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# Ba c a d c a c c a c a d indi id al di erence in rai ac a

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Al ho gh con iderable e or ha e been made o nder and he ne ral nderpinning of a e ac a , c d b ca c d a , ab ne ral correla e of proac i e aggre ion hich i dri en b in r men al mo i a ion o ob ain per onal gain hro gh aggre i e mean and hich arie drama icall acro indi id al in erm of endenc of appealing o ch mean Here b combining r c ral gre ma er den i GMD and f nc ional re ing a e f nc ional connec ion RSFC fMRI e in e iga ed brain r c re and f nc ional ne ork rela ed o rai proac i e aggre ion We fo nd ha indi id al di erence in rai proac i e aggre ion ere po i i el a ocia ed i h GMD in bila eral dor ola eral prefron al cor e DLPFC and nega i el correla ed i h GMD in po erior cing la e cor e PCC he ere al o nega i el correla ed i h he reng h of f nc ional connec i i be een lef PCC and o her brain region incl ding righ DLPFC righ IPL righ MPFC ACC and bila eral prec ne The e nding hed ligh on he di eren ial brain ba e of proac i e and reac i e aggre ion and gge ed he ne ral nderpinning of proac i e aggre ion

Aggression refers to behavior that is carried out with an intention to cause physical or psychological harm to other individuals who are motivated to avoid the harm[1,2]. It has negative in uence on individuals' health and social relationships and can lead to considerable psychological or physical costs when aggressive behavior is expressed in exaggeration[3]. Aggression can be categorized into di erent categories along various dimensions. According to one common classi cation, reactive/impulsive aggression is triggered by provocation and/or perceived threat, whereas proactive/instrumental aggression is driven by instrumental motivations to achieve personal goals or to obtain personal gains through aggressive means with prior deliberation[1,4–6]. Two aspects of aggression, trait and state, can be further categorized correspondingly for the two types of aggression. While state reactive or proactive aggression is an aggressive response triggered by a speci c provocation or incentive, trait reactive or proactive aggression refers to disposition that individuals tend to conduct reactive or proactive aggressive behavior in daily life across times and situations[7–9].

Previous studies have shown that these two types of aggression di er in their psychological, physiological, and biological manifestations as well as in etiology[3,6,10,11]

[14]. Proactive aggression, but not reactive aggression, is positively correlated with positive expectation of outcomes that aggressive behavior would result in[15,16]. Individuals with high proactive aggression scores are more likely to overvalue the outcome of aggression. Increasing neural activity of right dorsolateral prefrontal cortex (DLPFC) with anodal transcranial direct current stimulation (tDCS) can reduce the proactive aggression but not reactive aggression in males[4].

Previous neural studies have been focused mostly on state reactive aggression, measuring participants' responses to provocation in controlled experimental tasks, such as the Taylor Aggression Paradigm (TAP) and

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the Point Subtraction Aggression Paradigm (PSAP)[9,17–20]. e results suggest that brain regions involved in state reactive aggression include orbitofrontal cortex (OFC), ventromedial prefrontal cortex (VMPFC), anterior cingulate cortex (ACC), dorsolateral prefrontal cortex (DLPFC), superior temporal gyrus, and amygdala. Both behavioral[3,21,22] and brain imaging studies demonstrate that emotion processing is crucially involved in state reactive aggression.

Comparatively, there are only a few studies investigating the neural basis of proactive aggression[18,23,24]. By increasing neural activity of right frontal cortex or inhibiting neural activity of le frontal cortex with brain stimulation technologies (tDCS and continuous theta-burst magnetic stimulation, cTBS), two studies induced right fronto-hemispheric dominance to explore the causal relationship between DLPFC and proactive aggressive behaviour measured by TAP and PSAP[4,23]. e proactive aggression was reduced a er increasing neural activity of right frontal cortex in men[18] and was increased a er inhibiting neural activity of le frontal cortex, compared with the one a er inhibiting neural activity of right frontal cortex[23]. But compared with the one a er sham stimulation, the proactive aggression had not changed a er inhibiting neural activity of le and right frontal cortex[23]. A third study, more similar to the current one, explored the brain structures responsible for trait proactive aggression in an adolescent sample[24]. e authors recruited 104 14-year-old adolescent twins and measured their brain structural MRI signals for tensor-based morphometry (TBM) and cortical thickness. A er scanning, the authors asked participants to ll out Reactive-Proactive Aggression Questionnaire (RPQ)[5], which contained items tapping into the prepotencies of trait proactive and reactive aggression, respectively. ese items cover a broad spectrum of daily activities, including both verbal and physical threats and actions. Respondents were asked to evaluate how o en such behaviours occurred to them. Across participants, the authors observed positive correlations between the total aggression scores and volumes of le caudate nuclei, bilateral putamen and right lateral orbitofrontal cortex, and between the total aggression scores and cortical thickness of superior temporal gyrus (STG), bilateral inferior temporal gyri (ITG), right middle temporal gyrus (MTG), right superior parietal lobe (SPL), bilateral inferior parietal lobes (IPL), and bilateral occipital lobes. ey also observed a negative correlation between the total scores and right middle frontal cortex (MFC) in both TBM and cortical thickness. In post hoc analyses, authors additionally found that proactive aggression was positively correlated with volumes of le caudate, le putamen and right orbitofrontal cortex, and cortical thickness of right STG, right STG, le ITG and le paracentral gyrus, and was negatively correlated with volumes of right middle frontal cortex, cortical thickness of bilateral superior frontal cortex (SFC), bilateral MFC and le anterior cingulate cortex (ACC). ese studies suggest that proactive aggression is correlated with grey matter structure and brain function of prefrontal cortex (DLPFC, OFC), parietal lobe (e.g. IPL and SPL), and cingulate cortex (e.g. ACC). And these regions have been found to be involved in the key aspects of trait proactive aggression as discussed below.

Individual di erences in trait proactive aggression may comprise at least three aspects: (1) proactive aggressive motivation, which refers to approach motivation to attain instrumental goals through aggressive means[4,25]; (2) the ability and tendency of behavioral execution and monitoring (e.g., goal-orienting, planning, & premeditation)[26–28]; and (3) the abilities and tendencies of moral disinhibitions for proactive aggressive behavior, such as ability or tendency of moral disengagement, low moral cognitions and emotions[29]. Accordingly, we expected to nd individual di erences in brain structure or activity related to these three aspects of trait proactive aggression.

Firstly, individuals with stronger trait proactive aggression may have higher approach motivation. In RPQ, this approach motivation is measured by items like "used physical force to get others to do what you want". Given that approach motivation involves le dorsolateral prefrontal cortex (DLPFC)[28,30], it is likely that we would observe individual di erences in DLPFC.

Secondly, compared with low proactive aggressive individuals, high proactive aggressive individuals exhibit more "cool-blooded", organized, and planned aggressive behaviors in non-provoking contexts[25,26,28]. In RPQ, items like "carried a weapon to use in a ght" are related to this type of goal-driven behavior. Bilateral DLPFC plays a critical role in executive control[31–33]; harming others for self-gain activates regions including DLPFC, insula, and temporoparietal junction (TPJ) extending into the posterior STS[34]. us, we predicted that individual di erences in trait proactive aggression could also involve DLPFC and some other regions.

irdly, highly proactive aggressive individuals typically have ability or tendency of low level of moral cognition and emotion, including lack of empathy[35–37], theory of mind and guilt[12,35,38,39]. ese individuals tend to use strategies such as moral disengagement to relieve or avoid moral inhibition (e.g., self-criticism) when approving proactive aggression[40–42]. Although items in RPQ did not describe the immoral features of high trait proactive aggression directly, given that moral disinhibition underlies the proactive aggressive behaviors, we predicted that brain regions involved in empathy, theory of mind and morality, such as ventral medial prefrontal cortex (VMPFC), precuneus, anterior cingulate cortex (ACC), posterior cingulate cortex (PCC), and temporoparietal junction (TPJ)[43,44], could also exhibit individual di erences regarding the moral aspect of trait proactive aggression.

In the current study, we continued this line of prior researches by focusing on adult participants and by examining the neuroanatomical feature and functional networks underlying the individual di erences in trait proactive aggression. We collected structural imaging data from 240 participants and resting-state functional imaging data from 162 (out of the 240) participants and examined the correlations between the brain measures and the trait proactive (and reactive) aggression scores on RPQ.

## R

**De crip i e da a** Table 1 shows the mean scores and SDs for reactive and proactive aggression and the age of the males and females for the 240 participants. e di erences between females and males in proactive aggression ($F = 1.43$, $p = 0.23$), reactive aggression ($F = 0.15$, $p = 0.70$) or age ($F = 0.21$, $p = 0.65$) were not statistically signi cant.

| | Males | | Females | |
|---|---|---|---|---|
| | Means | SD | Means | SD |
| Age | 20.32 | 1.851 | 20.31 | 2.03 |
| proactive aggression | 1.07 | 2.40 | 0.92 | 1.84 |
| reactive aggression | 8.74 | 4.21 | 8.18 | 4.32 |

**Table 1.** Demographic and behavioral data (n = 240). Note: n = number; SD = standard deviation.

| Brain regions | Peak coordinates x y z | Cluster size | Peak T value |
|---|---|---|---|
| **Positive correlation** | | | |
| L-DLPFC | −41 24 45 | 235 | 5.08 |
| R-DLPFC | 48 32 32 | 241 | 4.50 |
| **Negative correlation** | | | |
| PCC | 6 −65 14 | 637 | −4.58 |

**Table 2.** Brain regions with signi cant correlations between rGMD and trait proactive aggression. GMD indicates Grey Matter Density; DLPFC, dorsolateral prefrontal cortex; PCC, posterior cingulate cortex. e Alphasim correction was conducted ( e threshold of corrected cluster was set $p < 0.05$. Single voxel was set at $p < 0.001$. Cluster size >219 voxels).

**Correla ion of regional GMD i h core of proac i e aggre ion** For the all participants, multiple regression analysis found that residual scores of proactive aggression were positively correlated with GMD in bilateral DLPFC (x, y, z = −41 24 45, $t = 5.08$; x, y, z = 48 32 32, $t = 4.50$), and were negatively correlated with GMD in posterior cingulate cortex (PCC, x, y, z = 6, −65, 14, t = −5.08, see Table 2, Fig. 1).

e prediction analysis was then carried out to examine the stability of the relation between regional GMD and trait proactive aggression in all participants. e GMD in le DLPFC [$r_{(predicted,\ observed)} = 0.18$, $p < 0.001$, 1-$\beta = 0.80$], right DLPFC [$r_{(predicted,\ observed)} = 0.26$, $p < 0.001$, 1-$\beta = 0.98$] and PCC [$r_{(predicted,\ observed)} = 0.31$, $p < 0.001$, 1-$\beta = 0.99$] signi cantly predicted residual scores of trait proactive aggression.

Multiple regression analysis found that residual scores of reactive aggression were positively correlated with GMD in superior temporal gyrus (STG; x, y, z = 50, −44, 23, $t = 4.33$, $p < 0.001$, clusters > 50 voxels, uncorrected, see Table 3). We then carried out prediction analysis to con rm the relation between regional GMD in STG and residual scores of trait reactive aggression by machine learning method. e GMD in STG signi cantly predicted residual scores of trait reactive aggression [$r_{(predicted,\ observed)} = 0.23$, 1-$\beta = 0.95$, $p < 0.001$].

For the participants who did not score 0 for proactive aggression, multiple regression analysis found that residual scores of proactive aggression was positively correlated with GMD in bilateral DLPFC (x, y, z = −32 36 45, $t = 4.03$; x, y, z = 39 23 54, $t = 5.77$), and was negatively correlated with GMD in posterior cingulate cortex (x, y, z = 9–66 11, t = −4.83, see Supplementary Table S1 and Supplementary Fig. S1).

**F nc ional ne ork a oci ed i h rai proac i e and reac i e aggre ion** To explore whether the identi ed brain regions in the GMD analysis function synergistically with other brain regions to predict trait proactive aggression, a multiple regression analysis was performed. e signi cant brain regions (le DLPFC, x, y, z = −41 24 45; right DLPFC, x, y, z = 48 32 32; PCC, x, y, z = 6–65 14) in the GMD analysis were set as seeds in the functional connectivity.

For all participants who have resting data, with le DLPFC as the seed brain region, the residual scores of proactive aggressions were negatively correlated with strength of functional connectivity between le DLPFC and le IPL (x, y, z = −45–57 42, t = −4.89, see Table 4, Fig. 2). With the right DLPFC as the seed brain region, the residual scores of proactive aggressions were not signi cantly correlated with strength of functional connectivity between right DLPFC and any brain region. With PCC as the seed brain region, the residual scores of proactive aggression were negatively associated with the strength of the functional connectivity between the seed and the following regions: MPFC/ACC, precuneus, DLPFC (x, y, z = 6 45 −3, t = −4.93; x, y, z = 9–63 33, t = −5.03; x, y, z = 36 15 42, t = −5.15) and inferior parietal lobes (IPL, x, y, z = 48–57 39, t = −3.71) (see Table 4, Fig. 3).

We then performed prediction analysis to examine the stability of the relation between RSFC and trait proactive aggression in the sample. e strength of the functional connectivity between le DLPFC and IPL signi cantly predicted residual scores of trait proactive aggression [$r_{(predicted,\ observed)} = 0.28$, 1-$\beta = 0.94$, $p < 0.001$]. e strength of the functional connectivity between PCC and the regions including MPFC/ACC [$r_{(predicted,\ observed)} = 0.29$, 1-$\beta = 0.96$, $p < 0.001$], precuneus [$r_{(predicted,\ observed)} = 0.32$, 1-$\beta = 0.98$,$p < 0.001$], DLPFC [$r_{(predicted,\ observed)} = 0.37$, 1-$\beta = 0.99$, $p < 0.001$], IPL [$r_{(predicted,\ observed)} = 0.31$, 1-$\beta = 0.98$, $p < 0.001$] signi cantly predicted residual scores of trait proactive aggression.

To explore whether the identi ed brain region (right STG, x, y, z = 50–44 23, t = 50–44 23) in the GMD analysis function synergistically with other brain regions to predict trait reactive aggression, a multiple regression analysis was performed. e signi cant brain regions in the GMD analysis were set as seeds in the functional

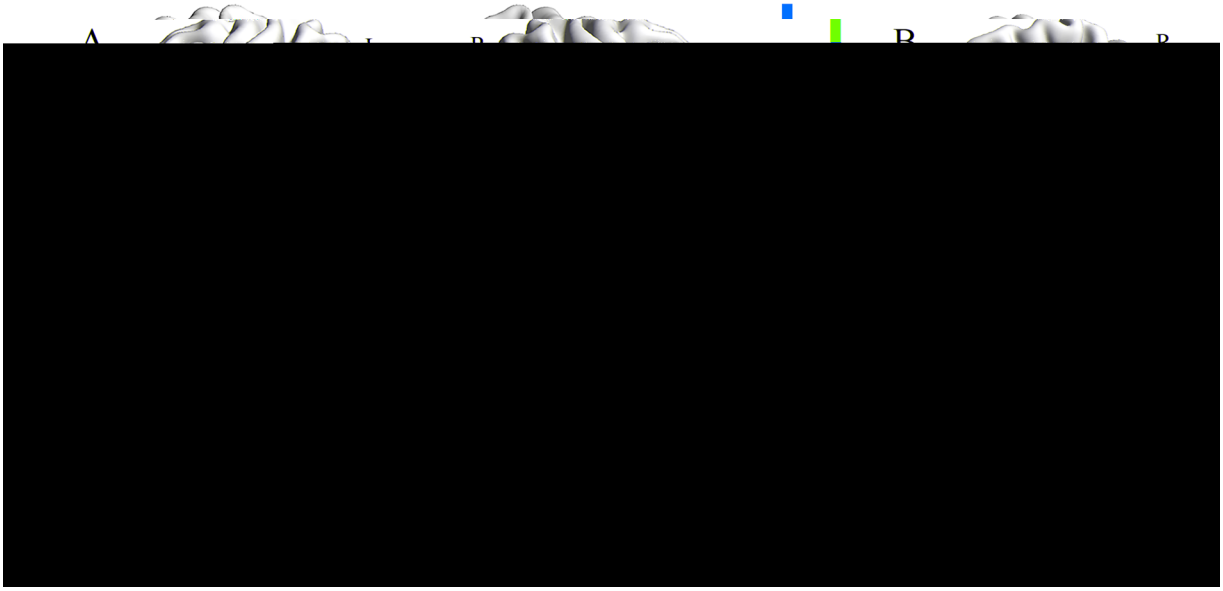


**Figure 1.** Correlations between regional grey matter density and proactive aggression. Scatter plots show the Pearson correlations between proactive aggression and GMD in the le DLPFC, right DLPFC and PCC, respectively, while reactive aggression scores were regressed out from proactive aggression scores. e scatterplots are shown for illustration purposes only. e threshold of the corrected cluster was set at $p < 0.05$ (single voxel $p < 0.001$, cluster size >219 voxels).

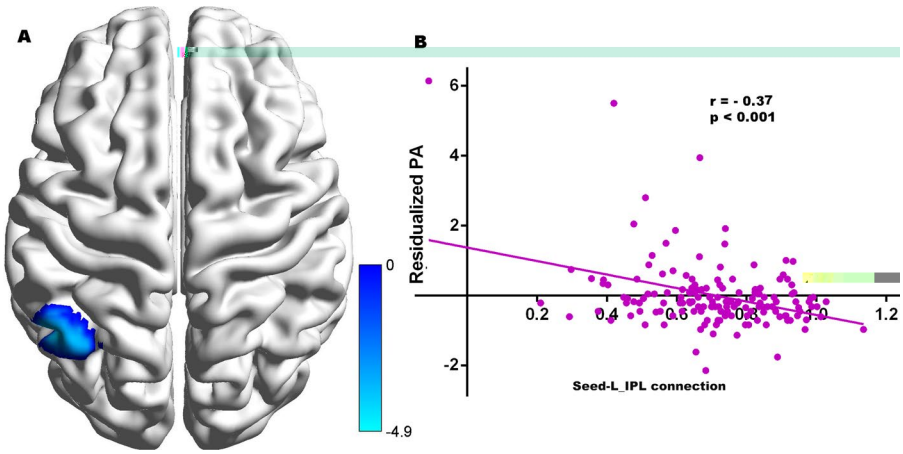
| Brain regions | Peak coordinates x y z | Cluster size | Peak T value |
|---|---|---|---|
| **Reactive aggression** | | | |
| **Positive correlation** | | | |
| STG | 50 −44 23 | 80 | 4.33 |
| **Negative correlation** | | | |
| ——— | | | |

**Table 3.** Brain regions with signi cant correlations between rGMD and trait reactive aggression. GMD indicates Grey Matter Density; STG, Superior Temporal Gyrus. e result was Uncorrected (Single voxel $p < 0.001$, Cluster size >50 voxels).

| Brain regions | Peak coordinates x y z | Cluster size | Peak T value |
|---|---|---|---|
| **L DLPFC as the seed** | | | |
| IPL | −45 −57 42 | 131 | −4.89 |
| **R DLPFC as the seed** | | | |
| ——— | | | |
| **PCC as the seed** | | | |
| MPFC/ACC | 6 45 −3 | 315 | −4.93 |
| precuneus | 9 −63 33 | 895 | −5.03 |
| IPL | 48 −57 39 | 140 | −3.71 |
| DLPFC | 36 15 42 | 289 | −5.15 |

**Table 4.** Brain regions in which functional connectivity strengths with seeds were signi cantly related to proactive aggression in all samples. Note: DLPFC indicates dorsolateral prefrontal cortex; MPFC, medial prefrontal cortex; ACC, anterior cingulate cortex; IPL, inferior parietal. e Alphasim correction was conducted ( e threshold of corrected cluster was set $p < 0.05$. Single voxel was set at $p < 0.001$. Cluster size >83 and 115 voxels).

connectivity. With STG as the seed brain region, a er controlling age and gender, multiple regression analysis revealed that residual scores of reactive aggressions were not signi cantly correlated with functional connectivity strength between STG and any region.




For the participants who did not score 0 for proactive aggression, with le DLPFC as the seed brain region, the residual scores of proactive aggressions were negatively correlated with strength of functional connectivity between le DLPFC and le IPL (x, y, z = −48, −57, 42, t = −3.35, uncorrected, $p < 0.001$, 50 voxels). With the right DLPFC as the seed brain region, the residual scores of proactive aggressions were not signi cantly correlated with strength of functional connectivity between right DLPFC and any brain region. With PCC as the seed brain region, the residual scores of proactive aggression were negatively associated with the strength of the functional connectivity between the seed and the following regions: MPFC/ACC, precuneus, DLPFC (x, y, z = 9 45–3, t = −4.35; x, y, z = 15–60 33, t = −4.93; x, y, z = 36 12 42, t = −4.08, see Supplementary Table S2, Supplementary Fig. S2).

**In erac ion e ec be een e and proac i e aggre ion on brain r c ral correla ion and f nc ional connec i i** A er controlling for the e ects of age and mean FD, the voxel-wise ANCOVA revealed no signi cant interaction e ects between sex and residual scores of proactive aggression scores in terms of the GMD and the strength of RSFC with the identi ed brain regions in both all samples and the samples who did not score 0 for proactive aggression.

**In erac ion e ec be een e and reac i e aggre ion on brain r c ral correla ion and f nc ional connec i i** A er controlling for the e ects of age and mean FD, the voxel-wise ANCOVA revealed no signi cant interaction e ects between sex and residual scores of reactive aggression scores in terms of the GMD and the strength of RSFC with the identi ed brain region.

## Di c ion

In this study, we investigated the brain correlates of individual di erences in trait proactive and reactive aggression by combining structural (GMD) and functional (RSFC) approaches. Current study showed that residual scores of trait proactive aggression were positively related to the GMD in the bilateral DLPFC and negatively related to the one in the PCC. Additionally, we found that the functional connectivity between the le DLPFC and the IPL was negatively correlated with residual scores of proactive aggressions. Moreover, the strength of the functional connectivity between PCC and some brain regions, including bilateral DLPFC, bilateral IPL, ACC/MPFC, and precuneus, was negatively correlated with residual scores of trait proactive aggression. e results support that individual di erences in trait proactive aggression relate to morphology and connectivity of some brain areas such as DLPFC and PCC. e details are provided in the following paragraphs.

First, as expected, the GMD of DLPFC was correlated with residual score of trait proactive aggression, suggesting that DLPFC may play an important role in proactive aggressive motivation (approach motivation towards instrumental goals via aggressive means) and the ability or tendency of behaviour monitoring (i.e., the ability of executive control of aggressive cognition and behaviour). As we illustrated in the introduction, individuals with high trait proactive aggression have high approval motivation and should be good at regulating cognitive con ict between bene t and morality, integrating information relevant to goal pursuit and using information guide behaviors in accordance with motivational goals[30]. Individual di erence in grey matter volume in DLPFC is involved in one's ability to exert control of dietary behaviours[45]. Additionally, DLPFC can exibly encod speci c attributes according to current goals[46]. us, DLPFC may represent the brain structure basis underlying individual di erences in proactive aggressive motivation and the ability of cognitive regulation and control.

However, our results seem to be inconsistent with the previous study[24], which found that trait proactive aggression scores were negatively correlated with adolescents' volumes and cortical thickness of MFG, an area anatomically close to DLPFC. e inconsistence may be due to developmental changes in neural basis of behaviors[47].

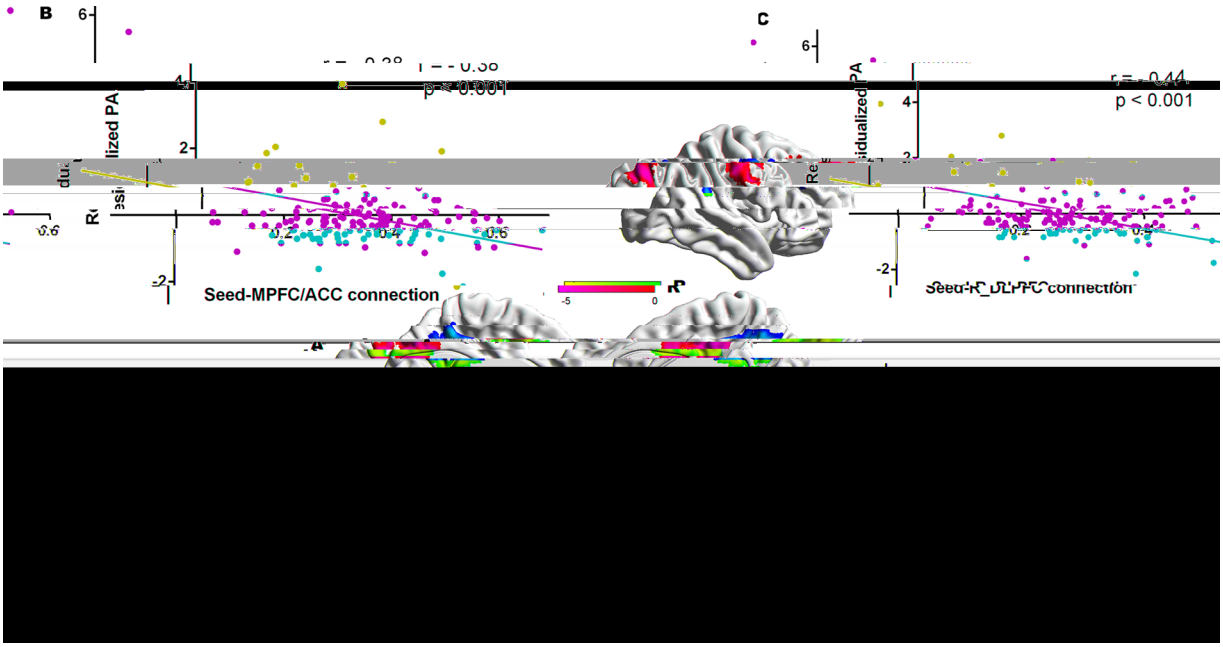



**Figure 3.** Clusters in which the strength of functional connectivity with the PCC (seed) were signi cantly correlated with proactive aggression (Panel A). Colour bars represent t-values. Scatter plots (panels B–E) indicate a signi cant association between proactive aggression and functional connectivity strength between the PCC and MPFC/ACC (panel B), right DLPFC (panel C), precuneus (panel D), and right IPL (panel E). e scatterplots are shown for illustration purposes only. e threshold of the corrected cluster was set at $p < 0.05$ (single voxel $p < 0.001$, cluster size $>115$ voxels).

For example, there are di erential patterns of brain activation for the same task in subgroups at di erent ages[48]. Speci cally, cognitive performance measured by a Stroop task was positively correlated with parietal activation during adolescence, whereas cognitive performance measured by the same task was positively correlated with prefrontal activation during adulthood[49].

Second, as predicted, the GMD of the PCC was negatively associated with trait proactive aggression, suggesting that PCC may be related to proactive aggression-related moral cognition and emotion. As discussed earlier, some abilities and tendencies of moral cognition and emotion (such as low empathy and callousness) play an important role in trait proactive aggression. Prior studies[50,51] suggest that PCC may be the neural basis underlying these abilities and tendencies of moral emotion and cognition. For example, structural evidence has shown that patient with empathic de cits (conduct disorder and schizophrenia) have smaller grey matter volume in PCC than healthy subjects do[52–54]. And psychopathy (which include low empathy and callousness) is negatively associated with grey matter volume in PCC[55,56] too. Additionally, PCC activity was found to be positively correlated with the sensitivity of a moral issue and evaluating the appropriateness of solutions to personal moral dilemmas[50,51]. Compared with promoting goals (e.g., making good things happen), preventing goal achievement (e.g., keeping bad things from happening) activates PCC more strongly[57,58]. In summary, PCC may be the neural basis of individual di erences in moral cognition and the emotional aspects of trait proactive aggression.

ird, RSFC analysis found that trait proactive aggression is negatively related to the strength of functional connectivity between DLPFC and both IPL and PCC. ese results are consistent with our perspectives that people with high level of trait proactive aggression must be good at or like relieving or reducing moral inhibition and easily justifying their proactive aggression. Harmful behaviours are moral events[59], and proactive aggression is a typical immoral behaviour. People's moral systems inhibit harmful behaviours for personal interests[1,27]. us, the intentions or behaviours related to proactive aggression would be inhibited by moral systems, and the ability or tendency of moral disinhibition (e.g., ignoring negative moral outcomes and moral disengagement) can facilitate proactive aggression. As mentioned above, DLPFC plays a critical role in the ability or tendency of behaviour monitoring. e IPL plays a critical role in calculating the social cost of harming others[27]. More importantly, e connectivity between IPL and DLPFC may re ect individuals' other-regarding tendencies[60]; IPL and PCC have been found to be involved in moral emotion (e.g., guilt and pain empathy)[61–63]. Presumably, the weaker strength of functional connectivity between DLPFC and IPL, PCC for high progressively aggressive people may re ect the brain network basis of the ability or tendency of moral disinhibition in trait progressive aggression, by which high proactive aggressive individuals more easily ignore victims' anticipated pain or loss and negative emotions and outcomes resulting from aggressive behaviour.

In addition, RSFC analysis found that trait proactive aggression was negatively associated with the strengths of functional connectivity between PCC and bilateral IPL, MPFC/ACC, precuneus. ese regions and coupling among PCC, bilateral IPL, MPFC/ACC, precuneus involved most of the regions and connections from the brain's default model network (DMN)[64–66]. Presumably, not only the regions and coupling among PCC, bilateral IPL, MPFC/ACC, precuneus, but the DMN may be linked to trait proactive aggression. e DMN plays an important role in moral

components of proactive aggressive motivation and the ability of proactive aggressive cognitive regulation and behaviour monitoring. PCC, the functional connectivity between DLPFC and both IPL and PCC, and the functional connectivity between PCC and other brain regions, including MPFC/ACC, bilateral IPL, and precuneus, may be the brain bases of moral cognition and emotion components of trait proactive aggression. ese ndings suggest trait proactive aggression may be correlated with multiple components including approval motivation, moral cognition and emotion.

## Me hod

**Par icipan** In current study, 240 healthy, right-handed college students (112 males; mean age = 20.32, SD = 1.95) from Southwest University in China participated as part of our ongoing project to explore the association between aggression and mental health with brain imaging. None of them had a history of psychiatric or neurological disorders. All of the 240 participants were included in the VBM analysis. However, only 162 of them were scanned for the resting-state MRI. Seven of these participants were excluded due to excessive head motion (translational or rotational parameters >3 mm), resulting in 155 participants (62 males; mean age = 19.85, SD = 1.57) included in the RSFC analysis. All the participants completed the Reactive-Proactive Aggression Questionnaire (RPQ; Raine *et al*., 2006) a er scanning. ey provided informed consent and were paid for their participation. e experimental protocol was approved by the Southwest University Brain Imaging Center Institutional Review Board. e experimental protocol was performed in accordance with the standards of the Declaration of Helsinki.

**Reac i e proac i e aggre ion q e ionnaire RPQ** The 23-item RPQ was used to measure to trait reactive-proactive aggression on a three-level scale[79]. In RPQ, 12 items assess responders' proactive

of proactive aggression scores was skewed, and one hundred and forty students got zero scores for proactive aggression. To examine the in uence of participants who scored 0 on brain correlates of proactive aggression, we conducted a multiple linear regression between residual scores of trait proactive and brain structure in the sample of participants (n = 100) who did not score 0 for proactive aggression using structural data, with gender, age, and total GMD as nuisance covariates. To e ectively exclude noise, limit the search areas and avoid edge e ects around the borders between grey matter and white matter, we used an absolute voxel signal intensity threshold masking of 0.2, ensuring that voxels with the probability of being grey matter lower than 0.2 would be excluded from the statistical analysis. A multiple comparison correction was performed using the AlphaSim program in REST so ware[84]. e threshold was set at cluster-level $P < 0.05$ and individual voxel level $P < 0.001$.

**Re ing a e f nc ional imaging da a pre proce ing** e data processing was conducted with SPM8 and Data Processing Assistant for Resting-State fMRI (DPARSF) so ware[84]. First, images from the rst 10 time points were discarded to ensure fMRI signal stabilization. e remaining 232 volumes were corrected for slice order and head motion artefacts. Second, the images were spatially normalized to the MNI template with spatial normalization parameters. Subsequently, nuisance covariates, including the cerebrospinal uid signal, white matter signal and Friston 24 motion parameters, were regressed out to eliminate the potential e ect of physiological artefacts. ird, spatial smoothing with an isotropic 6 mm full-width at half-maximum (FWHM) Gaussian kernel was performed. Fourth, the linear trend was removed to reduce physiological noise (e.g., eye movements). Finally, a bandpass lter (0.01–0.1 Hz) was employed to reduce low-frequency dri and high-frequency noise[85]. Participants with the translational or rotational parameters that were greater than 3 mm (7 participants) and the mean framewise displacement (FD) values that exceed 0.3 (0 participant) were excluded from analysis. e mean FD values were derived using Jenkinson's relative root mean square algorithm.

**RSFC beha io r correla ion anal i** To examine whether the clusters identified through the GMD-behaviour correlation analysis functioned with other regions as a network to explain trait proactive and reactive aggression, we performed RSFC-behaviour correlation analysis. First, the seed regions (le DLPFC, x, y, z = −41 24 45; right DLPFC, x, y, z = 48 32 32; PCC, x y z = 6, −65, 14; right STG, x, y, z = 50–44 23, t = 4.33) were de ned using the coordinates of peak points of clusters identi ed in GMD-behaviour correlation analysis in the sample of 240 participants. Following previous studies[86,87], we drew a radius sphere of 6 mm centred at these coordinates and extracted averaged time series for each seeds. We then examined the correlation coe cient between these seeds and the time series of all other voxels in the whole brain and transformed the correlation coe cient maps into z-maps using Fisher's r-to-z transformation. Finally, at the group-level, we conducted a multiple linear regression analysis to identify the regions in which strength of functional connectivity to the seeds in z-maps was correlated with residual scores of trait proactive aggression in the sample of all participants that had resting data (n = 155), with age, gender and FD as nuisance covariates. AlphaSim was utilised for multiple comparison correction (corrected cluster-level $P < 0.05$ and individual voxel $P < 0.001$).

To examine the in uence of participants who scored 0 on brain correlates of proactive aggression, we conducted a multiple linear regression analysis between residual scores of proactive aggression and strength of functional connectivity to the seeds in z-maps in both the sample of participants who did not score 0 for proactive aggression and had resting data (n = 65), with age, gender and FD as nuisance covariates. AlphaSim was utilised for multiple comparison correction (corrected cluster-level $P < 0.05$ and individual voxel $P < 0.001$).

**In erac ion e ec be een e and proac i e reac i e aggre ion on brain r c ral correla- ion** In order to further examine sex e ect on the brain basis of proactive/reactive aggression, we investigated whether the relationship between proactive aggression and structural correlation di ered between the sexes in both the all participants and the participants who did not score 0 for proactive aggression, and whether the relationship between reactive aggression and structural correlation di ered between the sexes in all samples. We conducted a voxel-wise analysis of covariance (ANCOVA) in SPM8, in which gender was de ned as a group factor. ree covariates (age, gender total GMD) were included in the model and residual scores of proactive/reactive aggression scores were interacted with gender using the interactions option in SPM8. We assessed these interaction e ects using t-contrasts.

**In erac ion e ec be een e and proac i e reac i e aggre ion on f nc ional connec i- i** We investigated whether the relationship between residual scores of proactive aggression and RSFC with the selected seeds di ered between the sexes in both the all participants who had resting data and the participants who did not score 0 for proactive aggression and had resting data, and the relationship between residual scores of reactive aggression and RSFC with the selected seed di ered between the sexes in all participants who had resting data. ree covariates (age, gender, mean FD) were included in the model and residual scores of proactive/reactive aggression were interacted with gender using the interactions option in SPM8. We assessed these interaction e ects using t-contrasts.

**Predic ion anal i** To con rm the robustness of the brain-trait proactive aggression relationship, we implemented a machine learning approach, which is based on balanced cross-validation with linear regression[88–90]. Mean GMD and RSFC values were extracted for each cluster identified in GMD-behaviour and RSFC-behaviour correlation analysis using REX. In the regression model, the mean GMD or RSFC values of di erent regions obtained from the GMD and RSFC analyses were input as independent variables, and residual scores of proactive (reactive) aggression a er regressing out reactive (proactive) aggression scores were dependent variables. e data was randomly and equally divided into four folds to ensure the distributions of independent variables and dependent variables across folds were balanced. Subsequently, three folds were employed to build a linear regression model and one-fold was le out. e model was used to predict the le -out fold data.

is procedure was repeated four times, and the average correlation coe cients between the observed data and the predicted data ($r_{(predicted, observed)}$) was obtained. e $r_{(predicted, observed)}$ measures how well the dependent variables are predicted by the independent variable. Nonparametric testing was employed to examine the statistical signi cance of the model. One thousand surrogate datasets were generated to estimate the empirical distribution of $r_{(predicted, observed)}$, against the null hypothesis that no correlation between trait proactive aggression or reactive aggression and regional GMD or RSFC. Each surrogate data set ($D_i$) of size equal to the observed data set was generated via permuting the labels at the observed variables points (i.e. scores of proactive aggression). en we calculated the $r_{(predicted, observed)}$ of $D_i$ (i.e., $r_{(predicted, observed)i}$) with the actual $D_i$ labels and the predicted labels using the four-fold balanced cross-validation procedure. is procedure produced a null distribution of r(predicted, observed)$_i$ for the regression model. e statistical signi cance (p-value) of the correlation between the independent variables (GMD and RSFC value) and dependent variables (proactive/reactive aggression) was determined by the number of r (predicted, observed)$_i$ values greater than r (predicted, observed) dividing the number of Di datasets (1,000)[89,91,92]. Finally, we used G*Power so ware (http://www.gpower.hhu.de) to calculate the statistical power of the prediction analysis in all samples.

## Da a A ailabili

e datasets generated during the current study are available from the corresponding author on reasonable request.

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