient calculation of someone else's perspective, whereas perspective selection is the effortful selection of either one representation, depending on task demands (Apperly and Butterfill, 2009; Qureshi et al., 2020; Todd et al., 2019). Therefore, a promising direction for future studies is to elucidate the effects of rTPJ stimulation on these two subprocesses of Level-1 VPT.

On the other hand, the ability for Level-2 VPT emerges around the same age as the ability to think about thoughts of others (Theory of Mind, ToM); hence the relationship of these processes received particular attention (Moll and Kadipasaoglu, 2013; Premack and Woodruff, 1978). Because of the proposed specificity of the rTPJ in ToM (Krall et al., 2015; Saxe and Wexler, 2005) and its implication in embodied processes, such as multisensory integration between proprioceptive and visual inputs (Blanke and Mohr, 2005; Ionta et al., 2011), it was suggested that the rTPJ might be involved in Level-2 allocentric perspective taking (Martin et al., 2020). In our quantitative synthesis, however, the aggregate effect of rTPJ stimulation on Level-2 VPT Other condition was negligible. Although this finding remains to be confirmed due to a relatively small sample size, a plausible explanation is that the relative contribution of the rTPJ-centered network to Level-2 VPT is smaller than its Level-1 counterpart, as Level-2 VPT is more complex and may rely on the coordinated effort of more distinct networks. This result also reconciles the finding that rTPJ stimulation did not affect ToM in healthy adults (Santiesteban et al., 2015).

In addition to the rTPJ, the dmPFC is another brain hub for complex social cognition (Lieberman et al., 2019), due to its critical role in merging the self- and other-related information to guide social decision-making (Schurz et al., 2013; Wittmann et al., 2016). In the context of VPT, we found that the dmPFC stimulation significantly decreased participants' performance during Level-1 egocentric perspective taking, possibly by increasing the salience of irrelevant information from the allocentric perspective (Martin et al., 2019b). Nevertheless, the effects of stimulation of this region on other conditions are negligible. Therefore, unlike the rTPJ, which may uniquely influence processes related to VPT from the other's perspective (Martin et al., 2019b, 2020; Santiesteban et al., 2012), the dmPFC is mainly recruited to integrate the external information into one's own perspective, especially when embodied rotation is less required (i.e., Level-1). This interpretation is bolstered by findings that the excitatory dmPFC stimulation decreased the self-reference effect in episodic memory (Martin et al., 2019b). However, it should be noted that all of these dmPFC stimulation studies were conducted by the same research group, thus, the validity and generalizability of these findings still need to be confirmed by studies from other researchers.

The general patterns of the current findings may indicate a functional dissociation of the rTPJ and dmPFC in

VPT, in which the former facilitates the translation of the self-related knowledge into an allocentric perspective, whereas the latter regulates the impact of the other's perspective on self-related processing. Moreover, the the rTPJ and dmPFC stimulation's selective impacts on different VPT conditions further suggest that distinct mechanisms are involved in these conditions. Therefore, it would be valuable to distinguish the target-specific effects on VPT-related variables, such as the perspective and embodied processing requirement (Bukowski, 2018). Moreover, some studies showed that trait factors, such as baseline perspective-taking ability (Fini et al., 2017) or empathetic understanding (Bukowski et al., 2020), may modulate the effect of NIBS (of other brain regions) on spatial or emotional perspective-taking. More studies are thus encouraged to examine if the effects of rTPJ or dmPFC stimulation on VPT are influenced by these dispositional factors.

On the other hand, the proposed functional specificity of rTPJ and dmPFC also faced challenges from studies that explored the causal relationship between VPT and other brain regions. For example, one study found that TMS stimulation of the right frontal pole selectively disrupted Level 1 egocentric perspective taking (Guise et al., 2007), which is similar to the effect caused by the dmPFC stimulation. Moreover, stimulating the dorsolateral PFC has been shown to affect the ability to take others' perspective during Level-1 (Qureshi et al., 2020) and Level-2 VPT (Conson et al., 2015). However, more studies are needed for conducting quantitative synthesis and generating solid and reliable results. Finally, although the potential of NIBS as an intervention for VPT-related disorders has been highlighted by some researchers (Martin et al., 2020; Santiesteban et al., 2012), the practical value of this approach is still in doubt at the current stage (Bell and DeWall, 2018), as the aggregate effects of the rTPJ and dmPFC stimulation on VPT are relatively small.

As one of the first meta-analytic studies that examined NIBS on VPT tasks, the present study has some limitations. First, the sample sizes for most subgroup analyses are limited. The current findings thus should be interpreted with caution. Results are expected to be more robust and reliable with future NIBS studies on VPT. Second, both the rTPJ and dmPFC are heterogeneous regions. Although previous studies proposed a functional lateralization of the TPJ in VPT, the involvement of the left TPJ has also been suggested (Santiesteban et al., 2015; Schurz et al., 2013; Yang et al., 2020). Moreover, at least three subregions have been identified in the TPJ (Mars et al., 2012). Specifically, the posterior region might be recruited during control of self and other representations and the anterior region during attentional reorientation (Corbetta et al., 2008; Krall et al., 2015; Scholz et al., 2009). Similarly, the dorsal and ventral parts of the dmPFC appear to mainly involve in other- and self-related processes, respectively (Lieberman et al., 2019). Due to the spatial precision of stimulation, most studies did not specify which subregions of the rTPJ or dmPFC were stimulated. Future studies may address this issue with the assistance of neuronavigation and more focal NIBS techniques (Donaldson et al., 2015).

Finally, most of the included studies focused on the role of an individual brain region in VPT. However, neuroimaging evidence suggests that complex social cognitive processes, such as VPT, depend on the interactions of multiple brain areas (Schurz et al., 2013). Therefore, another future avenue for research is to elucidate how NIBS influences interactions between brain networks during VPT.

5 Conclusions

The current meta-analytic study found that the rTPJ and dmPFC were causally involved in allocentric and egocentric VPT, respectively. Moreover, the stimulation of these two regions mainly influenced Level-1 instead of Level-2 VPT, suggesting that the impact is mostly unrelated to embodied processing. These findings contribute to a better understanding of the neural mechanisms of VPT and show the limitations and future directions of the NIBS technique as a potential intervention for patients with related deficits.

Study	Target	Type	Study design	N	NIBS control	Intensity	Off-/ On-line	Stimulation	Duration, pulse	DV	VPT level	Perspective
Conson et al. (2015)*	right dlPFC (F4), left dlPFC (F3)	tDCS	Cross-over	16	Sham	1.0mA	Off-line	Anodal, cathodal	15min	RT	2	Self, Other
Guise et al. (2007)*	right FC (FP2), left FC (FP1)	TMS	Within	7	Sham (to CZ)	90% RMT	On-line	Single pulse (inhibitory)	96 single pulses (24/condition)	RT	1	Self, Other
Martin et al. (2019b)	rTPJ (CP6), dmPFC (15% from Fz to FPz)	HD-tDCS	Cross-over	52	Sham	1.0mA	Off-line	Anodal	20min	RT CE, accuracy	1, 2	Self, Other
Martin et al. (2019a)	rTPJ (CP6), dmPFC (65% from Cz to Fpz)	HD-tDCS	Cross-over	52	Sham	1.0mA	Off-line	Anodal	20min	RT CE, accuracy	1, 2	Self, Other
Martin et al. (2020)	rTPJ (CP6), dmPFC (65% from Cz to Fpz)	HD-tDCS	Cross-over	88	Sham	1.0 mA	Off-line	Anodal	20min	RT	1, 2	Other
Martin et al. (2017)	dmPFC (15% from Fz to FPz)	HD-tDCS	Cross-over	40	Sham	1.0mA	Off-line	Anodal, cathodal	20min	RT	1, 2	Self, Other
Nobusako et al. (2017)	rTPJ (CP6), IFC (FC6)	tDCS	Between	10/group	Sham	1.0mA	Off-line	Anodal	20min	RT, Accuracy	1	Other
Qureshi et al. (2020)*	right dlPFC (F4)	TMS	Cross-over	31	Vertex stimulation	80% RMT	Off-line	cTBS (inhibitory)	Three-pulse bursts 50 Hz,600 pulses	RT, IES, Accuracy	1	Self, Other
Santiesteban et al. (2012)	rTPJ (CP6)	tDCS	Between	17: anodal, 17: cathodal, 15: sham	Sham	1.0mA	Off-line	Anodal, cathodal (ref.: vertex)	20min	Accuracy	1	Other
Santiesteban et al. (2015)	rTPJ (CP6), lTPJ (CP5)	tDCS	Between	15/group	OZ stimulation	1.0mA	Off-line	Anodal (ref.: vertex)	20min	Accuracy, RT	1	Other
Santiesteban et al. (2017)	rTPJ (MNI: 54, -47, 26)	rTMS	Within	19	Mid-occipical stimulation	110% RMT	On-line	inhibitory	6 pulses/trial 10Hz	RT	1	Self, Other
Soutschek et al. (2016)	rTPJ (MNI: 50, -60, 32)	TMS	Between	20: rTPJ, 18: vertex, 21: S1	Vertex, S1 stimulation	80% RMT	Off-line	cTBS (inhibitory)	Three-pulse bursts 50Hz, 600 pulses	Accuracy	1	Self, Other
van Elk et al. (2017)	rTPJ (CP6)	tDCS	Between	16: anodal, 15: cathodal, 14: sham	Sham	1.0mA	1/2 On-line, 1/2 Off-line	Anodal, cathodal (ref.: C3)	20min	RT	2	Self, Other
Wang et al. (2016)	rTPJ (MNI: 50, -60, 32)	TMS	Within	15	Sham	110% RMT	On-line	Dual pulse (inhibitory)	80 dual pulses	RT	2	Other
Yang et al. (2020)	rTPJ (CP6), lTPJ (CP5)	tDCS	Cross-over	45	Sham	2.0mA	On-line	Anodal (ref.: vertex)	29min (10min rest)	RT,accuracy, IES, switching cost	2	Self, Other

Table 1: * These studies were not included in the meta-analyses because they targeted different regions. CE: congruency effect; cTBS: continous theta burst stimulation; dlPFC: dorsolateral prefrontal cortex; dmPFC: dorsomedial prefrontal cortex; FC: frontal pole cortex; IES: Inverse efficiency scores; lTPJ: left temporoparietal junction; NIBS: Non-invasive brain stimulation; RMT: resting motor threshold; rTPJ: right temporoparietal junction; rTMS: repetitive TMS

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7 Conflicts of interest

None

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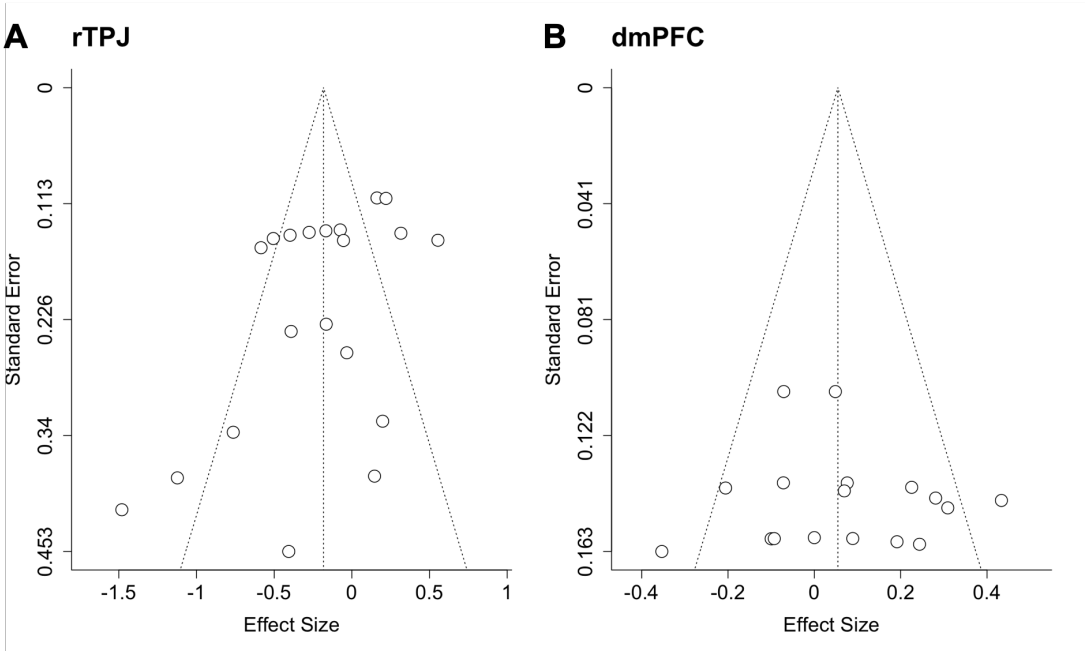

Figure S1: Funnel plots for A) rTPJ and B) dmPFC examining publication bias in meta-analyses. The Egger's test for the overall rTPJ model is significant (p = 0.02), but not for the dmPFC (p = 0.99).

A Appendix

Condition	Cor 0.5 vs. Cor 0.7	Cor 0.9 vs. Cor 0.7
rTPJ, all	z = 0.204, p = 0.839	z = 0.368, p = 0.713
rTPJ, VPT1 self	z = 0.407, p = 0.684	z = 1.076, p = 0.139
rTPJ, VPT1 other	z = -0.027, p = 0.978	z = -0.032, p = 0.974
rTPJ, VPT2 other	z =0.141, p = 0.888	z =0.311, p =0.756
dmPFC, all	z =-0.203, p = 0.839	z = 1.181, p = 0.238
dmPFC, VPT1 self	z = -0.189, p = 0.850	z = -.310, p = 0.757
dmPFC, VPT1 other	z = 0.028, p = 0.978	z = 0.060, p = 0.952
dmPFC, VPT2 self	z = -0.073, p = 0.942	z = -0.197, p = 0.844
dmPFC, VPT2 other	z =0.135, p = 0.893	z = 0.279, p =0.780
rTPJ, all	z =-0.174, p = 0.862	z = -0.370, p = 0.711

Table S1: Comparisons of meta-analyses with different assumed correlation coefficients for within-subject studies

Meta-analysis	Min overall ES	Max overall ES
rTPJ, all	-0.219	-0.136
rTPJ, VPT1 self	-0.174	0.097
rTPJ, VPT1 other	-0.554	-0.330
rTPJ, VPT2 other	-0.273	-0.064
dmPFC, all	0.032	0.074
dmPFC, VPT1 self	0.189	0.250
dmPFC, VPT1 other	-0.109	0.068
dmPFC, VPT2 self	0.001	0.140
dmPFC, VPT2 other	-0.049	-0.003

Table S2: Results of leave-one-study-out analyses