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Modulatory role of the right ventrolateral prefrontal cortex in crowd emotional perception following social exclusion

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Abstract

The right ventrolateral prefrontal cortex (rVLPFC) is a crucial region involved in modulating social exclusion. Although prior studies have focused primarily on how social exclusion influences the perception of single faces, the effect of social exclusion on the crowd emotional perception and the neural mechanisms remain elusive. The current research examined whether social exclusion causes a biased perception of crowd emotions, and whether this effect would be modulated by transcranial magnetic stimulation (TMS) over the rVLPFC. Participants were either socially included or excluded, while TMS stimulation was applied over the rVLPFC or the vertex. Next, they viewed sets of happy or disgusted faces and assessed the mean emotions of each set. Socially excluded participants overestimated the mean emotions for disgusted crowd faces compared to socially included participants, which was positively correlated with need threat. Compared to the vertex, stimulating the rVLPFC reduced socially excluded participants' biased perception of disgusted crowd faces. Moreover, stimulation of the rVLPFC decreased discrimination performance for crowd faces expressing disgust but increased it for happy crowd faces. The results provide a causal test for the role of rVLPFC in alleviating the biased perception of negative crowd emotions following social exclusion.

Keywords: social exclusion; crowd emotion perception; crowd facial expressions; transcranial magnetic stimulation; right ventrolateral prefrontal cortex

Introduction

Social exclusion, a pervasive and powerful form of social threat, does not only elicit negative emotions, threats to fundamental needs, and aggressive behavior, but also changes how people process social information (Williams 2009, Riva et al. 2012, Syrjämäki and Hietanen 2019, Timeo et al. 2019). Although some studies have shown that the threat of social exclusion increases attention to smiling faces (Dewall et al. 2009, Xu et al. 2015), other studies have found that individuals perceive more sadness (Rajchert et al. 2022) and exhibit an enhanced negative interpretation bias (interpret ambiguous facial information as signs of disapproval) after exclusion than after inclusion (Azoulay et al. 2020). These biases in social information processing predict aggressive behavior (Dodge et al. 2003), and even confer risk for anxiety and depression (Sharma et al. 2022).

However, empirical research in this field has primarily focused on the effect of social exclusion on the perception of individual facial expressions. In contrast, less is known about what happens during the perception of crowd facial expressions in response to the threat of social exclusion. We routinely encounter and interact with groups of people in social situations. Reading the emotions of the groups through facial expressions is critical in shaping our attitudes and responses toward them (Im et al. 2021). Meanwhile, we explored whether transcranial magnetic stimulation (TMS) could modulate the perception of crowd faces following the threat of social exclusion.

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The effects of social exclusion on the processing of emotional facial expressions

How do people perceive emotional facial expressions when they are socially excluded? Two very different outcomes seem plausible. Participants who experience the threat of social exclusion feel more sad than those who are socially included (Rajchert et al. 2022). Individuals with social anxiety also exhibit a stronger negative interpretation bias after exclusion than after inclusion (Azoulay et al. 2020). These findings lend support to the rejection sensitivity model (Downey et al. 1997), which posits that the threat of social exclusion would lead individuals to become sensitive to the possibility of future rejection. However, other studies show that compared to socially included individuals, excluded individuals attend selectively and preferentially to smiling faces (Dewall et al. 2009), and perceive neutral faces as nicer, friendlier, or more desirable (Maner et al. 2007). These findings provide evidence in support of the social reconnection hypothesis (Maner et al. 2007), which holds that social exclusion stimulates a desire to affiliate and reconnect with others. These contrasting viewpoints reflect the effects of social exclusion on the processing of emotional facial expressions.

Even though a significant body of research indicates that we frequently encounter and interact with groups of people in social situations, how to perceive crowd emotion following social exclusion has rarely been investigated. Most studies have focused on the impact of social exclusion on the perception of a single face, whereas a study conducted by Lerche et al. (2021) examined its influence on the perception of crowd faces. In this study, participants were presented with crowds consisting of happy and angry facial expressions, and they were instructed to assess whether the majority of the crowd faces were happy or angry. Participants who experienced the threat of exclusion increased the probability of angry classifications. Moreover, they increased their preferences for fixations on angry faces. Is it possible that this negative bias in crowd emotional perception after the threat of social exclusion could be modulated by TMS of regions related to the regulation of negative emotions?

The regulatory function of the right ventrolateral prefrontal cortex

Several neuroimaging studies suggest that the right ventrolateral prefrontal cortex (rVLPFC) regulates pain-related distress and negative affect (NA) (Eisenberger et al. 2003, Wager et al. 2008, Meyer et al. 2011). For instance, Eisenberger et al. (2003) determined which brain region(s) is active when participants are socially excluded during a Cyberball game. During social exclusion, there was a significant increase in rVLPFC activity, which was negatively correlated with the level of self-reported distress. These findings suggest that the rVLPFC plays a crucial role in modulating the distress of social exclusion.

Neuromodulation techniques, such as TMS and transcranial direct current stimulation (tDCS), enable the observation of neural activity and behavioral changes by activating or inhibiting the function of specific brain regions (i.e. rVLPFC), thereby establishing the causal relationship between specific brain regions and cognitive functions. Neuromodulation studies have also demonstrated a causal relationship between rVLPFC activity and the regulation of social pain (Riva et al. 2012, 2015a, 2015b). In these studies (Riva et al. 2012, 2015a), participants received tDCS or sham stimulation over the rVLPFC, and were manipulated to experience feelings of either social inclusion or exclusion. Socially excluded participants who received anodal tDCS over the rVLPFC reported lower levels of hurt feelings, and were less aggressive than those who received sham stimulation. Similarly, using TMS, researchers discovered that active stimulation of the rVLPFC could reduce participants' subjective negative emotions during emotion regulation (He et al. 2020, Mo et al. 2021, Yu et al. 2023). Furthermore, activating the rVLPFC could decrease anger recognition on excluders' facial expressions (Rajchert et al. 2022), and encourage participants to give more positive evaluations to unfamiliar peers (Yu et al. 2023). These results provide evidence that stimulation of rVLPFC could improve emotion regulation and alleviate the painful effects of social exclusion.

Current study

We aimed to answer two main research questions: (1) does social exclusion lead to a bias in the perception of crowd emotion; and (2) can this bias be modulated by the stimulation of rVLPFC? Participants were randomly assigned to receive TMS stimulation over the rVLPFC or the vertex control site. Then participants were either socially included or excluded during an online Cyberball game. After the TMS and Cyberball game, participants were presented with a set of faces of varied emotions and asked to evaluate the average emotion expressed in the set. We made two predictions. First, we expected that socially excluded participants, as compared to socially included participants, would overestimate the mean emotion of disgust or happy crowd faces. Second, we predicted TMS to modulate the effect of social exclusion on crowd face perception, with socially excluded participants receiving stimulation over the rVLPFC reducing the estimate of the mean emotion of disgust or happy crowd faces than those receiving stimulation over the vertex.

Materials and methods

Participants

The sample size was calculated based on a power analysis conducted with G*Power 3.1 (Faul et al. 2007). Under the medium effect size $f = 0.25$, $\alpha = 0.05$, and power $(1-\beta) = 0.95$, a sample of at least 76 participants was needed. Thus, we recruited 88 college students (all right-handed with normal or corrected-to-normal vision) from Liaoning Normal University. Seven participants were excluded because of their poor data (see section on Statistical analysis), and another one misunderstood the rules of the task. After these exclusions data from 80 participants (82.5% females; mean age = 21.31 years, SD = 1.89, range: 18–25 years) remained for analysis.

Participants were assigned to four groups varying for the Cyberball inclusionary status (social exclusion vs. inclusion) and type of stimulation (rVLPFC vs. vertex). Participants completed four questionnaires on the day before the experiment, including the Connor–Davidson Resilience Scale (CD-RISC; Connor and Davidson 2003), the Tendency to Expect Rejection Scale (TERS; Jobe 2003), the Beck Depression Inventory-II (BDI-II; Beck et al. 1996), and the State-Trait Anxiety Inventory (STAI; Lothar 1981). No significant differences were found in these characteristics across the four groups (Table 1). The experiment protocol was conducted in accordance with the Declaration of Helsinki and was approved by the Ethics Committee of Liaoning Normal University. Participants gave written consent prior to the experiment, and received monetary compensation after the experiment.

Table 1. Demographical characteristics of the participants (M ± SE).

	Exclusion ($n = 40$)		Inclusion ($n = 40$)		Statistics[a]	
Items	rVLPFC ($n = 20$)	vertex ($n = 20$)	rVLPFC ($n = 20$)	vertex ($n = 20$)	F	P
CD-RISC	63.80 ± 2.67	64.30 ± 2.68	68.65 ± 3.15	69.00 ± 3.15	0.90	0.45
TERS	54.50 ± 2.16	56.55 ± 2.01	55.15 ± 2.32	56.05 ± 2.57	0.16	0.92
BDI-II	5.85 ± 1.64	5.15 ± 1.73	5.55 ± 1.50	5.50 ± 1.52	0.11	0.96
STAI-T	43.10 ± 1.70	42.40 ± 1.65	41.95 ± 1.98	39.30 ± 1.69	0.89	0.45
STAI-S	42.35 ± 2.35	39.25 ± 2.18	38.45 ± 2.66	37.00 ± 2.60	0.85	0.47

[a]One-way analysis of variance (ANOVA) across the four groups.

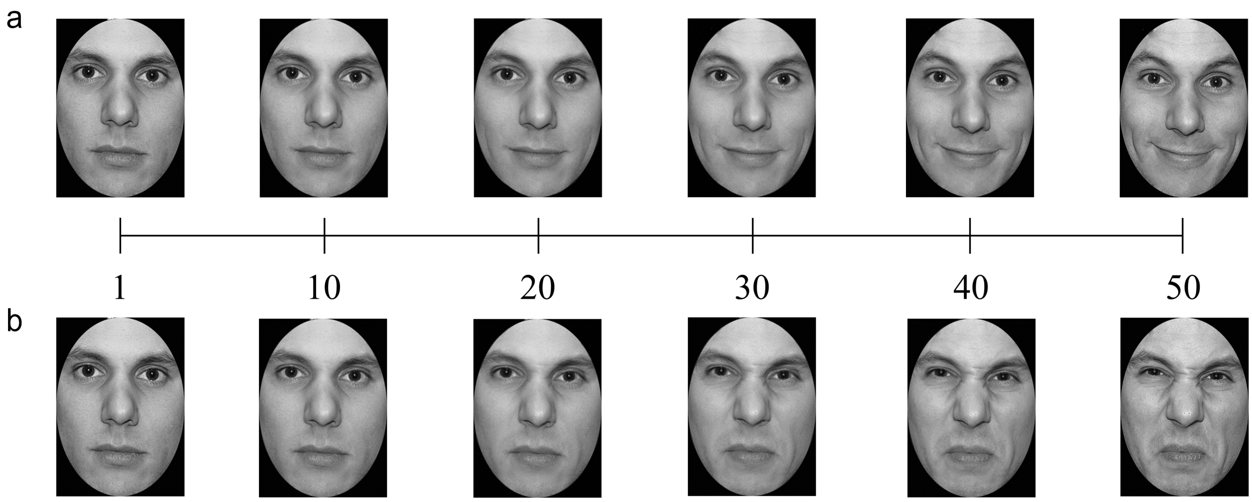

Figure 1. A sample of six facial expressions from the neutral-to-happy scale (a) and the neutral-to-disgust scale (b) were used in the present study. Numbers represent "emotional units."

Stimuli

One male face identity showing happy, disgusted, and neutral expressions was selected from the NimStim database (Tottenham et al. 2009). We used FantaMorph 5 software (Abrosoft Co., Beijing, China) to generate a stimuli set containing 50 morphed faces from neutral to extremely happy/disgusted. Morphed faces were separated from one another by emotional units, with face number 1 being the most neutral and face number 50 being the most happy or disgusted (Fig. 1). The group's mean emotional intensity was randomly set to be between 12 and 39. Once the mean was selected, the set was then assembled around the mean: two more neutral (−3 and −9 units below the mean) and two more happy/disgust (3 and 9 units above the mean). The distance between each face displayed in the set was at least 6, which was well above the participants' discrimination threshold (Haberman and Whitney 2009). The single test face was more neutral or happy/disgusted than the set face by 2, 6, or 10 emotional units. Faces were presented in a 2 × 2 matrix, and the set of 4 faces subtended 6.94 × 9.53 degrees of the visual angle.

Cyberball game

We used a Cyberball game to manipulate social exclusion versus inclusion (Williams et al. 2000). Participants were informed that they would play an online ball-tossing game with two other players. However, participants would, in reality, pass the ball to players controlled by the computer program. Based on the previous study (Xu et al. 2018), the Cyberball program was set for 42 throws. In the exclusion condition, participants received the ball twice at the beginning of the game and were excluded by the other two players for the rest of the game. In the inclusion condition, participants received 14 throws. The negative effects of a single social exclusion experience induced by the Cyberball game could last about 45–55 min (Buelow et al. 2015).

Measures

Positive and Negative Affect Schedule

The Positive and Negative Affect Schedule (PANAS; Watson et al. 1988) measures two dimensions of emotional experience: positive affect (PA), the tendency to feel positive mood states; and NA, the tendency to feel negative mood states. This scale has 20 items using a 5-point scale (1 "not at all" to 5 "extremely," PA: Cronbach's $\alpha = 0.95$; NA: Cronbach's $\alpha = 0.88$).

Need Threat Scale

The Need Threat Scale (NTS; Williams 2009) measures threat needs in four dimensions: belonging, self-esteem, meaningful existence, and control. Participants responded to 20 items on a 5-point scale (1 "not at all" to 5 "extremely"). Lower scores indicate a higher need threat (Cronbach's $\alpha = 0.97$).

Connor–Davidson Resilience Scale

The Connor–Davidson Resilience Scale (CD-RISC; Connor and Davidson 2003) measures psychological resilience. This scale has 25 items using a 5-point scale (0 "not true at all" to 4 "true all the time"), with higher scores indicating greater resilience capacity (Cronbach's $\alpha = 0.93$).

Tendency to Expect Rejection Scale

The Tendency to Expect Rejection Scale (TERS; Jobe 2003) measures the likelihood of rejection during social situations. This scale has 18 items using a 5-point scale (1 "strongly disagree" to 5 "strongly agree"), with higher scores indicating higher levels of rejection sensitivity (Cronbach's $\alpha = 0.83$).

Beck Depression Inventory-II

The Beck Depression Inventory-II (BDI-II; Beck et al. 1996) measures the severity of depressive symptoms. This scale has 21 items using a 4-point scale, with higher scores indicating higher levels of depression symptoms (Cronbach's $\alpha = 0.92$).

State-Trait Anxiety Inventory

The State-Trait Anxiety Inventory (STAI; Lothar 1981) measures the severity of state and trait anxiety symptoms with two subscales of STAI-S and STAI-T, each containing 20 items. This scale asked participants to make a self-assessment on a 4-point scale (1 "not at all" to 4 "very much"), with high scores indicating higher levels of anxiety (STAI-S: Cronbach's $\alpha = 0.95$; STAI-T: Cronbach's $\alpha = 0.89$).

Transcranial magnetic stimulation protocol

Neuronavigated TMS was performed with a PowerMAG stimulator (Mag & More, Berlin, Germany) connected to a figure-of-eight-shaped coil. Before stimulation, a T1-weighted structural MRI was obtained from each participant (GE MR750 3.0 T scanner using an 8-channel head coil; TR = 7 ms, TE = 3 ms, flip angle = 8°, field of view = 256 × 256 mm^2, voxel size = 1.0 × 1.0 × 1.0 mm^3, matrix = 256 × 256, slice thickness = 1 mm). The anatomical data were imported into the neuronavigation software (Visor2, ANT-Neuro, Berlin, Germany), and used for stereotaxic coregistration of the participant's brain with the TMS coil, allowing for online coil positioning. As shown in Fig. 2C, the simulated electric fields induced by TMS over the rVLPFC and vertex were computed using SimNIBS software (Thielscher et al. 2015). The MIN coordinate of the rVLPFC ($x = 52$, $y = 36$, $z = 4$) was taken from a previous neuroimaging study (Masten et al. 2009) reporting activation in the rVLPFC sector during being socially excluded. The coordinate of the vertex ($x = 1$, $y = -16$, $z = 76$) was determined by the prior study (Soutschek et al. 2013).

Single pulses of TMS were delivered over the left primary motor cortex to determine the resting motor threshold (RMT). RMT was defined as the minimal stimulation intensity that elicited motor evoked potentials with amplitudes of larger than 50 μV in at least 5 out of 10 trials (Rossini et al. 1994). Stimulation intensity was set at 90% of the participant's RMT, which is consistent with prior TMS studies targeting the VLPFC (He et al. 2020, 2023, Yu et al. 2023). In total, 10 Hz stimulation was applied for 20 min at 4 s on and 26 s off for a total of 1600 pulses (40 trains) (Mo et al. 2021). Furthermore, this TMS protocol has been shown to evoke after-effects that last for at least 30 min (see Thut and Pascual-Leone 2010, Valero-Cabré et al. 2017 for reviews), therefore covering the duration of both the Cyberball game and the mean emotion discrimination task.

Procedure

E-Prime 2.0 software (Psychology Software Tools Inc., Pittsburgh, PA) was used for stimulus presentation, data collection, and TMS triggering. The overall procedure is shown in Fig. 2A. Participants received TMS for 20 min. After 15 min of stimulation (with 5 min of stimulation remaining), participants played a Cyberball game. After TMS and the Cyberball game, participants completed the Positive and Negative Affect Schedule (PANAS; Watson et al. 1988) and the Need Threat Scale (NTS; Williams 2009).

Subsequently, participants performed a mean emotion discrimination task, which was employed in previous studies to represent crowd emotions (Haberman and Whitney 2007, 2009). As shown in Fig. 2B, each trial started with a fixation cross appearing in the middle of the screen (500–800 ms), followed by crowd stimuli consisting of four faces (1000 ms), and then a single test face, during which time participants' responses were recorded. The test face remained on the screen until participants responded. Participants were required to indicate whether the single test face was more emotional than the mean emotion of the preceding face set. Participants responded as accurately and quickly as possible by pressing either the key "F" or the key "J" on a computer keyboard. After a training session consisting of 12 trials, participants performed 4 experimental blocks (a total of 336 trials). In each trial, participants saw a set containing 4 faces. These faces expressed different intensities of emotion from either neutral-to-happy (happiness condition) or neutral-to-disgust (disgust condition) continua. We used within-emotion continua in separate blocks. Thus, participants performed consecutively two blocks of 168 trials for each emotion condition. The order of emotional conditions was counterbalanced across participants. Moreover, the duration of the mean emotion discrimination task was approximately 20 min, which was within the timeframe of the effects of social exclusion.

Statistical analysis

For each participant, the proportions of "more emotional" responses were calculated at each level of test face distance (±2, ±6, ±10). These data were fitted to a logistic psychometric function $f(x) = 1/[1 + e^{-b(x-a)}]$, where a was the point of subjective equality (PSE) and b was the slope. Note that the quality of each psychometric fit was reflected by the R^2 for each curve, the participants were excluded if their data did not meet the standard criterion of the goodness-of-fit ($R^2 < 0.8$) for the logistic function (i.e. poor data). We plotted the psychometric curves using GraphPad Prism 9 software (GraphPad Software Inc., CA, USA). The x-axis depicted the distance of the single test face from the mean of the face set in emotional separation units (i.e. distance from the mean). The y-axis showed the proportion of making a "the single test face is more emotional than the mean of the face set" response at each distance from the mean for the participants. In this study, when participants estimated the single test face, they had a chance to respond with a probability (i.e. 50%) that it was more emotional than the mean of the face set, and a chance probability that it was less emotional. Therefore, individual PSE was defined as the number of emotional separation units that corresponded to a 50% "more emotional" response to the psychometric function, as shown in Figs 4A, 5A, and 5B. If participants estimated happier or more disgusted test faces as emotionally equal to the mean of the face set, we concluded that their corresponding mean emotions were overestimated (Zhang et al. 2015). The present study was conducted by calculating the PSE and slope of each participant to reflect their perceptual bias and sensitivity toward crowd faces. PSE and slope were analyzed using repeated-measures ANOVA, with group (social exclusion, inclusion) and TMS type (rVLPFC, vertex) as the between-subjects factors, and emotion type (happy, disgust) as the within-subjects factor. In addition, the relationship between behavioral outcomes (i.e. PSE and slope) and need threat rating was analyzed using a two-tailed Person's correlation.

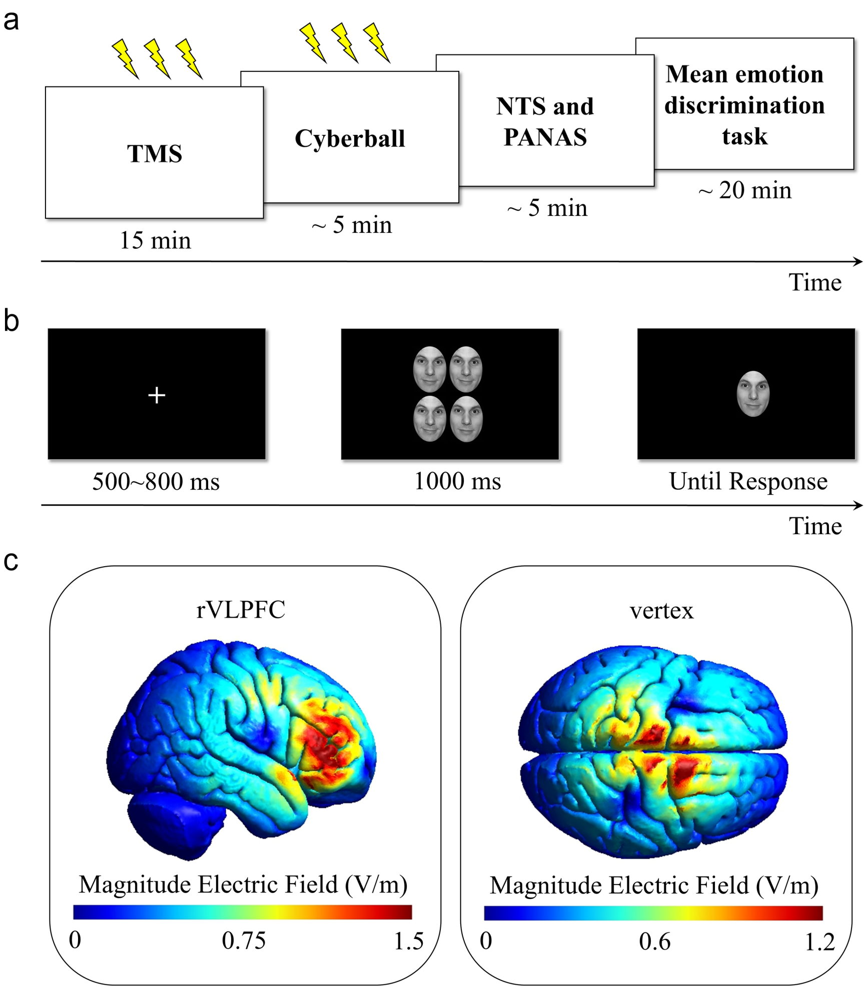

Figure 2. (a) Overall procedure. (b) Illustration of each trial in the mean emotion discrimination task. (c) Illustration of TMS-induced electric fields modeling for rVLPFC and vertex targets.

Moreover, we performed additional exploratory analyses. Discrimination response times and accuracy for each distance from the mean were analyzed using repeated-measures ANOVA, with group (social exclusion, inclusion) and TMS type (rVLPFC, vertex) as the between-subjects factors; emotion type (happy, disgust) and distance from the mean (−10, −6, −2, +2, +6, +10) as the within-subjects factors.

Statistical analyses were performed using SPSS Statistics 27.0 software (IBM Core Inc., Armonk, USA). Descriptive data were presented as mean ± standard error. The Greenhouse-Geisser correction was used to correct the *p*-values if Mauchley's sphericity assumption was violated, and the Bonferroni correction was made for post-hoc multiple comparisons. Partial eta-squared ($\eta 2\ p$) values were reported to estimate the effect sizes for the ANOVA results.

Results

Manipulation check

Socially excluded participants (2.22 ± 0.06) felt more threatened by fundamental human needs than socially included participants (3.81 ± 0.08, $F_{(1,76)} = 244.08$, $P < .001$, $\eta 2\ p = 0.76$; Fig. 3A), thereby confirming the effectiveness of the social exclusion manipulation.

Assessment of positive and negative affects

A 2 (social exclusion vs. inclusion) × 2 (rVLPFC vs. vertex) between-subjects ANOVA on PA rating revealed a main effect of group, such that socially excluded participants (20.43 ± 0.59) reported less PA than socially included participants (35.95 ± 0.30; $F_{(1,76)} = 248.29$, $P < .001$, $\eta 2\ p = 0.77$). The main effect of the TMS type was significant. Participants who received TMS stimulation over the rVLPFC (30.33 ± 1.06) reported more PA than those who received TMS stimulation over the vertex (26.05 ± 1.48; $F_{(1,76)} = 18.83$, $P < .001$, $\eta 2\ p = 0.20$). Furthermore, the interaction between the group and TMS type was significant ($F_{(1,76)} = 6.83$, $P = .01$, $\eta 2\ p = 0.08$; Fig. 3B). Socially excluded participants who received TMS stimulation over the rVLPFC (23.85 ± 0.25) reported more PA than those who received TMS stimulation over the vertex (17.00 ± 0.36; $F_{(1,76)} = 24.17$, $P < .001$, $\eta 2\ p = 0.24$). Among socially included participants, no significant PA differences emerged between the stimulation over the rVLPFC (36.80 ± 0.35) and the vertex (35.10 ± 0.40; $F_{(1,76)} = 1.49$, $p = 0.23$, $\eta 2\ p = 0.02$).

A 2 (social exclusion vs. inclusion) × 2 (rVLPFC vs. vertex) between-subjects ANOVA on NA rating revealed a main effect of group, such that socially excluded participants reported more NA (19.73 ± 0.61) than socially included participants (12.10 ± 0.21; $F_{(1,76)} = 62.96$, $P < .001$, $\eta 2\ p = 0.45$). The main effect of the TMS

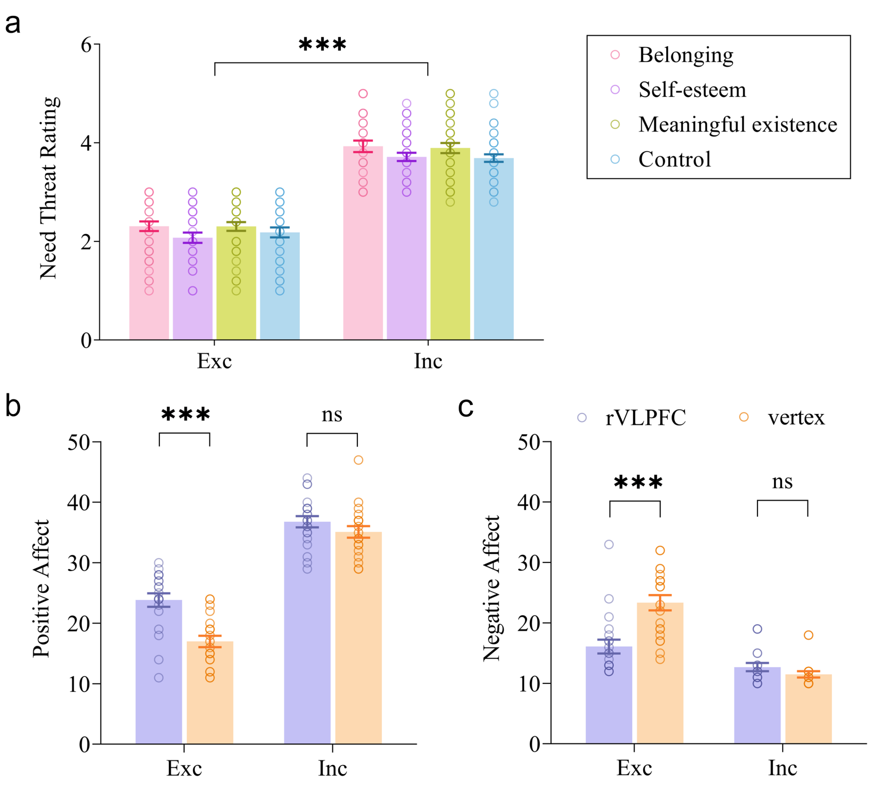

Figure 3. (a) Mean ratings of need threat for socially excluded and included participants. Mean ratings of positive (b) and negative (c) affect as a function of whether participants were made to feel socially excluded or included and the type of brain stimulation they received. Error bars represent the standard error of the mean. The small circles represent the individual's data. *** $P < .001$, ns = nonsignificant. Exc = exclusion, Inc = inclusion.

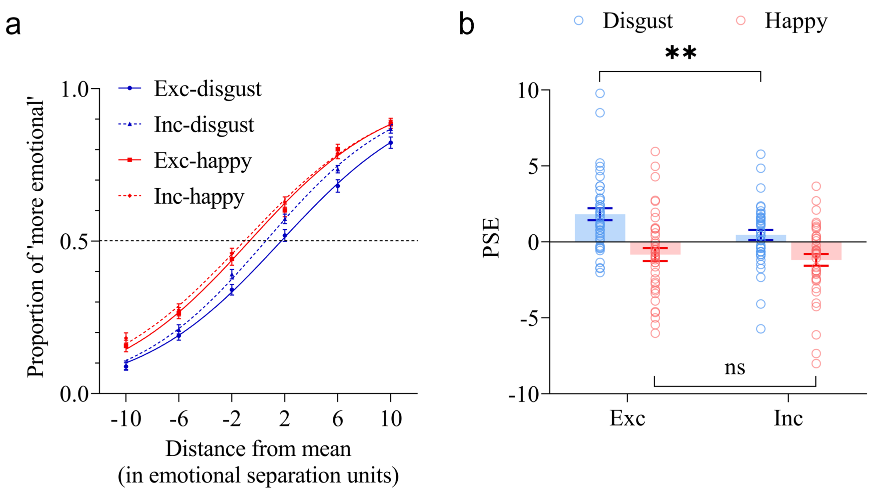

Figure 4. (a) The mean proportion of "more emotional" responses in each distance from the mean was fitted as a logistic function. (b) The estimated PSE parameters. Error bars indicate the standard error of the mean. The small circles represent the individual's data. ** $p < 0.01$, ns = nonsignificant. Exc = exclusion, Inc = inclusion.

type was significant as well. Participants receiving TMS stimulation over the vertex (17.43 ± 0.96) reported more NA than those receiving TMS stimulation over the rVLPFC (14.40 ± 0.34; $F_{(1,76)} = 9.91$, $P < .01$, $\eta2\ p = 0.12$). Furthermore, the interaction between the group and TMS type was significant ($F_{(1,76)} = 19.33$, $P < .001$, $\eta2\ p = 0.20$; Fig. 3C). Socially excluded participants who received TMS stimulation over the rVLPFC (16.10 ± 0.27) reported less NA than those who received TMS stimulation over the vertex (23.35 ± 0.23; $F_{(1,76)} = 28.46$, $P < .001$, $\eta2\ p = 0.27$). Among socially included participants, no significant NA differences emerged between the stimulation over the rVLPFC (12.70 ± 0.32) and the vertex (11.50 ± 0.21; $F_{(1,76)} < 1$, $P = .38$, $\eta2\ p = 0.01$).

Point of subjective equality

The two-way interaction between emotion type and group was significant ($F_{(1,76)} = 4.14$, $P < .05$, $\eta2\ p = 0.05$; Fig. 4B). Socially excluded participants' average points of subjective equality for disgust crowd faces (1.83 ± 0.40) were significantly higher than that of socially included participants (0.46 ± 0.33; $F_{(1,76)} = 7.49$, $P < .01$, $\eta2\ p = 0.09$). However, no significant average points of

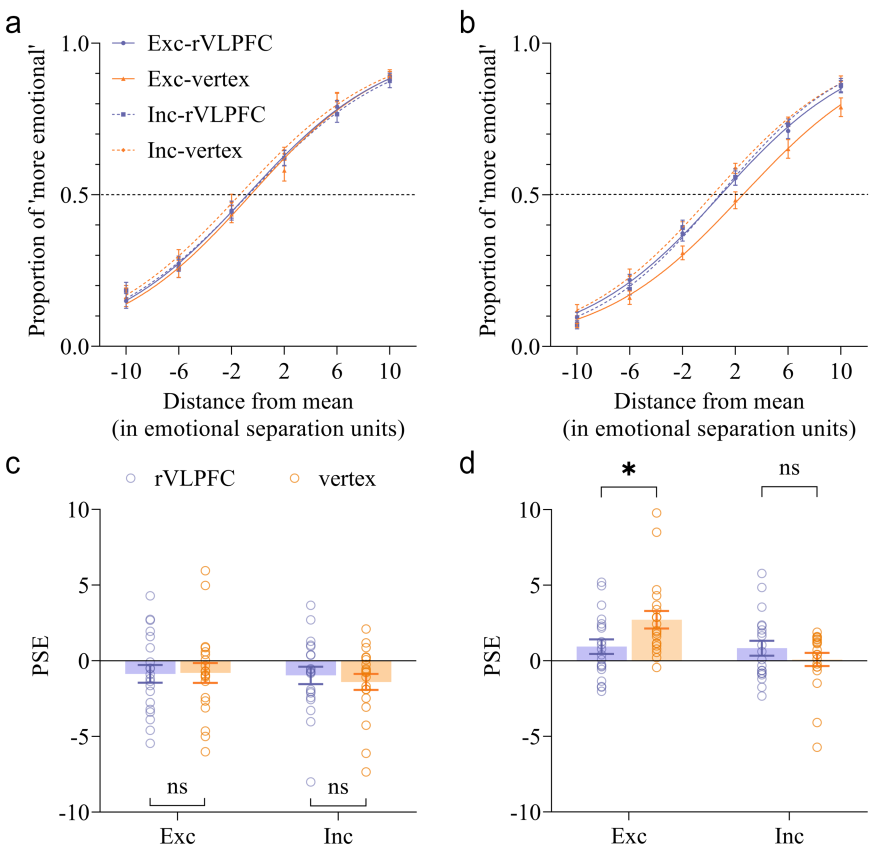

Figure 5. PSE for socially excluded and included participants who received TMS stimulation over the rVLPFC or vertex. (a) Psychometric curves for the happiness condition. (b) Psychometric curves for the disgust condition. (c) The estimated PSE parameters for the happiness condition. (d) The estimated PSE parameters for the disgust condition. Error bars indicate the standard error of the mean. The small circles represent the individual's data. * $p < 0.05$, ns = nonsignificant. Exc = exclusion, Inc = inclusion.

subjective equality differences emerged for happy crowd faces between socially excluded (−0.83 ± 0.43) and included participants (−1.18 ± 0.39; $F_{(1,76)} < 1$, $P = .56$, $\eta 2\ p = 0.01$). Moreover, points of subjective equality were negatively correlated with need threat rating for disgust faces ($r = -0.316$, $P < .01$), while no significant correlation was observed for happy faces ($r = -0.097$, $P = .39$).

The three-way interaction of emotion type, group, and TMS type was significant ($F_{(1,76)} = 4.11$, $P < .05$, $\eta 2\ p = 0.05$). To clarify the three-way interaction, we tested the interaction between the TMS type and group for the disgust and happiness conditions, respectively. For disgust condition, the interaction between TMS type and group was significant ($F_{(1,76)} = 6.40$, $P = .01$, $\eta 2\ p = 0.08$; Fig. 5D). Socially excluded participants who received TMS stimulation over the rVLPFC (0.94 ± 0.48) reduced average points of subjective equality than those who received TMS stimulation over the vertex (2.72 ± 0.58; $F_{(1,76)} = 6.35$, $P = .01$, $\eta 2\ p = 0.08$). Among socially included participants, no significant points of subjective equality differences emerged between the stimulation over the rVLPFC (0.84 ± 0.49) and the vertex (0.09 ± 0.44; $F_{(1,76)} = 1.12$, $P = .29$, $\eta 2\ p = 0.02$). For the happiness condition, the interaction between TMS type and group was not significant ($F_{(1,76)} < 1$, $P = .68$, $\eta 2\ p = 0.01$; Fig. 5C).

Slope

The main effects and interactions of all factors were nonsignificant for the slope results (P's ≥ .20), indicating that social exclusion did not affect the perceptual sensitivity for processing crowd faces.

Discrimination response times

Exploratory analysis found that the main effect of emotion type was significant ($F_{(1,76)} = 13.58$, $P < .001$, $\eta 2\ p = 0.15$). The average mood of disgusted crowd faces (868.97 ± 27.62 ms) was identified faster compared to happy faces (927.05 ± 36.92 ms). The remaining main effects and interactions were nonsignificant ($ps \geq 0.17$).

Discrimination accuracy

Exploratory analysis found that the main effect of emotion type was significant ($F_{(1,76)} = 67.06$, $P < .001$, $\eta 2\ p = 0.47$). The discrimination accuracy of disgusted crowd faces (0.78 ± 0.01) was higher than that of happy faces (0.70 ± 0.01). The three-way interaction of TMS type, group and emotion type was significant ($F_{(1,76)} = 23.03$, $P < .001$, $\eta 2\ p = 0.23$; Fig. 6). Socially excluded participants who received TMS stimulation over the rVLPFC (0.74 ± 0.01) exhibited a significantly higher discrimination accuracy for the mean of happy crowd faces than those who received TMS stimulation over the vertex (0.65 ± 0.02; $F_{(1,76)} = 18.19$, $P < .001$, $\eta 2\ p = 0.19$). Socially excluded participants who received TMS stimulation over the rVLPFC (0.74 ± 0.01) exhibited a significantly lower discrimination accuracy for the mean of disgust faces than those who received TMS stimulation over the vertex (0.82 ± 0.02; $F_{(1,76)} = 16.17$, $p < 0.001$, $\eta 2\ p = 0.18$). Among socially included participants, both the main effect of TMS type and the interaction between TMS type and emotion type were not significant (all $ps \geq 0.28$).

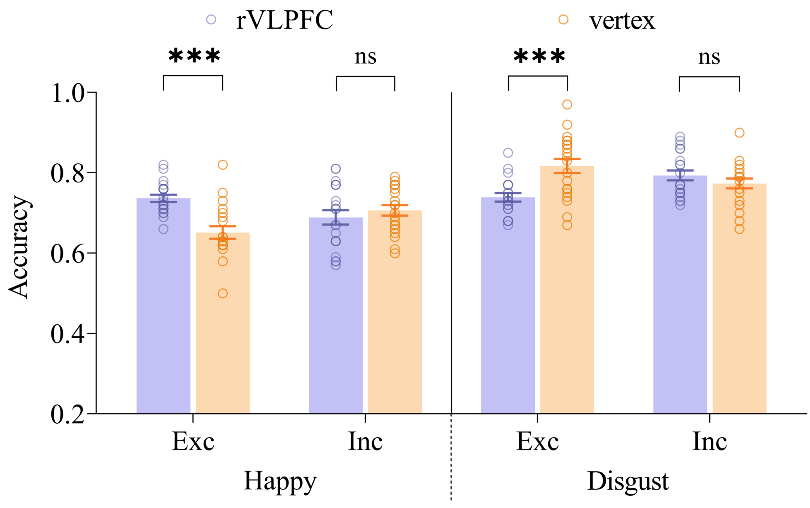

Figure 6. Socially excluded and included participants' discrimination accuracy for crowd faces expressing disgust and happy when they received TMS stimulation over the rVLPFC or vertex. Error bars indicate the standard error of the mean. The small circles represent the individual's data. *** $P < .001$, ns = nonsignificant. Exc = exclusion, Inc = inclusion.

Discussion

The current study sought to test whether social exclusion leads to a bias in perceiving crowd emotion, as well as the possible modulatory role of the rVLPFC on the relationship. The present study found that socially excluded participants overestimated the mean emotion of disgust crowd faces more than socially included ones. Additionally, a high level of need threat during social exclusion was positively correlated to an overestimation of disgust crowd faces. In accordance with the rejection sensitivity model (Downey et al. 1997) and extending prior research (Azoulay et al. 2020, Rajchert et al. 2022), our results indicated that the threat of social exclusion causes overperceiving emotion of disgust crowd faces, namely, a negative bias in the perception of crowd emotion that was modulated by need threat levels.

Social exclusion elicited preference and vigilance toward threatening facial expressions, which generally signify a threat to social connection (Kraines et al. 2018, Azoulay et al. 2020, Lerche et al. 2021, Rajchert et al. 2022). In particular, disgust faces serve as a signal of social exclusion (Lindner et al. 2014), indicating that disgust stimuli are excluded from the group. This is, to some extent, aligned with the current study as negative experiences (being rejected) resulted in an over-perception of disgust. This suggests that people who have experienced social exclusion may be hypervigilance to social threat signals to avoid being rejected again. Moreover, an event-related potential study has demonstrated that an increased level of need threat is associated with a larger neural response (N170) to emotional facial expressions (Kawamoto et al. 2014). Similarly, the present findings indicated that individuals with higher levels of need threat are more likely to exhibit a perceptual bias toward negative crowd emotions.

More importantly, our findings offer evidence that negative bias decreased after brain stimulation was applied over the rVLPFC following social exclusion. Socially excluded participants who received TMS stimulation over the rVLPFC reduced the estimation of the mean emotions of disgust crowd faces than those who received TMS stimulation over the vertex. This finding is consistent with a tDCS study, which causally demonstrated that the activation of the rVLPFC can effectively reduce hostility bias induced by social exclusion (Rajchert et al. 2022). As such, the major findings of the present study provide robust causal evidence to support the crucial role of rVLPFC in reducing negative crowd emotion bias after social exclusion.

Previous research has found socially anxious individuals perceived facial crowds more negatively, which may adversely impact their social interactions (Yang et al. 2012). In addition, abstinent heroin abusers exhibited negative biases when processing a group of expressions, which might negatively influence their overall assessment of the social environment and ultimately constitute a trigger for relapse (Zhang et al. 2015). Therefore, our findings of the functional specificity of rVLPFC in modulating crowd emotional perception may provide the feasibility of treating this brain region as an effective target to reduce negative bias toward social information in abstinent heroin abusers and socially anxious individuals.

Furthermore, disgust, a subtle expression of social rejection, is linked to avoidance and social withdrawal, which mitigates social interactions (Terrizzi et al. 2023). Hypervigilance to disgust might arguably be an obstacle in social communication and promote interpersonal distancing and social alienation (Lindner et al. 2014). Accordingly, our study complementally revealed that TMS stimulation over the rVLPFC could effectively ameliorate the adverse effect of social exclusion on social interactions by reducing the over-perception of disgust crowd emotion.

Moreover, our results provide evidence for the causal role of rVLPFC in the emotion regulation associated with social exclusion. We replicated the well-documented finding (Zhang et al. 2017, 2023) that social exclusion in a Cyberball game induces more NA and less PA than social inclusion. Importantly, we found that socially excluded participants who received TMS stimulation over the rVLPFC experienced greater PA and less NA than those who received TMS stimulation over the vertex. These findings were consistent with prior studies showing that stimulation of rVLPFC could reduce participants' negative emotions resulting from social exclusion during emotion regulation (Riva et al. 2012, He et al. 2018, Mo et al. 2021, Yu et al. 2023). Our study supports and extends previous research indicating that rVLPFC might be involved in various forms of emotion regulation, including the reduction of aggressive behaviors (Riva et al. 2015a) and painful experiences (Riva et al. 2012). Furthermore, the rVLPFC plays a crucial role in regulating a wide range of negative emotions (i.e. fear, sadness, and anxiety), not limited to social exclusion stimuli (Marques et al. 2018, Vergallito et al. 2018).

Our study also suggests that stimulation of rVLPFC can influence crowd facial expression recognition. Specifically, we found that rVLPFC stimulation increased the emotion discrimination of happy crowd faces and decreased the emotion discrimination of disgusted crowd faces as compared to the vertex control site. Interestingly, these results were consistent with the PSE findings of this study, indicating that a decrease in TMS-induced negative bias (PSE) is accompanied by a decrease in the discrimination of negative crowd emotions (accuracies). This study is partially compatible with prior research (Rajchert et al. 2022) showing that tDCS stimulation of the rVLPFC decreased anger recognition. Results of their research also showed that stimulation of rVLPFC decreased happiness recognition. Our study differed from prior research as it aimed to investigate whether social exclusion affected emotion recognition of the excluders' faces, but we employed stranger stimuli for emotion recognition, which could account for the discrepancies in results regarding emotion recognition. Notably, in the present study, the perception of happy crowd faces was designed to evoke approach-like behaviors/feelings and the perception of disgusted crowd faces was designed to elicit avoidance-like behaviors/feelings. Vergallito et al. (2018) have found that applying anodal tDCS over the rVLPFC might have an effect on the negative emotions of the right-lateralized avoidance systems. Yet, the results of our study are somewhat aligned with previous results showing a lower perception of negative crowd emotions and a higher perception of positive crowd emotions. These findings also further supported the view that stimulation of this region might significantly improve group interaction patterns for socially excluded individuals. That is, the activation of rVLPFC increases the desire for social reconnection and decreases the desire to withdraw from social interactions after the experience of social exclusion.

To the best of our knowledge, this study is the first one to investigate how noninvasive brain stimulation shapes people's biased perception of crowd emotions following social exclusion. However, the current study included limitations that warrant further investigation. First, more women took part in the study. Thus, generalizing the present results to the male group requires caution. Second, in order to avoid the interaction between face identity and emotional intensity caused by the picture materials, the participants were simultaneously exposed to crowd faces with the same identity. However, in real life, people generally respond to a more realistic heterogeneous crowd situation. To boost ecological validity, future work should adopt heterogeneous crowds in which the images presented within one crowd show different identities. Third, future research should incorporate single facial stimuli to further compare the similarities and differences in the perception of emotions from single faces versus crowd faces after social exclusion. Fourth, future research should test whether inhibiting the cortical excitability (through low-frequency TMS stimulation) of this brain region would increase the negative bias following social exclusion.

Conclusion

Our results demonstrate that social exclusion causes a negative bias in the perception of disgust crowd emotion, and modulating the cortical excitability of rVLPFC affects negative bias. Our study extends previous research on the modulatory role of rVLPFC in a wide range of domains such as perception of crowd emotion. More generally, our findings support the feasibility of applying noninvasive brain stimulation techniques to mitigate adverse consequences of social exclusion on perception of crowd emotion, and feelings of NA.

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Data availability

The data underlying this article will be shared on reasonable request to the corresponding author.

Author contributions

P.G. contributed to Investigation, Visualization, Formal analysis, Writing-original draft and Writing-review & editing. P.L. contributed to Conceptualization, Methodology, Software, Writing-original draft and Writing-review & editing. C.F. contributed to Writing-review & editing. M.Z. contributed to Formal analysis and Data curation. W. L. contributed to Conceptualization, Validation, Supervision and Writing-review & editing. W.H. contributed to Supervision, Writing-review & editing and Funding acquisition.

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