

## RESEARCH ARTICLE

# The roles of the LpSTS and DLPFC in self-prioritization: A transcranial magnetic stimulation study

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**Abstract**

The Self-Attention Network (SAN) has been proposed to describe the underlying neural mechanism of the self-prioritization effect, yet the roles of the key nodes in the SAN—the left posterior superior temporal sulcus (LpSTS) and the dorsolateral prefrontal cortex (DLPFC)—still need to be clarified. One hundred and nine participants were randomly assigned into the LpSTS group, the DLPFC group, or the sham group. We used the transcranial magnetic stimulation (TMS) technique to selectively disrupt the functions of the corresponding targeted region, and observed its impacts on self-prioritization effect based on the difference between the performance of the self-matching task before and after the targeted stimulation. We analyzed both model-free performance measures and HDDM-based performance measures for the self-matching task. The results showed that the inhibition of LpSTS could lead to reduced performance in processing self-related stimuli, which establishes a causal role for the LpSTS in self-related processing and provide direct evidence to support the SAN framework. However, the results of the DLPFC group from HDDM analysis were distinct from the results based on response efficiency. Our investigation further the understanding of the differentiated roles of key nodes in the SAN in supporting the self-salience in information processing.

**KEYWORDS**

HDDM, self-attention network, self-matching task, self-prioritization effect, the dorsolateral prefrontal cortex, the left posterior superior temporal sulcus, the transcranial magnetic stimulation

## 1 | INTRODUCTION

The human brain is fine-tuned to prioritize the processing of self-related information. For example, in a crowded and noisy bar, one's attention may be automatically captured when his/her name is mentioned by someone in the room. This *self-prioritization effect* has been well-documented and can manifest in various domains, such as own-face processing (Tong & Nakayama, 1999), own-name processing

(Cherry, 1953; Wood & Cowan, 1995), and self-referential memory (Cunningham, Turk, Macdonald, & Macrae, 2008). From a neural perspective, the self-prioritization effect originated from an interplay between the brain's attentional and self-processing networks, yet the precise neural mechanism that drives this process remains to be clarified.

Recently, Humphreys and Sui (2016) proposed the self-attention network (SAN) as a theoretical framework to understand the brain

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mechanism that underpins the self-prioritization effect. The SAN model argues that self-prioritization emerges through interactions between the default mode network and the executive control network through specific processing nodes, including (a) the ventromedial prefrontal cortex (VMPFC), (b) left posterior superior temporal sulcus (LpSTS), (c) the frontoparietal network (including the dorsolateral prefrontal cortex (DLPFC) and intraparietal sulcus (IPS), as represented in Figure 1.

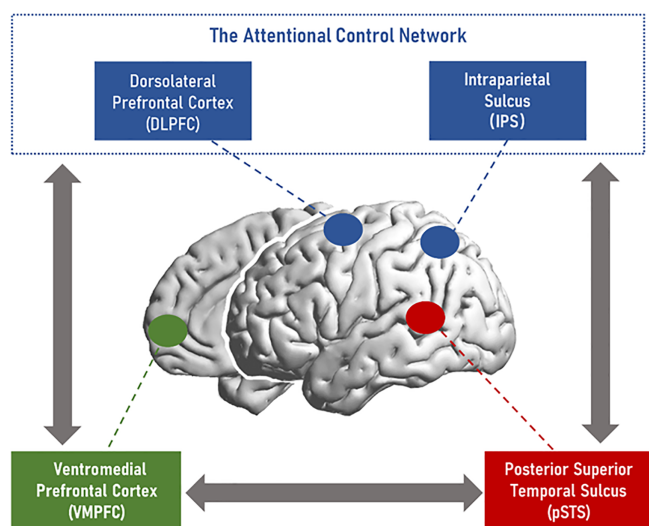
The VMPFC, in particular, is a region that has been determined to have prominent roles in self-referential processing and is considered to be the central hub of the self-network (Denny, Kober, Wager, & Ochsner, 2012; Frewen et al., 2020; Murray, Schaer, & Debbane, 2012; Northoff et al., 2006; van der Meer, Groenewold, Nolen, Pijnenborg, & Aleman, 2011). The LpSTS is part of a ventral attentional network that is primarily triggered by social cues (DiQuattro & Geng, 2011; Patel, Sestieri, & Corbetta, 2019; Saxe & Kanwisher, 2003). The SAN proposes when a stimulus is attributed to the self, the VMPFC and LpSTS couple together to register the social salience of a self-relevant stimulus and drive one's attention toward this stimulus. The frontoparietal network, on the other hand, is associated with a goal-related task demand; greater activity in the network is associated with more difficult tasks. Therefore, the frontoparietal network (attentional control) plays the opposite role of the VMPFC and LpSTS in the self-prioritization effect. More specifically, the processing of self-related stimuli requires less control effort, thus less involvement of the frontoparietal network (Sui, Rotshtein, & Humphreys, 2013), while other related stimuli require more difficult control processing, leading to its enhanced involvement.

There have been empirical findings that support the SAN's theoretical prepositions. In an fMRI study, Sui et al. (2013) utilized a recently developed self-matching task (Sui, He, & Humphreys, 2012) to investigate the neural basis of the self-prioritization effect. They found that both the VMPFC and LpSTS showed enhanced activities when making matching judgments about newly learned associations

between the geometry and concept of the self (vs. the concept of others). Furthermore, dynamic causal modeling revealed a strong excitatory top-down connection from the VMPFC to the LpSTS, and the strength of their functional connectivity predicted the magnitude of the self-prioritization effect. Conversely, other-matching judgments (vs. self-matching judgments) were associated with increased activation in the DLPFC. These results were supported by neuropsychological data where patients with VMPFC damage showed a hypo self-prioritization effect, while patients with brain lesions in the attentional control network showed a hyper self-prioritization effect, which may be due to a decrease in attentional control (Philippi, Duff, Denburg, Tranel, & Rudrauf, 2012; Sui, Enock, Ralph, & Humphreys, 2015; Verfaellie, Wank, Reid, Race, & Keane, 2019).

However, there are two critical unresolved issues in the SAN model regarding the relationship between the components of the SAN. First, while converging evidence has supported the VMPFC as a hub of self-related processing (Murray et al., 2012; Northoff et al., 2006; van der Meer, Costafreda, Aleman, & David, 2010), there has been no clear evidence regarding the role of the LpSTS in self-processing. In some cases, the LpSTS showed *decreased* rather than *increased* activities during self-related processing in comparison to other-related processing (van der Meer et al., 2011). Furthermore, neuropsychological studies showed that damage to the LpSTS enhanced the self-prioritization effect in self-matching and self-face perception tasks (Sui, Chechlacz, Rotshtein, & Humphreys, 2015; Sui, Enock, et al., 2015). These conflicting results invite future investigation. Second, the function of the DLPFC in the self-prioritization effect remains unknown. The fMRI study has shown that processing other-related pairings requires increased attentional effort, as reflected by increased activity in the DLPFC. This is not observed in self-related processing, and its strength, in comparison to other-related pairs, negatively correlated with the activity in the DLPFC but positively correlated with the activity over the VMPFC (Sui et al., 2013). The results indicate that there might be direct interactions between the default mode network (e.g., VMPFC) and dorsal frontoparietal (e.g., DLPFC) network for control of behavior in the presence of self-related stimuli. These results suggest that DLPFC might have a potential role in self-related processing; however, its causal effect in self-related processing remains to be tested.

One of the obstacles to fully test the SAN model, and the neural mechanism underlying the self-prioritization effect in general, lies in the shortcomings of the commonly used paradigms in the field. Since self-related stimuli (e.g., own-name, own-face) are usually more familiar to oneself than other types of stimuli, previous findings could be alternatively attributed to a familiarity effect (Yang, Wang, Gu, Gao, & Zhao, 2013; Yankouskaya et al., 2017). To rule out this confounding factor, Sui et al. (2012) developed the above-mentioned self-matching paradigm. In this task, participants first learn arbitrary association rules between simple geometrical shapes and social labels (e.g., "A circle represents yourself; a triangle represents your best friend; a square represents a stranger"). They are then immediately presented with shape-label pairs (e.g., circle-stranger, triangle-friend) and judged whether these pairs are matching the rules they were presented with.



**FIGURE 1** The self-attention network (SAN)

A substantial self-prioritization effect was observed; the performance of the pairs related to the self was determined with reduced reaction times and enhanced perceptual sensitivity (Sui et al., 2012; Sui & Humphreys, 2015a, 2015b; Sui, Ohrling, & Humphreys, 2016). Despite the argument that the self-prioritization effect may be driven by social labels, recent research has demonstrated that in the matching paradigm, the self-prioritization effect is independent of the presence of a label (Sui, Yankouskaya, & Humphreys, 2015; Wozniak & Knoblich, 2019; Yankouskaya et al., 2017). In an fMRI study, researchers also found that newly learned sensory stimuli (e.g., shapes) that are tagged to the self, rapidly modulate neural responses in a pattern similar to changes in perceptual saliency, which suggests the social modulation of perception (Sui, Liu, Mevorach, & Humphreys, 2015). Since the matching rules are arbitrary and novel to the participant, the task provides new means of examining neural networks that specifically support the self-prioritization effect by controlling stimulus familiarity and complexity.

In the current study, we aimed to address the unresolved issues in the SAN model by employing transcranial magnetic stimulation (TMS) and establishing a causal relationship between the LpSTS and DLPFC and the self-prioritization effect, which was measured through the self-matching task. For indexes of task performance, in addition to model-free analyses of response efficiency (reaction time/accuracy), we applied a hierarchical drift-diffusion model (HDDM) to decompose the effect to different stages of processing (Wiecki, Sofer, & Frank, 2013). Previous studies using the HDDM showed that the self-prioritization effect was underpinned by an increased rate of information uptake (Golubickis et al., 2017, 2020), therefore we focused on how the drift rate  $V$  would be influenced by selected neural disruptions. We hypothesized that (a) perturbation with TMS on the LpSTS would lead to a reduction in performance in self-associations, (a) perturbation on the DLPFC would impair performance in other-related associations because it has been found that other-matching judgments (vs. self-matching judgments) were associated with increased activation in the DLPFC (Sui et al., 2013).

## 2 | MATERIALS AND METHODS

### 2.1 | Participants

A total of 109 healthy volunteers were recruited for the study (50 males,  $21.37 \pm 2.50$  years old, mean  $\pm$  SD, the same below). They were randomly assigned into a sham rTMS group ( $N = 36$ ), rTMS over LpSTS group ( $N = 38$ ), and rTMS over left DLPFC group ( $N = 35$ ). All participants were right-handed and had normal or corrected-to-normal visual acuity and had no mental disorders, history of epilepsy, or cardiovascular complications. This study was conducted under the Declaration of Helsinki and has been approved by the local Ethics Committee of human research at the Department of Psychology, School of Social Sciences, Tsinghua University. Informed consent was given prior to the experiment. Participants signed an informed consent form prior to the experiment and were paid ¥1 per minute for their participation.

### 2.2 | Stimuli and tasks

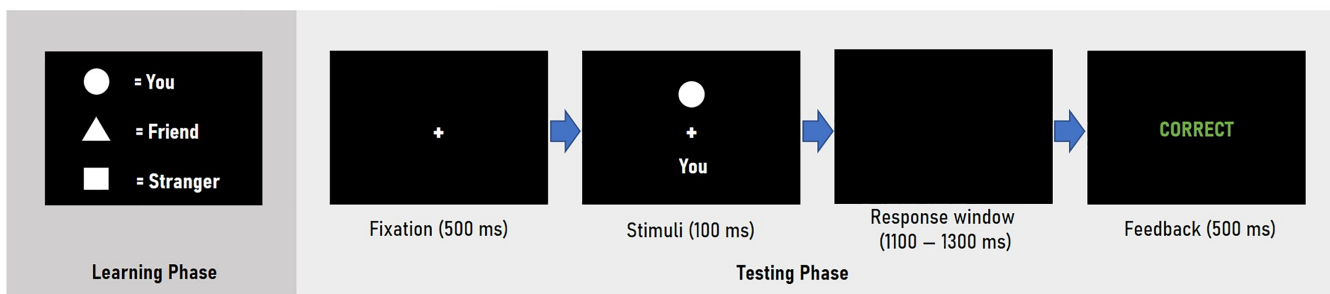
Six geometric shapes (circle, triangle, square, pentagon, hexagon, and rhombus, each  $3.8^\circ \times 3.8^\circ$ ) were presented above a white fixation cross ( $0.8^\circ \times 0.8^\circ$ ) at the center of the screen. The associations to the self, friend, or stranger target of three geometric shapes were counterbalanced across participants (to minimize practice effect, geometric shapes were different between pretest and posttest stages, e.g., the circle, pentagon, and rhombus were used in the pretest stage, while the triangle, square and hexagon were used in posttest stage). The word “You”, “Friend,” or “Stranger” ( $2.4^\circ \times 1.6^\circ$ ) was displayed below the fixation cross. The distance between the center of the shape or the word and the fixation cross was  $3.5^\circ$ . All stimuli were shown on a gray background and were viewed from 57 cm. Participants judged whether the pairings of shape and label matched. The experiment was run on a PC using E-prime software (Version 2.0). The stimuli were displayed on a 17-in. monitor ( $1,024 \times 768$  at 60 Hz).

### 2.3 | Procedure

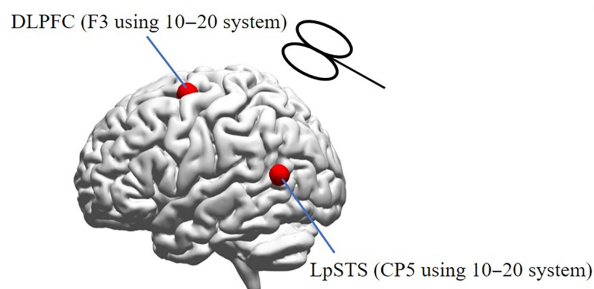
In this study, the experiment was conducted on 2 consecutive days (Figure 2a,c). On Day 1, participants completed the self-matching task and measured their motor threshold to calibrate the intensity of stimulation for the TMS session. Each participant was randomly assigned to a group (DLPFC or LpSTS or sham) according to a computer-generated randomization sequence. The motor threshold was determined by finding the lowest intensity that induced a motor response in the right abductor pollicis brevis muscle, which produced five motor-evoked responses of at least 50 mV in 10 trials (Liang et al., 2018). Following Sui et al. (2012), the task involved two phases. In the first phase, participants learned to associate geometric shapes (i.e., circle, triangle, square) with three targets: self, friend, and stranger. The shapes were not presented until the second stage. In the second stage, participants were required to judge whether the shape-label pairings were correct. Each trial started with the presentation of a central fixation cross for 500 ms. Subsequently, a pairing of shape and label (you, friend, or stranger) was presented for 100 ms. The next frame showed a blank screen for a variable time ranging from 1,100 to 1,300 ms, during which participants were required to judge whether the pairing was correct. Feedback (correct, incorrect, or too slow) was given on the screen for 500 ms at the end of each trial. Participants were informed of their overall accuracy at the end of each block. Each participant performed six blocks of 60 trials following the practice block (participants were required to reach the criterion of six consecutive correct trials in practice block). Thus, there were 60 trials in each condition (self-matched, self-non-matched, friend-matched, friend-non-matched, stranger-matched, and stranger-non-matched).

On Day 2, participants received a 40-s continuous theta-burst TMS (cTBS) protocol over the corresponding location—consisting of 50 Hz trains of 3 TMS pulses repeated every 200 ms continuously for 40 s (600 pulses total). The intensity of TMS was set at 80% of individual resting motor threshold, which is commonly used in the TMS

## (a) The self-matching task



## (b) Locations of TMS targets



## (c) Experimental procedure

Day 1	Day 2		
Each participant	LpSTS group	DLPFC group	Sham group
Self-matching + Motor threshold	LpSTS TMS + Self-matching	DLPFC TMS + Self-matching	Sham TMS + Self-matching
(Randomly assigned into each group)			

FIGURE 2 Study design

literature (Huang, Edwards, Rounis, Bhatia, & Rothwell, 2005; Zafar, Paulus, & Sommer, 2008) and would not induce much skin/muscle response. The standard cTBS for 40 s could reduce cortical excitability in the stimulated region of the cortex for at least 20 min (Huang et al., 2005; Zafar et al., 2008; for an overview, see Hoogendam, Ramakers, & Di Lazzaro, 2010), which is much longer than the duration of the current task (~11 min). TMS was delivered by a figure-of-eight coil (Magstim coated Alpha Flat 50 mm diameter) attached to a Magstim Rapid<sup>2</sup> stimulator (Magstim, Carmarthen, UK). In line with prior studies (Camsari et al., 2019; Merchant et al., 2020; Norouzi-Gheidari et al., 2021), the coil was placed tangentially to the scalp in the present study to maximize the impact of TMS on the cortex. For the DLPFC group (Figure 2b), TMS stimulation was targeted to the left DLPFC at F3 using the 10–20 system (Curtin et al., 2019); for the LpSTS group, TMS stimulations were targeted to the left LpSTS at CP5 using the 10–20 system (Peretz & Lavidor, 2013); for the sham group, the Vertex (Cz of the 10–20 international system, e.g., Okabe, Ugawa, & Kanazawa, 2003) was chosen as the sham stimulation site based on previous studies (Pelisson, Habchi, Panouilleres, Hemoux, & Fame, 2018; Thakral, Madore, Kalinowski, & Schacter, 2020; Veniero et al., 2021), and the coil was tilted away from the scalp in a 90° angle, so there was no cortical stimulation but still touching the head (Jansen et al., 2019; Kaller et al., 2013). In addition, participants in both the real TMS group (over DLPFC and LpSTS) and the sham group received the same cTBS protocol and were required to wear earplugs during TMS sessions. Thus, sham stimulation is accompanied by similar auditory (clicking noise) and somatosensory. Participants were TMS-naïve (never having received TMS sessions before) so that the tilting could not be a hint for the kind of

stimulation given. Participants in the three groups were also asked about their subjective experience during TMS stimulation and there was no reporting of somatic sensation. After a continuous theta-burst TMS session, participants performed the self-matching task again (geometric shapes were different from stimuli on Day 1) which lasted 20 min.

## 2.4 | Statistical analysis

We analyzed both model-free performance measures and HDDM-based performance measures for the self-matching task. For the model-free analyses, the primary dependent measure was response efficiency (RT/ACC, lower is better), controlling the speed-accuracy tradeoff. Firstly, we calculated the response efficiency toward different shape categories (self, friend, stranger) in matched and non-matched trials following TMS to corresponding target site (DLPFC, LpSTS, and sham). After this, the response efficiency in matched and non-matched trials were separately submitted to a 3 (Shape Category: self vs. friend vs. stranger) × 2 (Test Stage: pretest vs. posttest) × 3 (Target Site: sham vs. DLPFC vs. LpSTS) mixed-model analysis of variance (ANOVA), with Shape Category and Test Stage as within-subject variables and Target Site as between-subject variable. Model-free analyses were performed using SPSS 21.0 software.

To further explore the underlying cognitive mechanism, data were submitted to HDDM. HDDM is an open-source software package written in python for the hierarchical Bayesian parameter estimation of the Drift Diffusion Model (Wiecki et al., 2013). Drift Diffusion Models have been used widely in the research on perceptual

decision-making which decomposes the decision process into distinct components (i.e., drift rate, threshold, starting point, nondecision time) representing underlying cognitive processes. Specifically, drift diffusion model simulates two-choice decision processes as an accumulation of noisy evidence. Each choice is represented as an upper and lower boundary. A drift-process accumulates evidence with average drift rate until a decision has been reached (e.g., cross one of the two boundaries; see Figure 3 for an illustration).

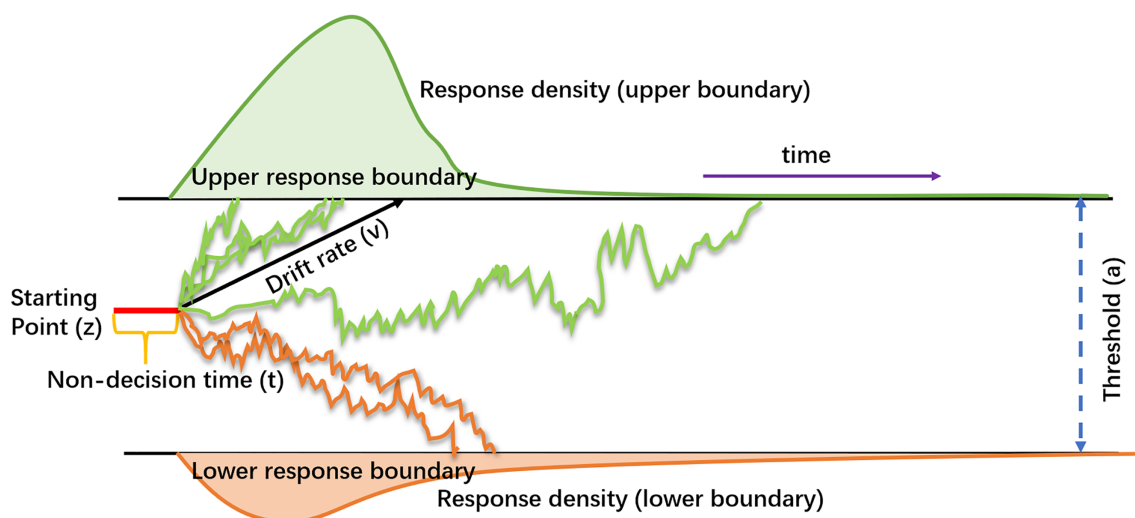
For the HDDM based analyses, we focused on the parameter  $V$  (drift rate, which represents the speed of information accumulation). Models were response coded such that a matching response was coded to the upper threshold and a mismatching response to the lower threshold (Golubickis et al., 2017). Twenty models which have been included all conditions were estimated to establish which model best fits the data (following the method in Golubickis et al., 2020). Bayesian posterior distributions for each parameter were modeled using a Markov Chain Carlo (MCMC) with 10,000 samples (following 1,000 burns in samples). The model with the lowest DIC (Deviance Information Criterion) value yielded the best fit, which is routinely used for hierarchical Bayesian model comparison (Spiegelhalter, Best, Carlin, & Van der Linde, 1998). Based on the best fit model, we calculated each parameter ( $V$  and  $Z$ ) in different conditions. Considering that the available evidence indicates that the self-prioritization effect was underpinned by increased rate of information uptake (Golubickis et al., 2017, 2020), therefore we focused on how the drift rate would be influenced by selected neural disruptions. For the primary purposes of this study, we examined the Bayesian posterior distributions of drift rate in specific types of trials and tested the differences between TMS conditions (See Wiecki et al. (2013) and Navarro and Fuss (2009) for the specific analytic solution). First, we examined whether the perturbation with TMS on the LpSTS site would reduce drift rate during the shape-label pairings related to the self when compared with the

perturbation on the sham/DLPFC site. We expected to observe a lower drift rate in the self-matched trials for the LpSTS condition relative to the sham or DLPFC conditions. In addition, we compared the difference of the TMS impairment on drift rate during the shape-label pairings related to the stranger between the perturbation on the DLPFC site and the perturbation on the sham/LpSTS site. It would be expected to have a lower drift rate in the stranger-matched trials following DLPFC TMS compared to the other two sites.

### 3 | RESULTS

#### 3.1 | Model-free analyses

Table 1 presents the response efficiency (RT/ACC, lower is better) data, which controls for speed-accuracy trade-offs. Matched and non-matched pairs were separately conducted a 3 (Shape Category: self/friend/stranger)  $\times$  2 (Test Stage: pre-stage vs. post-stage)  $\times$  3 (Group: sham/LpSTS/DLPFC) mixed-model analysis of variance (ANOVA). Results for the matched pairs yielded a main effect of Shape Category,  $F(2, 212) = 60.97, p < .001, \eta_p^2 = .37$ , reflecting a self-association advantage over other associations ( $ps < .001$ ) and a familiar other association advantage relative to unfamiliar other association ( $p < .001$ ). The main effect of Test Stage was significant,  $F(1, 106) = 79.88, p < .001, \eta_p^2 = .43$ , revealing that judging performance was better during post-stage. The interaction of Shape Category and Test Stage was also significant,  $F(2, 212) = 19.02, p < .001, \eta_p^2 = .15$ . This interaction showed a self-association advantage over other associations during pre-stage and post-stage ( $ps < .001$ ), but a familiar other (friend) association advantage relative to unfamiliar other (stranger) association vanished during post-stage ( $p = .09$ ). None of the other effects were significant (all  $p > .27$ ). However,



**FIGURE 3** Schematic representation of the two-choice drift diffusion model. Evidence is accumulated gradually (start from starting point) over time until it reaches one of the two boundaries (separated by threshold). Drift rate represents the efficiency of evidence accumulation, and nondecision time accounts for processes that occur outside of the decision process (e.g., evidence accumulation). For full details, please refer to Wiecki et al. (2013)

Group	Trial type	Shape category	Test stage	Response efficiency
LpSTS	Matching	Self	Pre-stage	733.11
			Post-stage	709.17
		Friend	Pre-stage	896.64
			Post-stage	763.82
		Stranger	Pre-stage	968.05
			Post-stage	798.00
	Nonmatching	Self	Pre-stage	908.25
			Post-stage	794.81
		Friend	Pre-stage	944.99
			Post-stage	823.79
		Stranger	Pre-stage	927.70
			Post-stage	810.52
DLPFC	Matching	Self	Pre-stage	739.52
			Post-stage	686.89
		Friend	Pre-stage	820.63
			Post-stage	745.22
		Stranger	Pre-stage	931.89
			Post-stage	767.54
	Nonmatching	Self	Pre-stage	900.46
			Post-stage	800.68
		Friend	Pre-stage	919.88
			Post-stage	811.16
		Stranger	Pre-stage	890.40
			Post-stage	771.46
Sham	Matching	Self	Pre-stage	741.17
			Post-stage	687.33
		Friend	Pre-stage	832.72
			Post-stage	750.55
		Stranger	Pre-stage	926.92
			Post-stage	786.93
	Nonmatching	Self	Pre-stage	898.43
			Post-stage	782.99
		Friend	Pre-stage	886.28
			Post-stage	787.34
		Stranger	Pre-stage	891.80
			Post-stage	790.65

**TABLE 1** Mean response efficiency (RT/ACC) as a function of shape category, test stage and trial type in LpSTS/DLPFC/sham group

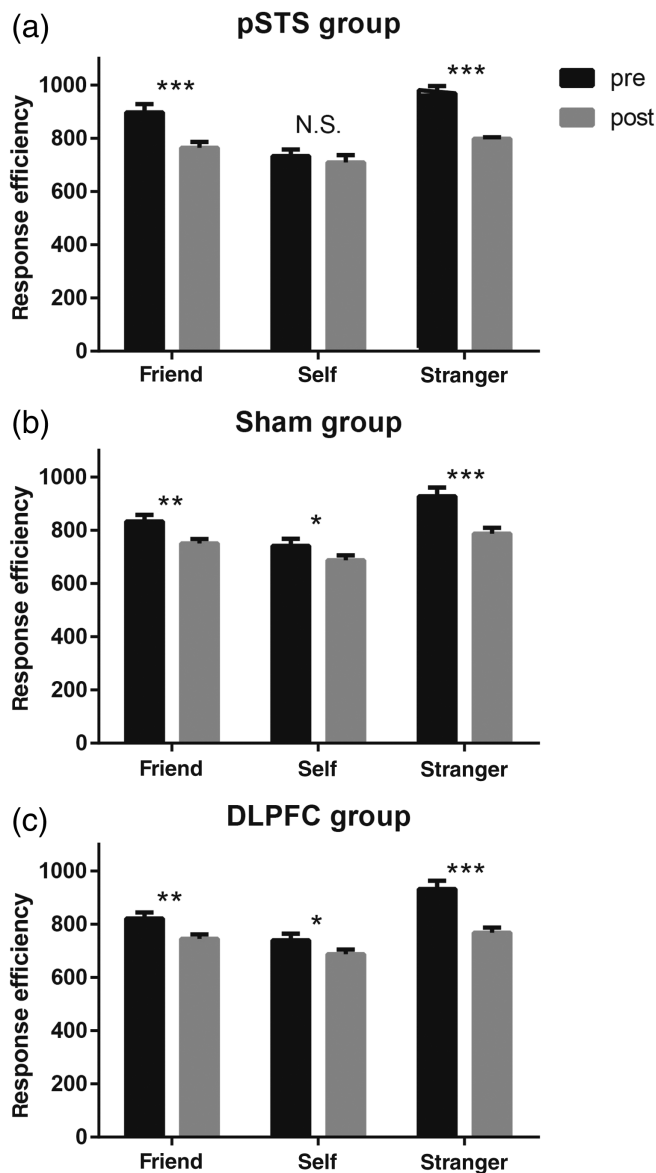
Note: Response efficiency = reaction time/accuracy.

results for non-matched trials revealed a main effect of Test Stage,  $F(1, 106) = 96.81, p < .001, \eta_p^2 = .48$ , indicating that response efficiency was higher (lower value) during post-stage relative to pre-stage. None of the other effects were significant (all  $p > .12$ ).

Next, we conducted a 3 (Shape Category: self/friend/stranger)  $\times$  2 (Test Stage: pre-stage vs. post-stage) repeated-measures analysis of variance (ANOVA) separately in the three groups to investigate the role of left LpSTS and left DLPFC in self-related processing (Figure 4). This analysis showed a significant interaction effect between Shape

Category and Test Stage in all groups for matched pairs (DLPFC:  $F(2, 68) = 7.75, p = .002, \eta_p^2 = .19$ ; LpSTS:  $F(2, 74) = 9.29, p = .001, \eta_p^2 = .20$ ; sham:  $F(2, 70) = 4.12, p = .02, \eta_p^2 = .11$ ), but such an effect was not observed for the nonmatched pairs ( $ps > .60$ ). Pairwise comparison showed that in the DLPFC and sham groups, response efficiency for the three shape categories was significantly lower (lower response efficiency represents better performance) during post-stage relative to pre-stage ( $ps < .03$ ), but the effect of the Test Stage was nonsignificant on self-shape category trials in the





**FIGURE 4** Mean response efficiency (RT/ACC) as a function of shape category and test stage for matched pairings in LpSTS/DLPFC/sham groups. Error bars represent +1 SEM. \* $p < .05$ ; \*\* $p < .01$ ; \*\*\* $p < .001$

LpSTS group ( $p = .41$ ) rather than on friend and stranger shape categories ( $ps < .001$ ). The nonsignificant change for self-matching trials between prestimulation and poststimulation over LpSTS was the key result of the present study. Therefore, we conducted the Bayesian paired samples  $t$ -tests using JASP 0.14.0.0 to examine the differences between the two stages on self/friend/stranger-matching trials in the LpSTS group (Love et al., 2019). The Bayesian paired samples  $t$ -test provided strong evidence in support of the negative results for the LpSTS group ( $H_1$ : Measure 1 (value in pre-stage)  $\neq$  Measure 2 (value in post-stage);  $H_0$ : Measure 1 (value in pre-stage) = Measure 2 (value in post-stage); for self-matching trials:  $BF_{10} = 0.24$ ; for friend-matching trials:  $BF_{10} = 214.90$ ; for stranger-matching trials:  $BF_{10} = 112,421.63$ ).

**TABLE 2** Deviance information criterion (DIC) values for each model

Model	Trial type	Shape	Session	Group	DIC
1	Z	-	-	-	-13,918
2	Z	V	-	-	-15,065
3	Z, V	V	-	-	-16,640
4	Z, V	V	V	-	-18,509
5	Z, V	V	V	V	-18,505
6	Z	Z	-	-	-15,295
7	Z,	Z, V	-	-	-16,489
8	Z, V	Z, V	-	-	-17,259
9	Z, V	Z, V	V	-	-19,155
10	Z, V	Z, V	V	V	<b>-19,165</b>
11	Z	-	Z	-	-14,100
12	Z	V	Z	-	-15,259
13	Z, V	V	Z	-	-16,826
14	Z, V	V	Z, V	-	-18,818
15	Z, V	V	Z, V	V	-18,823
16	Z	-	-	Z	-13,918
17	Z	V	-	Z	-15,071
18	Z, V	V	-	Z	-16,634
19	Z, V	V	V	Z	-18,507
20	Z, V	V	V	Z, V	-18,502

Note: V = drift rate, Z = starting point. Bold indicates a DIC difference of 10 is strong evidence for a model (Kass & Raftery, 1995). In models 1, 6, 11, and 16, the drift rate is fixed across conditions (i.e., a single V is estimated).

### 3.2 | HDDM analyses

We estimated 20 models which have been included all conditions to establish which model best fits the data (described in Section 2.4, for a similar approach, see Golubickis et al. (2020)). We first examined whether a starting point bias (Z) between the two types of responses (matching or mismatching) could fit the data, where five combinations of drift rate (V) varied across experimental conditions (e.g., trial type, shape category (Shape), test stage (Session), group, see Table 2 for specific combination) (models 1–5). Second, in models 6–10, we investigated whether shape category could affect the starting point when the five similar combinations of drift rate varied across conditions. Third, in models 11–15, we tested whether TMS intervention could shift the starting point of information accumulation using a similar assignment of drift rate. Fourth, we examined whether group assignment with five combinations of drift rate varying across conditions could explain the data (models 16–20). As shown in Table 2, model 10 yielded the best fit according to the deviance information criterion where a lower DIC value indicated a model with better fit (Spiegelhalter et al., 1998; Spiegelhalter, Best, Carlin, & van der Linde, 2002).

Interrogation of the posterior distributions revealed that (Table 3), on matching trials (Figure 5), drift rate (V) was higher

**TABLE 3** Parameter means and the upper (97.5q) and lower (2.5q) quantiles of the best fitting model

Group	Diffusion model parameter	Mean	Quantile	
			2.5q	97.5q
	Z_self	0.58	0.57	0.59
	Z_friend	0.56	0.55	0.57
	Z_stranger	0.53	0.52	0.54
pSTS	Vpre_self_matching	2.05	1.81	2.27
	Vpost_self_matching	2.28	2.05	2.52
	Vpre_friend_matching	1.42	1.20	1.64
	Vpost_friend_matching	1.92	1.67	2.16
	Vpre_stranger_matching	1.28	1.06	1.51
	Vpost_stranger_matching	1.98	1.74	2.21
	Vpre_self_mis-matching	2.17	1.94	2.41
	Vpost_self_mis-matching	2.60	2.38	2.83
	Vpre_friend_mis-matching	1.83	1.60	2.06
	Vpost_friend_mis-matching	2.32	2.10	2.54
	Vpre_stranger_mis-matching	1.78	1.56	2.01
	Vpost_stranger_mis-matching	2.21	1.96	2.45
Sham	Vpre_self_matching	2.08	1.83	2.31
	Vpost_self_matching	2.39	2.15	2.62
	Vpre_friend_matching	1.60	1.37	1.84
	Vpost_friend_matching	1.97	1.72	2.21
	Vpre_stranger_matching	1.37	1.13	1.61
	Vpost_stranger_matching	1.93	1.68	2.17
	Vpre_self_mis-matching	1.96	1.73	2.19
	Vpost_self_mis-matching	2.42	2.17	2.66
	Vpre_friend_mis-matching	1.91	1.68	2.14
	Vpost_friend_mis-matching	2.32	2.07	2.57
	Vpre_stranger_mis-matching	1.90	1.66	2.13
	Vpost_stranger_mis-matching	2.28	2.05	2.52
DLPFC	Vpre_self_matching	2.09	1.85	2.35
	Vpost_self_matching	2.33	2.08	2.59
	Vpre_friend_matching	1.74	1.50	1.98
	Vpost_friend_matching	2.04	1.80	2.29
	Vpre_stranger_matching	1.46	1.23	1.70
	Vpost_stranger_matching	2.12	1.88	2.36
	Vpre_self_mis-matching	2.11	1.87	2.35
	Vpost_self_mis-matching	2.53	2.28	2.76
	Vpre_friend_mis-matching	1.92	1.67	2.16
	Vpost_friend_mis-matching	2.33	2.09	2.57
	Vpre_stranger_mis-matching	1.87	1.62	2.10
	Vpost_stranger_mis-matching	2.35	2.12	2.60

(i.e., information accumulation was faster) for self-category pairing during post-stage than that during pre-stage in the sham group ( $p_{\text{Bayes}}(\text{post-self}) > p_{\text{Bayes}}(\text{pre-self}) = .97$ ), but this effect was not significant in LpSTS ( $p_{\text{Bayes}}(\text{post-self}) > p_{\text{Bayes}}(\text{pre-self}) = .91$ ) and DLPFC

group ( $p_{\text{Bayes}}(\text{post-self}) > p_{\text{Bayes}}(\text{pre-self}) = .92$ ). In addition, drift rates were higher for friend- and stranger-category pairings during post-stage than that during pre-stage in all groups (all  $p_{\text{Bayes}} > .96$ ). On mismatching trials, all drift rates were higher for the three category pairings during post-stage than during pre-stage in all groups (all  $p_{\text{Bayes}} > .98$ ).

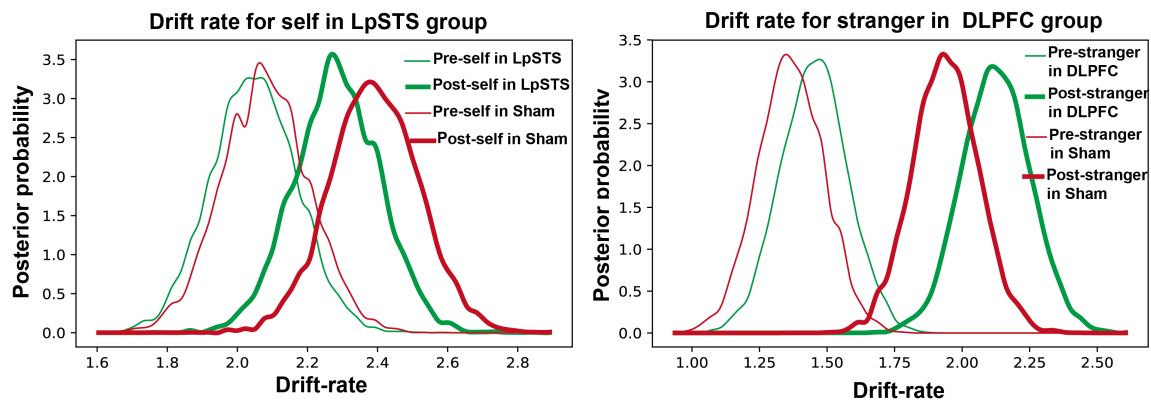
Furthermore, a comparison of the observed starting values ( $Z$ ) with no bias ( $Z = 0.50$ ) indicated extremely strong evidence of a prior bias toward matching judgments (vs. mismatching) in all category pairings (i.e., self-category,  $M = 0.58$ ; friend-category,  $M = 0.56$ ; stranger-category,  $M = 0.53$ ; all  $p_{\text{Bayes}} = 1.00$ ). Also, evidence suggested that less information was required (i.e., the starting value was larger) for the self-category pairing than for the friend- and stranger-category pairings ( $p_{\text{Bayes}}(\text{self}) > p_{\text{Bayes}}(\text{friend}) = 1.00$ ,  $p_{\text{Bayes}}(\text{self}) > p_{\text{Bayes}}(\text{stranger}) = 1.00$ ), and less information was required for the friend-category pairing than for the stranger-category pairing ( $p_{\text{Bayes}}(\text{friend}) > p_{\text{Bayes}}(\text{stranger}) = .99$ ). These results are consistent with previous results (Golubickis et al., 2017, 2020) and are not the primary outcome, we therefore will not discuss the results in Section 4.

## 4 | DISCUSSION

In the present study, to address the roles of LpSTS and DLPFC in the self-attention network (Humphreys & Sui, 2016), we used TMS combined with the self-matching task to elucidate their causal roles in the self-prioritization effect. Although geometric shapes were counter-balanced between pretest and posttest stages, an overall practice effect manifested. Importantly, this practice effect was absent in the LpSTS condition for self-matched trials. Consistently, similar patterns emerged in HDDM analyses with the drift rate, indicating that inhibitory stimulation on the LpSTS impaired the self-prioritization effect. For the DLPFC, our findings fail to confirm the causal role of the DLPFC during other-matching. Specifically, similar to the sham condition, the DLPFC condition manifested practice effects on response efficiency and drift rate for friend and stranger associations during posttest than that during pretest. In addition, there was no significant difference in drift rate for self-related matching before and after DLPFC condition.

To the best of our knowledge, this is the first study using inhibitory rTMS to provide causal evidence that LpSTS directly modulates self-salience in information processing. The LpSTS is part of the ventral attentional network (VAN), which is primarily responsible for orienting attention to the environment and detecting the social salience of external stimuli (DiQuattro & Geng, 2011; Pageler et al., 2003; Sliwiska & Pitcher, 2018). Sui et al. (2013) found that enhanced activity in the VMPFC and LpSTS respond to paired self-associations compared with paired other associations and demonstrated functional connectivity between the VMPFC and the LpSTS particularly increased for self-associations using dynamic causal modeling. Based on this, Sui and Humphreys (2015a, 2015b) speculated that the self-prioritization effect in perception and attention is





**FIGURE 5** Mean posterior distributions of drift rate ( $V$ ) as a function of Test-stage and Group. Left panel: Drift rate for the self in the LpSTS group (relative to the sham group) during pre- and post-stages; Right panel: Drift rate for stranger in the DLPFC group (relative to the sham group) during pre- and post-stages

through the rapid activation of the VMPFC and that this then activates the LpSTS. If this conjecture holds, damage to either one of the two regions should decrease or abolish the self-prioritization effect. However, this assumption somewhat contradicts the findings of Sui, Chechlacz, et al. (2015) in which damage to the LpSTS increases the self-prioritization effect. This finding was based on a unique patient whose lesion involved the LpSTS and neighborhood regions (e.g., left angular, and left insula), thus it should be interpreted cautiously. The current study used a sham-controlled design and measured behavioral performance supplemented with a causal method, TMS, which provides direct causal evidence supporting the key role of the LpSTS in the self-prioritization effect.

Based on the SAN, we hypothesized that TMS stimulation over the DLPFC would impair the processing of the other-related stimuli, whereas our findings fail to confirm the causal role of the DLPFC during other-matching. Evidence that supports the DLPFC's involvement in the other-related processing is mainly based on correlational neuroimaging studies. For example, Sui et al. (2013) measured brain activity while participants performed the self-matching task and observed that, unlike the LpSTS-VMPFC circuit, decreased activity in the DLPFC was associated with enhanced self-related processing and was primarily involved in representing other associations. To date, only one study attempted to test the causal role of the DLPFC, in which Martinez-Perez, Campoy, Palmero, and Fuentes (2020) employed high-definition transcranial direct current stimulation (HD-tDCS) to establish a causal link between the DLPFC and the processing of other-related stimuli. Our null results are consistent with those of this study, showing that brain stimulation (both tDCS and TMS) over the DLPFC did not succeed in modulating the processing about others. The negative results might be because other brain areas are also involved in processing information about others. For example, the temporoparietal junction (TPJ) is crucial for self/other differentiation (Brass, Ruby, & Spengler, 2009; Fuentes-Claramonte et al., 2020; Spengler, von Cramon, & Brass, 2009), facilitating the processing of others (van der Meer et al., 2011), and is more responsive to others (Pfeifer et al., 2013). Future research should measure changes in

activation pattern with fMRI and TMS to define whether there are other brain regions involved in the other representations when the DLPFC is deactivated.

Several recent studies have employed brain stimulation techniques to elucidate the roles of the core brain regions in the SAN involved in self-prioritization effect (Martinez-Perez et al., 2020; Schafer & Frings, 2019; Yin, Sui, Chiu, Chen, & Egner, 2019). Two of these studies used tDCS to manipulate the cortical activity of the VMPFC and/or DLPFC, and both observed no change in the performance of the self-matching task (Martinez-Perez et al., 2020; Schafer & Frings, 2019). On the other hand, Yin, Bi, Chen, and Egner (2021) found that cathodal tDCS (inhibitory) delivered to VMPFC could eliminate the self-prioritization effect in a working memory task. Compared to these studies, the current study has some novelties and strengths. First, while recent studies focused on the role of VMPFC (Martinez-Perez et al., 2020; Schafer & Frings, 2019; Yin et al., 2021) and DLPFC (Martinez-Perez et al., 2020), the current study provides novel evidence regarding the role of the LpSTS. Second, null results in previous studies might be partially attributed to the relative impreciseness of tDCS targeting while the TMS technique in the current study allows for more precise stimulation (Elder & Taylor, 2014; Ferreira et al., 2019; Kurmakaeva et al., 2021). Third, the usage of HDDM analysis allowed us to separate the effect of TMS on different processing components and indicated that the modulatory effect of LpSTS TMS was manifested in the process of information accumulation (Golubickis et al., 2017, 2020; Wiecki et al., 2013).

The current findings add to the growing body of literature showing that the self-influences information processing not only at a higher level of cognition but also in low-level processes such as perception. Recently, Northoff (2016) proposed the basis model of self-specificity (BMSS) which highlights that the self is a basis function of the brain's spontaneous activity. This model has been supported by a recent EEG study showing that temporal integration of different psychological levels of the self is associated with temporal integration on the neuronal level (Kolvoort, Wainio-Theberge, Wolff, & Northoff, 2020). In line with this research, the current results demonstrate a causal

relationship between self-specificity at the perceptual level and the role of the pSTS (in linking the self to external stimuli in the matching task), suggesting self-integration on psychological and neuronal levels. Qin, Wang, and Northoff (2020) used the meta-analysis approach to analyze the neural processes underlying different aspects of the self. They proposed a multi-layered nested hierarchical model of self, in which external stimuli can become self-related and thereby integrated within the self at three levels: interoceptive-processing (prerequisite of the integration of self and external information), exteroceptive-processing (linking the self and external information), and mental-self-processing (realizing the integration). While this model and the SAN model have their specific focuses, the models interpret how we as humans interact with the environment (e.g., external stimuli) around us. Specifically, they highlight the role of pSTS/TPJ in integrating external stimuli and the self. Our finding regarding the LpSTS supports this view.

The current investigation raises several points of interest for future studies. First, the present study employed a 2-day pretest/posttest design, such that participants performed the self-matching task on the first day, and performed the task again the next day after receiving TMS stimulation. Participants in both the real TMS group (over DLPFC and LpSTS) and sham group were received the same cTBS protocol. Thus, sham stimulation is accompanied by a similar mild auditory sensation (under the use of earplugs) compared to that of real stimulation. In addition, Participants were TMS-naïve (never having received TMS sessions before) so that the tilting could not be a hint for the kind of stimulation given. Overall, these could be integrated to support that sham group in the present study could be considered as an effective baseline condition. However, the inevitable presence of the practice effect makes interpretation of the results less straightforward even under the use of different stimuli in self-matching tasks prestimulation and poststimulation. Future research could add a fourth group without even sham stimulation, allowing more accurately quantify the practice effect. Second, although locating targeted regions based on international 10–20 system has been extensively utilized and validated (Beam, Borckardt, Reeves, & George, 2009; Koch et al., 2008; Noh et al., 2017; Sahlsten et al., 2019; Veniero et al., 2021; Zhao, Li, Liu, Voon, & Yuan, 2020), future work with neuronavigational-guided TMS based on anatomical brain scans is recommended to validate the results of the present study. Third, in the present study, the target site was a between-subject factor, such that each participant only received TMS to one of the sites. This might have contributed to the negative results of the DLPFC condition. Future research could change the target site to a within-subject factor to increase statistical power. Fourth, we did not concurrently acquire neural imaging during the TMS study; therefore, there is no way to quantify the intensity of disruption of the targeted region. We acknowledge that there might be differences between the LpSTS and DLPFC in the degree to which they were disrupted by TMS. However, previous works using similar TMS protocols did find disrupted DLPFC functioning (Georgiev et al., 2016; Xu et al., 2013). In addition, there is no evidence suggesting such systematic

differences in TMS responsiveness between these regions to the best of our knowledge. This invites future research that could directly measure the effects of TMS-driven perturbation with functional imaging technologies. In summary, with the aid of TMS and the self-matching paradigm, the present results demonstrate the causal role of LpSTS in the self-prioritization effect, supporting the theoretical propositions of the SAN model. In addition, no clear evidence was found for the DLPFC's role.

## ACKNOWLEDGMENTS

The funders have/had no role in study design, data collection, and analysis, decision to publish, or preparation of the manuscript.

## CONFLICT OF INTEREST

The authors declare no competing interests.

## AUTHOR CONTRIBUTIONS

Fei Wang and Jie Sui conceived and designed the study. Qiongdan Liang programmed the experimental and analysis scripts. Bozhen Zhang, Sinan Fu, and Qiongdan Liang conducted the pilot study and will perform the follow-up experiments and analyze the data. Fei Wang, Jie Sui, and Qiongdan Liang prepared the manuscript.

## DATA AVAILABILITY STATEMENT

All data and analysis code are accessible at [https://osf.io/u9ty6/?view\\_only=9bdbbaf95f9a4d9c8bc53dd1a29563ae](https://osf.io/u9ty6/?view_only=9bdbbaf95f9a4d9c8bc53dd1a29563ae).

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**How to cite this article:** Liang, Q., Zhang, B., Fu, S., Sui, J., & Wang, F. (2022). The roles of the LpSTS and DLPFC in self-prioritization: A transcranial magnetic stimulation study. *Human Brain Mapping*, 43(4), 1381–1393. <https://doi.org/10.1002/hbm.25730>