The Brain Mechanisms by Which Math Anxiety Affects Mathematical Conceptual Knowledge Processing: A Resting-State fMRI Study

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Abstract

Mathematics anxiety is an emotional response characterized by tension and anxiety toward mathematics. Previous studies have found that higher levels of mathematics anxiety in individuals are associated with poorer performance on various types of mathematical tasks, including mathematical conceptual knowledge. The present study aims to investigate the neural mechanisms through which mathematics anxiety influences the processing of mathematical conceptual knowledge. After controlling for the effects of generalized anxiety, 92 healthy adults were screened, and their levels of mathematics anxiety, language comprehension ability, intelligence, and performance on mathematical conceptual knowledge tasks were measured and analyzed. The results revealed that, after controlling for the effects of language comprehension ability and intelligence, individuals' levels of mathematics anxiety showed a significant negative correlation with their performance on mathematical conceptual knowledge tasks. Analysis of resting-state functional magnetic resonance imaging data revealed that the strength of functional connectivity between the right horizontal segment of the intraparietal sulcus and the right insula in individuals could significantly predict their mathematical conceptual knowledge performance, and this functional connectivity fully mediated the relationship between mathematics anxiety levels and mathematical conceptual knowledge performance. These findings suggest that the interaction between mathematics/computation-related brain regions (intraparietal sulcus) and anxiety-related brain regions (insula) may constitute the neural basis for the interference of mathematics anxiety with mathematical conceptual knowledge tasks.

The Neural Mechanism of How Math Anxiety Affects Mathematical Conceptual Knowledge Processing: A Resting-State fMRI Study

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Abstract

Math anxiety is an emotional response characterized by tension and anxiety toward mathematics. Previous studies have found that higher levels of math anxiety are associated with poorer performance on various mathematical tasks, including those involving mathematical conceptual knowledge. This study investigated the neural mechanisms through which math anxiety influences the processing of mathematical conceptual knowledge. After controlling for generalized anxiety, 92 healthy adults were screened and assessed for their math anxiety levels, language comprehension abilities, intelligence, and performance on a mathematical conceptual knowledge task. Results revealed a significant negative correlation between individuals' math anxiety levels and their performance on the mathematical conceptual knowledge task, even after controlling for language comprehension and intelligence. Analysis of resting-state fMRI data showed that the strength of functional connectivity between the right horizontal segment of the intraparietal sulcus (HIPS) and the right insula significantly predicted performance on the mathematical conceptual knowledge task, and this functional connectivity fully mediated the relationship between math anxiety level and mathematical conceptual knowledge performance. These findings suggest that the interaction between mathematics/computation-related brain regions (the intraparietal sulcus) and anxiety-related brain regions (the insula) may constitute the neural basis through which math anxiety interferes with mathematical conceptual knowledge tasks.

Keywords: Math anxiety, Mathematical conceptual knowledge, Resting-state fMRI, Intraparietal sulcus, Insula

1. Introduction

Math anxiety refers to the fear, tension, and apprehension that individuals experience when confronted with numerical or mathematics-related situations. It represents a trait-level anxiety distinct from generalized anxiety (Ashcraft, 2002; Ashcraft & Moore, 2009). Math anxiety significantly constrains individual development. At the physiological level, when individuals with high math anxiety anticipate mathematical tasks, brain regions associated with threat detection (e.g., cingulate cortex) and pain processing (e.g., insula) show significantly increased activation (Lyons & Beilock, 2012). At the psychological level, individuals with high math anxiety experience feelings toward mathematics similar to phobias, and this intense negative emotion occupies cognitive resources, substantially reducing their performance on mathematical tasks (Ashcraft et al., 1992; LeFevre et al., 2004; Lemaire et al., 1996). To avoid re-experiencing this negative emotion, individuals develop behavioral avoidance tendencies, actively escaping mathematics-related situations (Pizzie & Kraemer, 2017), such as refusing to engage in mathematical activities (e.g., number games, arithmetic tests) (Choe et al., 2019), which may even influence their career choices (Daker et al., 2021).

Individuals with high math anxiety exhibit significant abnormalities in neural activity when anticipating or executing mathematics-related tasks. Previous research has found that in individuals with high math anxiety, the amygdala—a brain region associated with processing negative emotions—shows enhanced activation (Young et al., 2012). Activation also increases in the cingulate cortex, which is involved in threat detection, and the insula, which is associated with pain perception (Lyons & Beilock, 2012). While the negative emotion network shows hyperactivation, the connectivity between the ventromedial prefrontal cortex (vMPFC), which is involved in emotion regulation, and the amygdala is also significantly enhanced (Young et al., 2012). Numerous neuropsychological and neuroimaging studies have demonstrated that various types of mathematical processing tasks consistently activate the bilateral horizontal segment of the intraparietal sulcus (HIPS) (Dehaene et al., 1999; Piazza et al., 2007; Santens et al., 2010). However, individuals with high math anxiety show significantly reduced activation in these mathematics-related brain regions, such as the bilateral intraparietal sulcus (IPS) and dorsolateral prefrontal cortex (DLPFC) (Pizzie et al., 2020). Young et al. (2012) also found that children with high math anxiety showed significantly weaker activation in the IPS during numerical calculation compared to control groups.

Mathematical conceptual knowledge refers to the implicit or explicit principles and interrelationships within the domain of mathematics. Arithmetic principles concerning computational relationships (including commutative and associative properties of addition and multiplication) represent one form of mathematical conceptual knowledge. Such arithmetic principles play a crucial role in children’ s early mastery of basic operations (Rittle-Johnson & Siegler, 1998; Rittle-Johnson et al., 2001). Mathematical conceptual knowledge is characterized by its abstract and highly logical nature, requiring deep understanding and refinement to form a conceptual knowledge structure. Computational ability refers to the capacity for numerical manipulation acquired through proficient mastery of various mathematical conceptual knowledge (Maclellan, 2001). Conceptual knowledge forms the foundation of learning and represents the essence of knowledge. Only after mastering basic principles and definitions can individuals effectively perform mathematical operations. Therefore, studying mathematical conceptual knowledge is essential for understanding mathematical cognitive processing.

Previous research has demonstrated a significant negative correlation between math anxiety levels and performance on mathematical conceptual knowledge tasks (Barroso et al., 2021; Hembree, 1990). One study conducted two assessments over eight months among 316 six-year-old children in Hong Kong, China, and found that mathematical conceptual knowledge scores were significantly negatively correlated with math anxiety levels (Ching et al., 2020). Additionally, research has indicated that providing students with tutoring focused on mathematical conceptual knowledge can effectively reduce their math anxiety levels (Khoule et al., 2017).

Although behavioral studies have established a relationship between math anxiety and mathematical conceptual knowledge performance, research on the underlying neural mechanisms remains relatively sparse. Investigation at the neural mechanism level can help us further understand why math anxiety affects mathematical performance and provide ideas and evidence for developing targeted neural intervention protocols. This study employed resting-state functional magnetic resonance imaging (rs-fMRI) to explore the neural mechanisms through which math anxiety influences mathematical conceptual knowledge processing.

Math anxiety is a domain-specific anxiety and a trait anxiety distinct from generalized anxiety (Kazelskis et al., 2001). That is, math anxiety levels measured through questionnaires remain relatively stable over time. Numerous studies have indicated that low-frequency fluctuations (< 0.1 Hz) in blood oxygen level-dependent (BOLD) signals at rest are associated with variability in personality traits (Di Martino et al., 2009; Oathes et al., 2015) and cognitive processing abilities (e.g., general semantic processing) in healthy individuals (Xu et al., 2016). Based on this, the present study utilized rs-fMRI to reveal the neural associations between math anxiety and mathematical conceptual knowledge performance. Neuroimaging studies on mathematical conceptual knowledge have found that processing mathematical conceptual knowledge activates not only mathematics/visuospatial processing brain regions but also brain regions related to general semantic and conceptual knowledge processing, such as the left inferior frontal gyrus (IFG) and left middle temporal gyrus (MTG) (Liu, 2017; 2019; Zhang et al., 2012). This study also examined the roles of both mathematics/visuospatial processing brain regions and general semantic processing brain regions in the relationship between mathematical conceptual knowledge and math anxiety.

This study employed a verbally described arithmetic principles test to assess individuals' mastery of mathematical conceptual knowledge, while simultaneously recording resting-state brain functional connectivity. We analyzed the relationship between math anxiety levels and mathematical conceptual knowledge task performance and its underlying neural mechanisms. Our hypotheses were: At the behavioral level, after controlling for generalized anxiety, intelligence, and semantic comprehension abilities, math anxiety would negatively predict individual performance on the mathematical conceptual knowledge task. At the neural level, functional connectivity between or within core brain regions involved in math anxiety and mathematical conceptual knowledge processing would correlate with the behavioral effects.

2.1 Participants

Power analysis using G*Power software (Faul et al., 2009) indicated that 111 participants were required to achieve a medium effect size (0.3). The planned sample size was 111 individuals. We administered the shortened Mathematics Anxiety Rating Scale (sMARS; Alexander & Martray, 1989) and the State-Trait Anxiety Inventory (STAI; Spielberger et al., 1983) to measure math anxiety and generalized anxiety levels among recruited participants. After excluding 11 individuals with abnormal trait and state anxiety (STAI total score ≥ 100), 100 healthy adult participants completed subsequent experiments. Based on rs-fMRI preprocessing results, we excluded 8 participants with head rotation $> 1.5°$ or translation > 1.5 mm, leaving data from 92 participants for final analysis. Participants ranged in age from 18 to 23 years (M = 20.91, SD = 2.33; 43 females). All participants had normal or corrected-to-normal vision, were right-handed, and had no history of neurological or psychiatric disorders. This study was conducted in accordance with the ethical principles of the Declaration of Helsinki and was approved by the Medical Ethics Committee of Shenzhen University Medical School (Ethics Approval Number: CBDCS202112140035). All participants provided written informed consent.

2.2 Cognitive Behavioral Tests

This experiment used a verbally expressed arithmetic principles test to assess individual mathematical conceptual knowledge levels, and vocabulary semantics and non-verbal matrix reasoning tests to measure semantic comprehension and intelligence levels.

2.2.1 Arithmetic Principles Test

This test assessed understanding and mastery of mathematical conceptual knowledge, focusing on five basic arithmetic principles (commutative property, associative property, subtraction rule, division rule, and bracket removal rule in stepwise operations). To avoid additional effects from math anxiety induced by numerical presentation, we used verbally expressed arithmetic principles for testing. For example, participants would see "Changing the order of addends does not change the sum" and needed to determine whether the statement was correct, pressing the "Q" key for correct and "P" key for incorrect (see Figure 1 [Figure 1: see original paper]A). The test consisted of 40 trials, and participants were required to respond as quickly and accurately as possible within 3 minutes. Higher completion and accuracy rates yielded higher scores.

2.2.2 Vocabulary Semantics Test

This test assessed language comprehension ability to control for this extraneous variable. In each trial, an incomplete sentence appeared on the screen, and participants needed to select the appropriate word from multiple alternatives to fill the blank, pressing "Q" for the left option and "P" for the right option (see Figure 1B). The test included 120 trials, and participants had 5 minutes to respond as quickly and accurately as possible.

2.2.3 Non-Verbal Matrix Reasoning Test

Adapted from Raven' s Standard Progressive Matrices (1998), this test assessed general intelligence to control for this extraneous variable. In each trial, an incomplete figure appeared on the screen, and participants needed to select the appropriate pattern from 6-8 options to complete the missing part based on the figure' s internal rules, using a mouse click (see Figure 1C). Participants had 10 minutes to respond as quickly and accurately as possible.

Figure 1. Schematic diagram of cognitive behavioral tests. (A) Arithmetic principles test; (B) Vocabulary semantics test; (C) Non-verbal matrix reasoning test.

Prior to the experiment, participants completed the math anxiety scale (sMARS) and trait-state anxiety scale (STAI) online. Participants with STAI scores ≤ 100 were invited to complete the cognitive behavioral tests and resting-state MRI scans. The cognitive behavioral tests included the verbally expressed arithmetic principles test, vocabulary semantics test, and non-verbal matrix reasoning test. A trained experimenter monitored participants as they completed the tests on a computer in a quiet room. Participants' responses and reaction times were automatically recorded through the "Online Psychological Experiment System (OPES)" (www.dweipsy.com/lattice). After ensuring participants' health and compliance with MRI safety standards, they completed an 8-minute resting-state scan in the MRI suite with eyes closed, accompanied by a professionally trained scanner operator, while maintaining stillness throughout, particularly of the head.

2.4 Functional Magnetic Resonance Data Acquisition

Resting-state MRI data were acquired using a Siemens Prisma 3.0T scanner. High-resolution structural images were obtained using a gradient-echo sequence with 3D sagittal T1-weighted magnetization-prepared rapid acquisition: repetition time (TR) = 2300 ms, echo time (TE) = 2.26 ms, flip angle = 8°, field of view (FOV) = 232×256 mm^2, acquisition matrix = 232×256 mm^2, slice thickness = 1 mm, voxel size = $1 \times 1 \times 1$ mm^3. Resting-state functional images were acquired using a gradient-echo T2-weighted echo-planar imaging sequence: TR = 1500 ms, TE = 30 ms, flip angle = 70°, FOV = 192×192 mm^2, acquisition matrix = 94×94 mm^2. The whole brain was divided into 46 slices with slice thickness = 3 mm, voxel size = $2.04 \times 2.04 \times 3$ mm^3.

2.5 fMRI Data Preprocessing

Resting-state fMRI data were preprocessed using DPABI software (http://www.restfmri.net/forum/DPABI) (Yan et al., 2016). All raw DICOM data were first converted to NIFTI format. Structural images were segmented into gray matter, white matter, and cerebrospinal fluid using the DARTEL method. Functional images were then processed through the following steps: (1) deletion of the first 10 time points; (2) slice timing correction; (3) alignment of structural and functional images; (4) spatial normalization to MNI (Montreal Neurological Institute) space with resampled voxel size of 3 × 3 × 3 mm^3; (5) Gaussian smoothing (FWHM = 6 mm); (6) linear detrending; (7) nuisance regression including white matter signal, cerebrospinal fluid signal (Fox et al., 2005), and 24 head motion parameters (6 head motion parameters at the current time point, 6 head motion parameters at the previous time point, and 12 corresponding squared terms) (Friston et al., 1996; Yan et al., 2013); and (8) band-pass filtering (0.01-0.1 Hz).

2.6.1 Definition of Regions of Interest (ROIs)

Neuroimaging studies on mathematical concepts have found that, compared to numerical calculation, mathematical conceptual knowledge (e.g., arithmetic principles, mathematical terms) processing relies more heavily on semantic/conceptual processing brain regions (such as left MTG and left orbital IFG), while compared to general semantic processing, it relies more on visuospatial processing brain regions (such as IPS) (Liu et al., 2017; Zhang et al., 2012). Based on these findings, we identified left MTG and left orbital IFG as semantic processing ROIs, and bilateral horizontal segments of the intraparietal sulcus (lHIPS and rHIPS) from a meta-analysis of visuospatial processing (Boccia et al., 2014) as visuospatial/numerical processing ROIs (see Table 1 and Figure 2 [Figure 2: see original paper] for coordinates and selection sources).

Table 1. Regions of Interest (ROI) Information

ROI	MNI Coordinates [X,Y,Z]	Source
Left horizontal intraparietal sulcus (lHIPS)	[−34, −54, 46]	Boccia et al. (2014)

ROI	MNI Coordinates [X,Y,Z]	Source
Right horizontal intraparietal sulcus (rHIPS)	[32, −56, 52]	Boccia et al. (2014)
Left middle temporal gyrus (MTG)	[−58, −44, 0]	Wu et al. (2012)
Left orbital inferior frontal gyrus (IFG)	[−46, 28, −4]	Binder et al. (2009)

Figure 2. Schematic diagram of the four Regions of Interest (ROI) coordinates.

2.6.2 Seed-Based Functional Connectivity and Correlation Analysis with Behavioral Data

Using the four selected ROIs as seed points for functional network analysis, we created 6-mm radius spheres centered on each ROI' s MNI coordinates and computed resting-state functional connectivity (rsFC) between each seed region and all other brain voxels for each participant. We performed partial correlation analyses between resting-state imaging data and arithmetic principles test scores while controlling for general intelligence and language ability scores. The same analysis was conducted separately for each ROI. Results were corrected using Gaussian Random Field (GRF) theory with a voxel-level threshold of $p < 0.005$ and cluster-level threshold of $p < 0.0125$ (uncorrected $p < 0.05$).

2.6.3 Mediation Analysis

To investigate the role of brain functional connectivity related to arithmetic principles processing in the relationship between math anxiety and arithmetic principles task performance, we used math anxiety level as the independent variable, arithmetic principles performance as the dependent variable, and the average estimated parameters from brain regions showing significant rsFC with seed points as mediators. The bootstrap method does not assume a normal sampling distribution but instead estimates the indirect effect and its sampling distribution through repeated resampling to compute confidence intervals (CI).

This study adopted this approach (Preacher & Hayes, 2008), setting bootstrap resampling to 5000 iterations for mediation effect testing.

3.1 Behavioral Results

Descriptive statistics for the three cognitive tests, including means, standard deviations, and internal consistency coefficients (α), are presented in Table 2 . Internal consistency for each test was within acceptable ranges (0.71-0.84). Math anxiety and trait anxiety scores were 67.39 ± 32.39 and 39.29 ± 8.41 [mean ± SD], respectively. Normality tests (Kolmogorov-Smirnov test) indicated that scores on all three cognitive tests followed a normal distribution. Pearson correlation tests showed that arithmetic principles performance was significantly negatively correlated with math anxiety level ($r = -0.26$, $p = 0.008$). This correlation remained significant after controlling for trait anxiety, language skill performance, and general intelligence scores ($r = -0.29$, $p = 0.004$).

Table 2. Descriptive Statistics of Cognitive Tests

Test	M (SD)	Score Range	Skewness	Kurtosis	Normality Test (K-S)	Internal Consistency (α)
Arithmetic Principles Test	18.98 (5.87)	5–32	$p > .05$			
Vocabulary Semantics Test (Correct Responses)	40.43 (7.68)	13–56	$p > .05$			
Non-Verbal Matrix Reasoning Test	30.40 (6.76)	12–51	$p > .05$			

3.2 fMRI Results

3.2.1 Validation of ROI Selection

We extracted functional connectivity values between each ROI and the other three ROIs, obtaining 16 connectivity values per participant (4 ROIs × 4 connections). Controlling for mean frame-wise displacement (FD), we correlated these 16 connectivity values with arithmetic principles performance and found that functional connectivity strength between the right HIPS and left MTG was significantly positively correlated with arithmetic principles performance (uncorrected $p < 0.001$). Specifically, when using HIPS as the seed, the FC between these regions correlated significantly with arithmetic principles scores ($r = 0.35$, $p < 0.001$); when using left MTG as the seed, the FC also correlated significantly ($r = 0.34$, $p < 0.001$). These results remained significant after FDR correction, confirming that our selected ROIs were indeed associated with arithmetic principles processing.

3.2.2 Seed-Based Functional Connectivity Predicting Behavioral Performance

After controlling for general intelligence and language comprehension scores, we computed partial correlation maps between seed-based FC maps (using bilateral HIPS, left IFG, and left MTG as seeds) and arithmetic principles scores. After cluster-level correction, only the connectivity map seeded in the right HIPS showed a significant negative correlation with arithmetic principles performance in the right insula (peak MNI [45, 3, −12], $r = -0.41$, cluster size = 368). Using a threshold of voxel-level $p < 0.005$ and cluster-level $p < 0.0125$ (uncorrected $p < 0.05$) for multiple comparison correction across the four ROIs, the results remained consistent: only seeding from the right HIPS yielded a significant cluster (peak MNI [45, 3, −12], $r = -0.41$, cluster size = 368) (see Figure 3 [Figure 3: see original paper]).

Figure 3. fMRI Results. (A) Significant functional connectivity between the right insula and right HIPS; (B) Correlation between insula-right HIPS functional connectivity and arithmetic principles scores.

Additionally, we computed correlation maps between FC maps (seeded in bilateral HIPS, left IFG, and left MTG) and math anxiety levels. Results showed no significant correlations between FC maps seeded in bilateral HIPS or left MTG and math anxiety. However, FC between the left orbital IFG and right parieto-occipital junction (peak MNI [33, −66, 45], $r = 0.43$, cluster size = 230) was significantly positively correlated with math anxiety level. Using voxel-level $p < 0.005$ and cluster-level $p < 0.0125$ (uncorrected $p < 0.05$) for multiple comparison correction across the four ROIs, the corrected results remained consistent.

3.2.3 Mediation Analysis

From the FC map seeded in the right HIPS, we extracted each participant' s average estimated parameter from the right insula and used it as a mediator variable. Results indicated that the functional connectivity strength between the right insula and right HIPS significantly mediated the relationship between math anxiety level and arithmetic principles performance. Normal theory tests showed that path a was significant ($t = 2.18$, $p = 0.032$) and path b was significant ($t = -4.75$, $p < 0.001$). When the mediator was included, the previously significant path c ($t = -2.63$, $p = 0.009$) became non-significant ($t = -1.79$, $p = 0.076$). The mediation effect remained significant even after controlling for mean frame-wise displacement (FD): path a was significant ($t = 2.03$, $p = 0.046$), path b was significant ($t = -4.28$, $p < 0.001$), and the previously significant path c ($t = -2.47$, $p = 0.015$) became non-significant ($t = -1.74$, $p = 0.085$) (see Figure 4 [Figure 4: see original paper]).

To eliminate potential verification bias, we conducted whole-brain voxel-level mediation analysis using the "Mediation toolbox" developed by Wager et al. (2008, 2009). With math anxiety level as independent variable X, arithmetic principles performance as dependent variable Y, and the FC map seeded in right HIPS as mediator M, we performed single-level mediation analysis. No significant results were found under FDR-corrected thresholds. When lowering the threshold to uncorrected $p < 0.01$, a cluster in the right insula emerged (peak MNI coordinates [45, 0, 3], cluster size = 297, statistic = 6.91). Although this result did not achieve strong statistical significance at the whole-brain level, it provided convergent validation and supplementary evidence for our findings. Furthermore, to examine whether this effect was specific to math anxiety rather than generalized anxiety, we entered trait anxiety as the independent variable into the mediation model and found that path c was not significant ($t = -0.071$, $p = 0.481$), indicating no significant negative correlation between trait anxiety and arithmetic principles performance.

Since the correlation analysis between FC maps and math anxiety levels revealed a significant relationship between FC from the left orbital IFG to the parieto-occipital junction and math anxiety, we further tested whether this connectivity could serve as a mediator. We extracted each participant' s average estimated parameter from the parieto-occipital junction in the FC map seeded in the left orbital IFG and used it as a mediator variable, with math anxiety level as the independent variable and arithmetic principles performance as the dependent variable. Mediation analysis indicated that the functional connectivity strength between the left orbital IFG and right parieto-occipital junction did not significantly mediate the relationship between math anxiety level and arithmetic principles performance.

Figure 4. Mediation analysis results.

4. Discussion

This study investigated mathematical conceptual knowledge mastery in individuals with varying levels of math anxiety using a verbally expressed arithmetic principles test, and combined resting-state fMRI to explore the relationship between math anxiety and mathematical conceptual knowledge performance and its neural mechanisms. At the behavioral level, our results replicated previous findings, confirming that math anxiety negatively predicts individual performance on mathematical conceptual knowledge tasks. At the neural level, we found that functional connectivity strength between the right HIPS—responsible for mathematics/visuospatial processing—and the right insula—associated with anxiety—fully mediated the relationship between math anxiety level and mathematical conceptual knowledge performance. This suggests that a neural circuit comprising mathematics/computation-related brain regions (HIPS) and anxiety-related brain regions may represent an important pathway through which math anxiety affects mathematical conceptual knowledge representation. We also found that brain regions responsible for general semantic processing during mathematical conceptual knowledge tasks were not correlated with arithmetic principles performance or math anxiety scores. No significant correlations were found between math anxiety level and whole-brain functional connectivity when using the right HIPS as a seed, possibly because math anxiety has high specificity for resting-state functional connectivity, while whole-brain correction requires strong signal intensity, making it difficult to detect positive results at the whole-brain level. This speculation was further supported by the whole-brain mediation analysis results, where the mediation effect did not reach significance under FDR correction but could be verified at an uncorrected threshold of $p < 0.01$, confirming the relationship between the HIPS-insula pathway and math anxiety level and its mediating role between arithmetic principles performance and math anxiety.

Previous research on emotional arousal in math anxiety has typically focused on the amygdala. For example, studies have found that individuals with high math anxiety show abnormal amygdala activation during numerical calculation tasks, and functional connectivity between the amygdala and dorsolateral prefrontal cortex (DLPFC) is significantly reduced (Pizzie et al., 2020; Young et al., 2012). Notably, the insula is also widely recognized as a key brain region in anxiety circuits (Bishop, 2007; Paulus & Stein, 2006; Somerville et al., 2013). Anxiety comprises two important components: excessive sympathetic nervous system activation leading to intense physiological responses, and increased psychological burden from worry. Previous research has proposed that emotions may acquire and maintain anxiety through the insula’ s awareness of internal physiological sensations, thereby enhancing anxiety experience (Hartley & Phelps, 2012; Paulus & Stein, 2006). Additionally, excessive or inappropriate emotional responses in anxiety disorders may result from regulatory failure of the insula-prefrontal system (Bishop, 2009; Kim & Whalen, 2009). The abnormal functional connectivity between the right insula and HIPS found in individuals with high math anxiety in this study may reflect both abnormal anxiety perception in the insula and cognitive resource occupation by excessive worry during arithmetic principles tasks.

The intraparietal sulcus (IPS) is widely recognized as a core system for quantity representation and is critically involved in numerical and mathematical problem solving (Ansari et al., 2006; Cohen Kadosh et al., 2005; Eger et al., 2003; Nieder & Dehaene, 2009; Pinel et al., 2001). Previous research has also confirmed that both numerical processing and mathematical conceptual knowledge processing activate bilateral HIPS (Liu et al., 2017). Although the verbally expressed mathematical conceptual knowledge test used in this study did not directly involve numbers, it concerned quantitative relationships after numerical computation, requiring participants to mentally compute described formulas and judge their correctness. This may explain why spontaneous neural activity in HIPS correlated with arithmetic principles performance. We speculate that HIPS activation may be reduced during arithmetic principles processing in individuals with high math anxiety. A previous task-based fMRI study also found that individuals with higher math anxiety showed significantly lower HIPS activation compared to those with lower math anxiety, with weaker functional connectivity between the amygdala and HIPS (Young et al., 2012), consistent with our findings. This suggests that individuals with high math anxiety have deficits in mathematics-specific functional brain regions during mathematical knowledge processing. Additionally, since previous studies have shown that the left inferior frontal gyrus and left middle temporal gyrus are also involved in arithmetic principles processing (Liu et al., 2017, 2019), our failure to find any correlations when using these regions as seeds suggests that impaired brain function in math-anxious individuals is limited to numerical processing domains and does not involve general semantic processing functions.

An alternative interpretation of HIPS function is that it primarily supports top-down attentional control rather than mathematics/visuospatial processing. The IPS is a key node in the frontoparietal network responsible for cognitive control (Dosenbach et al., 2008; Sylvester et al., 2012). fMRI studies have shown that individuals with high trait anxiety exhibit reduced activation in the frontoparietal network (Bishop, 2009) and abnormal functional connectivity within this network (Basten et al., 2011). Etkin et al. (2009) found that patients with generalized anxiety disorder showed significantly enhanced functional connectivity between the frontoparietal network and amygdala regions. For individuals with high math anxiety, altered functional connectivity between HIPS and insula may result from abnormal top-down attentional control rather than mathematical deficits per se. However, the validity of this alternative explanation requires further investigation. Both possible interpretations converge on the finding that math anxiety level and mathematical conceptual knowledge performance produce consistent changes in functional connectivity strength between insula and HIPS.

In addition to examining the separate effects of math anxiety on the insula and bilateral HIPS, this study quantified the functional connectivity strength between the right insula and right HIPS and used it as a mediator to reanalyze the relationship between verbal arithmetic principles test performance and math anxiety. We found that functional connectivity between the right insula and right HIPS decreased with improved mathematical conceptual knowledge performance, suggesting that this inter-regional connectivity may influence mathematical processing efficiency. Moreover, this connectivity strength increased with higher math anxiety levels, indicating that greater math anxiety may lead to excessive coupling between the right insula and right HIPS. Future research could further investigate this connectivity direction to explain the causal relationship between math anxiety and mathematical performance.

This study has several limitations. First, besides the insula, the amygdala is also considered a key brain region in anxiety circuits. Two previous task-based fMRI studies found increased amygdala activation during arithmetic tasks in individuals with high math anxiety (Pizzie et al., 2020; Young et al., 2012). However, we did not detect activity changes in this region in our data. Researchers should interpret our results cautiously and further validate the role of the amygdala in future studies. Second, this study only examined functional connectivity during resting-state imaging in individuals with different levels of math anxiety; task-based fMRI experiments represent an important direction for future research. Third, the functional interpretation of HIPS is not unitary. For example, abnormal HIPS activation may be related to top-down attentional control deficits (Dosenbach et al., 2008; Sylvester et al., 2012). Therefore, future studies should consider novel designs to exclude the possibility of attentional deficits caused by anxiety to further clarify our current findings.

With the development and application of neuroscience, examining brain mechanisms can provide empirical evidence for behavioral performance. At the applied level, neuroscience methods could be used to precisely intervene in relevant brain regions to alleviate math anxiety or remediate mathematical learning disabilities. A previous transcranial direct current stimulation (tDCS) study successfully improved reaction times and reduced cortisol concentrations—representing physiological stress arousal—in math-anxious individuals during simple arithmetic decision-making by applying excitatory stimulation to the left dorsolateral prefrontal cortex, a region involved in emotion regulation (Sarkar et al., 2014), providing new directions for math anxiety intervention. Based on our finding that individuals with higher math anxiety show stronger functional connectivity between the right HIPS and ipsilateral insula, we speculate that applying neuromodulation (e.g., transcranial electrical stimulation, transcranial magnetic stimulation) to the right HIPS, which is located on the cortical surface, may reduce right insula activation through this neural pathway, thereby alleviating math anxiety and improving mathematical performance. In recent years, China has launched major brain science initiatives, with adolescent brain and cognitive development being a key focus. The 20th National Congress further proposed the strategic goal of building a strong educational nation. This study reveals the neural mechanisms underlying the impact of math anxiety on arithmetic principles performance, suggesting that the effect of emotion on academic achievement may operate through the pathway connecting mathematics-processing brain region HIPS with negative emotion-processing brain region insula. This provides a neural modulation approach for the brain-cognitive development of adolescents with high math anxiety and offers a new intervention target for helping children and adolescents overcome learning difficulties.

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