

Neural Mechanisms of Symbolic Number Processing in Individuals with Math Anxiety

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Date: 2026-03-09T15:20:34+00:00

Abstract

Math anxiety impairs an individual's symbolic numerical processing ability, yet the specific deficits within the stages of visual perception and numerical concept processing remain unclear. This study employed three tasks—visual baseline, digit-color judgment, and numerical judgment—combined with event-related potential (ERP) techniques to investigate the underlying neural mechanisms. Individuals with high math anxiety exhibited reduced N170 amplitudes during the visual processing stage of digits and enhanced P2P amplitudes during the numerical processing stage, suggesting that their digital visual perception and numerical processing procedures are affected. Multivariate analysis revealed that high math anxiety individuals were slower and less accurate when distinguishing between numerical and non-numerical stimuli. Reduced P3 amplitudes during the anticipation stage fully mediated the impact of math anxiety on N170 and P2P, with source localization tracing back to the intraparietal sulcus region, indicating that emotional/cognitive control deficits are the key mechanism. High math anxiety individuals may possess multi-level impairments in symbolic numerical processing, ranging from anticipatory preparation to visual recognition and numerical representation. This study provides new evidence for understanding the neural mechanisms and developing interventions for math anxiety.

Full Text

Preamble

Neural Mechanisms of Symbolic Numerical Processing in Individuals with Math Anxiety

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Abstract

Math anxiety (MA) refers to a feeling of tension, apprehension, or fear that interferes with math performance. While extensive research has focused on the impact of math anxiety on high-level mathematical problem solving, recent evidence suggests that these deficits may originate from more fundamental symbolic numerical processing. This paper reviews the neural mechanisms underlying symbolic numerical processing in individuals with math anxiety, focusing on representation, comparison, and mapping processes. We discuss how math anxiety modulates activity in the intraparietal sulcus (IPS) and the frontoparietal network, and how these neural differences contribute to suboptimal mathematical performance.

1. Introduction

Math anxiety is a widespread phenomenon that significantly impacts academic achievement and career choices. Individuals with high math anxiety (HMA) often exhibit avoidance behaviors toward mathematics-related tasks and perform worse on mathematical assessments compared to their low math anxiety (LMA) peers. Traditionally, researchers attributed these performance gaps to the depletion of working memory resources by intrusive anxious thoughts. However, an emerging body of research suggests that the “bottleneck” of math anxiety may occur at a much more basic level: the processing of symbolic numbers (e.g., Arabic numerals).

2. Symbolic Numerical Representation and Comparison

The ability to represent and manipulate numerical magnitudes is foundational to mathematical competence. Symbolic numerical processing typically involves the identification of numerals and the comparison of their magnitudes.

2.1 The Numerical Distance Effect A robust finding in numerical cognition is the Numerical Distance Effect (NDE), where the reaction time and error rate decrease as the distance between two numbers increases. For example, comparing 2 and 8 is faster than comparing 7 and 8. In individuals with high math anxiety, the NDE is often modulated, suggesting a less precise representation of numerical magnitude. Neuroimaging studies have consistently identified the intraparietal sulcus (IPS) as the primary locus for magnitude representation. In HMA individuals, the IPS

摘要数学焦虑会削弱个体的符号数字加工能力，但其在视知觉与数量概念加工环节的缺陷

remains unclear. The present study employed three tasks—a visual baseline, numerical color judgment, and numerical magnitude judgment—combined with event-related potential (ERP) techniques to investigate the underlying neural mechanisms. Individuals with high math anxiety exhibited reduced N170 amplitudes during the visual processing stage of digits and enhanced P2P amplitudes during the magnitude processing stage, suggesting that both numerical visual perception and magnitude processing are impaired. Multivariate analysis revealed that high-math-anxiety individuals were slower and less accurate when distinguishing between numerical and non-numerical stimuli. Furthermore, reduced P3 amplitudes during the anticipatory stage fully mediated the effects of math anxiety on N170 and P2P. Source localization traced this activity to the intraparietal sulcus (IPS), indicating that deficits in emotional/cognitive control serve as a key mechanism. These findings suggest that high-math-anxiety individuals may suffer from multi-level impairments in symbolic numerical processing, ranging from anticipatory preparation to visual recognition and magnitude representation. This study provides new evidence for understanding the neural mechanisms of math anxiety and informs the development of interventions.

Keywords: math anxiety, symbolic numbers, EEG, N170, multivariate pattern analysis (MVPA) **Classification Code:** B849: G44 Math anxiety refers to a negative emotional response to participating in mathematical activities, which particularly impairs the learning of mathematics (Foley et al., 2017).

The cognitive deficit model proposed by Maloney (2016) suggests that math anxiety may originate from subtle deficits in early foundational mathematical abilities; these deficiencies subsequently accumulate into significant emotional and cognitive differences. Therefore, examining the cognitive characteristics and mechanisms of numerical processing in individuals with math anxiety is of great significance for understanding the mechanisms underlying their mathematical learning difficulties and for developing effective intervention strategies.

1 收稿日期: 2025*10-15

*National Science and Technology Major Project for Brain Science and Brain-Like Intelligence Technology (2021ZD0200500); Humanities and Social Sciences Project of the Ministry of Education (24YJC190009); Philosophy and Social Science Planning Project of Guangdong Province (GD24YXL01); Shenzhen-Hong Kong Institute of Brain Science-Shenzhen Fundamental Research Institutions (2025SHIBS0003).

Corresponding author: Shangfeng Han, E-mail: psyhanshang@gzhu.edu.cn. The processing of symbolic numbers (such as Arabic numerals) is a fundamental component of mathematical cognition. However, individuals with high math anxiety (HMA) exhibit poor performance in symbolic number

processing. They respond more slowly when completing simple numerical tasks and are more susceptible to the numerical distance effect when choosing the larger of two values [?, ?]. Importantly, the symbolic number processing ability of math-anxious individuals positively predicts their mathematical academic achievement. Statistical analyses of 17 studies using Arabic numeral comparison tasks, along with meta-analytic evidence, have consistently found a significant correlation between symbolic number comparison performance and mathematical achievement [?, ?, ?]. Therefore, an in-depth exploration of the cognitive characteristics of symbolic number processing in math-anxious individuals is of great significance for intervening in and improving their mathematical academic performance.

Compared to non-symbolic numbers, the cognitive representation of symbolic numbers possesses unique processing characteristics. At the behavioral level, reaction times and error rates for non-symbolic number judgments increase monotonically with numerical magnitude, a phenomenon not observed with symbolic numbers [?, ?]. At the neural level, research has found that the activation intensity of the bilateral parietal cortex is modulated by the ratio of non-symbolic quantities, following a Gaussian distribution as the distance between two quantities increases. However, similar results have not been found for symbolic numbers [?, ?]; instead, their processing is more closely associated with the frequency of the numbers' appearance [?, ?]. Identifying numerical symbols requires at least two cognitive stages: visual-perceptual processing (e.g., seeing "10") and quantity processing (e.g., understanding the magnitude of "10").

In terms of temporal dynamics, numerical color judgment and quantity judgment may involve sequential processing corresponding to different neural signals [?, ?]. The N170 component reflects the initial stage of visual processing sensitive to the properties of Arabic numerals [?, ?]. During early visual processing, the N170 reflects the brain' s preliminary classification and identification of different types of visual information [?, ?]. Proverbio et al. [?] found that when processing Arabic numerals, the N170 can be traced back to the right angular gyrus, the left fusiform gyrus, and the bilateral superior medial frontal regions. These areas may be involved in the identification and encoding of symbolic features and the construction of cognitive representations of numbers in the brain. Meta-analytic results support the existence of a "number form area (NFA)" in the fusiform gyrus specifically dedicated to processing Arabic numerals [?, ?]. Conversely, the P2p component is generally considered to be related to the concept of quantity [?, ?, ?]. The involvement of the P2p component is observed in the quantity processing of both symbolic and non-symbolic numbers. When participants are required to estimate or compare the quantity of two sets of dots, the amplitude of the P2p varies with the difference in the number of dots [?, ?]. During symbolic number comparison, a distinct P2p component and a clear numerical distance effect are observed: the smaller the distance between numbers, the larger the positive potential [?, ?].

Although previous research suggests that individuals with high math anxiety

perform poorly on symbolic number processing tasks, the specific cognitive components involved (such as visual-perceptual processing or quantity processing) remain unclear. This study hierarchically dissociates numerical processing to localize the functional impairments in HMA individuals. By constructing a three-level task structure—“non-numerical color judgment, numerical color judgment, and numerical concept”—we achieved a systematic separation of mathematical cognitive processing levels. This hierarchical process evolves from general visual-perceptual processing to domain-specific symbol recognition and finally to abstract quantity concept manipulation. Through an EEG study, we intend to explore the cognitive neural mechanisms of symbolic number processing in HMA populations to localize the impaired cognitive components. We designed three tasks: a visual baseline, numerical color judgment, and quantity judgment. By comparing the visual baseline with the numerical color judgment task, we aim to localize the characteristics of symbolic number visual perception in HMA individuals. By comparing numerical color judgment with quantity judgment, we aim to localize their characteristics in symbolic quantity processing. The visual baseline task uses two-digit numbers rotated at a certain angle for a color judgment task. Because this presentation format differs in shape from conventional numbers when entering the retina, it does not activate the visual representation of numbers in the early stages of visual recognition. Although it cannot be ruled out that subjects might use mental rotation strategies for numerical perception, this task serves as a baseline measurement since this study focuses primarily on early EEG components. The numerical color judgment task emphasizes visual-perceptual judgment; while it involves automatic quantity processing, its engagement of quantity processing is lower than that of explicit quantity judgment tasks, making it suitable for inducing visual-perceptual processing. The quantity judgment task is used to induce the quantity processing of numbers.

Furthermore, previous studies on symbolic number processing in HMA individuals have typically focused on the processing stage after stimulus presentation, neglecting the equally critical anticipatory preparation phase. Cognition does not begin with the appearance of a stimulus; the brain performs active prediction, constantly forecasting and preparing for incoming information based on past experience [?, ?]. This anticipatory process is crucial for subsequent cognitive processing and is expected to address the mechanistic questions regarding symbolic recognition difficulties in math-anxious individuals. Research has found that anxious individuals exhibit deficits in anticipatory processing, manifested as reduced activity in brain networks related to cognitive control [?, ?]. Cognitive control involves the inhibition of irrelevant stimuli to complete goal-directed behaviors [?, ?]. Lyons and Beilock [?] found that HMA individuals showed enhanced activity in frontoparietal regions during the anticipatory phase, which increased the inhibition of negative emotions and thereby improved their performance in mathematical calculations. However, fMRI cannot precisely determine the neural differences during the anticipatory phase—specifically, at which point in time before the stimulus they occur, or whether they involve early or late preparation. By locking the analysis to the antic-

ipatory cue stimulus, this study intends to explore the associations between temporally ordered EEG components. We aim to extend previous findings regarding how frontoparietal activity during the anticipatory phase affects HMA task performance (the “when”) to how it influences that performance (the “how”).

The P3 component is considered an indicator of emotional evaluation and regulation ability, reflecting the allocation of attentional resources and the efficiency of regulation toward emotional information. For example, Hajcak et al. [?] found that individuals with high emotional regulation capacity exhibit larger P3 amplitudes when facing negative emotional images, reflecting more active processing of emotional stimuli. When individuals are asked to use reappraisal strategies for emotional regulation, the P3 amplitude is significantly enhanced compared to passive exposure to emotional stimuli [?, ?], indicating that the P3 also reflects cognitive investment during emotional regulation. We hypothesize that HMA individuals exhibit cognitive control impairments during the anticipatory preparation phase (manifested as reduced P3 amplitude), and that this early functional abnormality is a key factor leading to their subsequent reduction in symbolic number recognition efficiency. This study aims to reveal the neural mechanisms underlying numerical processing difficulties in HMA, thereby providing more precise targets for the development of relevant intervention strategies and theoretical support for enhancing mathematical ability.

2.1 被试

An a priori power analysis was conducted using G*Power 3.1.9 to determine the required sample size (Faul et al., 2007). For a 2×3 repeated-measures ANOVA, targeting the main effects (between-subjects and within-subjects) and their interaction with a statistical power of $1 - \beta = 0.95$, a significance level of $\alpha = 0.05$, and a medium effect size ($f = 0.25$), a minimum of 44 participants (22 per group) was required. Initially, 454 participants were recruited to complete the Chinese version of the Shortened Mathematics Anxiety Rating Scale (sMARS; Alexander & Martray, 1989) and the State-Trait Anxiety Inventory (STAI; Spielberger et al., 1983). Participants were ranked by their mathematics anxiety scores; those in the top 27% were assigned to the high math anxiety (HMA) group ($N = 30$), and those in the bottom 27% were assigned to the low math anxiety (LMA) group ($N = 30$). Two participants were excluded due to excessive artifacts in their EEG data, resulting in a final sample of 29 HMA and 29 LMA participants (mean age 21.19 ± 2.16 years). Statistical analysis revealed that while the two groups differed significantly in trait mathematics anxiety ($t(56) = 27.01, p < 0.001$), there were no significant differences in general state anxiety ($t(56) = 0.58, p = 0.57$) or general trait anxiety ($t(56) = 1.05, p = 0.30$). This study was approved by the Human Research Ethics Committee of the Non-Clinical Faculties at Shenzhen University (Approval No.:

SZU_{{PSY}}_{{2024}}_{{022}}), and all participants provided written informed consent prior to the experiment.

2.2.1 量表

Subjective levels of math anxiety were assessed using the Chinese version of the Short Mathematics Anxiety Rating Scale (sMARS). This scale, translated from the original English version, consists of 25 items. Participants were required to rate their level of anxiety on a 5-point Likert scale (1 = not at all, 5 = very much) based on various math-related scenarios, such as “signing up for a math course” or “taking a final math exam.” The Cronbach’s alpha coefficient for the sMARS in this study was 0.79. Additionally, the State-Trait Anxiety Inventory (STAI; Spielberger et al., 1983) was employed to measure participants’ levels of state and trait anxiety. The STAI comprises 40 items, each scored on a 4-point Likert scale (ranging from 1 to 4).

The Cronbach’s alpha coefficient was 0.90 for the state anxiety subscale and 0.81 for the trait anxiety subscale.

实验提示材料使用正方形和圆形置于白色背景中央。数字刺激选取两位的阿拉伯数字

The experimental materials consisted of 70 items ranging from 20 to 89. Among these, 10 items (50–59) were designated as practice materials, while the remaining 60 items served as the formal experimental stimuli. These 60 stimuli included 30 odd numbers (e.g., 21, 23) and 30 even numbers (e.g., 20, 22), with the colors red and green balanced across the set.

To create non-number stimuli, the original numerical stimuli were rotated clockwise by 120°, 180°, and 240°. This approach ensured that the non-number stimuli maintained the same visual properties as the numerical stimuli while preventing participants from perceiving them as numbers during rapid visual processing. During the production process, the numbers 6, 9, 8, and 0 were excluded because they remain recognizable as numbers after a 180° rotation. A total of 108 non-number stimuli were generated, from which 60 were randomly selected for the formal experiment. The numerical stimuli were utilized for the number-color judgment and numerical magnitude judgment tasks, whereas the non-number stimuli were employed for the visual baseline task.

实验程序如图 1 所示。每个试次首先呈现 0.5 秒的提示 (“ ” 或者 “ ”), 然后在屏幕中心

A fixation cross “+” was presented for 1.5 seconds. Subsequently, a numerical stimulus appeared on a white background for 1 second. Participants then had 1.5 seconds to complete the key-press response for the conceptual task, the perceptual task, or the baseline task. When the cue was a “ ”, participants were required to perform the conceptual task. During the response screen, the prompt “Small + Large” was displayed, and participants were asked to compare the presented number with “50.” If the number was smaller than “50,” they pressed the “F” key; if it was larger than “50,” they pressed the “J” key. When

Figure 1

Figure 1: Figure 1

the cue was a “ ”, participants performed either the perceptual or baseline task. In this case, the response screen displayed “Red + Green,” and participants were required to judge the color of the number, pressing “F” for red and “J” for green.

Experimental trial flow chart. After participants completed the key-press response, a state math anxiety rating task appeared in 50% of the trials, lasting for 1.5 seconds. State math anxiety was assessed using a single question: “How anxious did you feel while performing this task?” Participants were asked to report their anxiety level on a 5-point Likert scale ranging from 1 to 5 (1 = not at all anxious; 5 = very anxious). Finally, a random blank screen was presented between trials for a duration of 0.8 to 1 second.

2.3 脑电记录及处理

EEG data were recorded using a 64-channel Brain Products system with Ag-AgCl scalp electrodes, positioned according to the extended international 10-20 system. EEG activity was initially recorded using FCz as the reference electrode. During offline analysis, data were re-referenced to the global average, band-pass filtered between 0.01 and 30 Hz, and sampled at a rate of 1000 Hz. Impedance for all electrodes was maintained below 10 k Ω . Artifacts such as electrooculograms (EOG) and electromyograms (EMG) were removed using Independent Component Analysis (ICA; Delorme & Makeig, 2004) via the EEGLAB software. Segments exceeding $\pm 80\mu V$ were excluded, resulting in the removal of 1.19% of the data as bad segments.

Univariate Amplitude Analysis: The electrode sites and time windows selected for calculating the mean amplitude of Event-Related Potential (ERP) components were based on grand average topographic maps and previous ERP research. We extracted data from two distinct periods: the anticipation phase and the stimulus phase.

For the anticipation phase, a total time window of 2200 ms was extracted, ranging from 200 ms pre-cue to 2000 ms post-cue. The P3 component (hereafter referred to as anticipation-P3) was analyzed using a time window of 280-500 ms at electrode sites Pz, P1, P2, and POz [?, ?]. For the stimulus phase, a 1200 ms window was extracted, ranging from 200 ms pre-stimulus to 1000 ms post-stimulus. The N170 component was analyzed at electrodes Oz, O1, and O2 within a 150-250 ms window [?, ?]. The P2p component was analyzed at electrodes PO7, PO8, O1, and O2 within a 250-300 ms window [?, ?]. Initially, a 2 (Group: High Math Anxiety / Low Math Anxiety) \times 3 (Task Type: Visual Baseline / Numerical Color Judgment / Quantity Judgment) two-way repeated-measures ANOVA was performed on the mean amplitudes of the ERP

components. To further explore the cognitive neural mechanisms by which math anxiety influences numerical processing, we conducted a mediation analysis.

分析和预期阶段 P3 波幅的溯源分析：将数学焦虑水平（分组变量）作为自变量，反映符号数

The N170 and P2P amplitudes, which are key electroencephalogram (EEG) components in the word recognition process, were used as dependent variables, while the P3 amplitude during the expectation phase was used as a mediating variable to establish a mediation model. Finally, standardized low-resolution brain electromagnetic tomography (sLORETA) was employed to perform source localization for the P3 component during the expectation phase, allowing for an investigation into the spatial characteristics of brain activation associated with this component [?, ?]. sLORETA is a linear statistical imaging technique based on EEG data.

方法，能够揭示大脑活动的三维定位。源空间的网格间距设置为 5 毫米，以确保计算精度与

Balancing computational efficiency, we performed source analysis on the group-averaged data to identify statistically significant electromagnetic dipoles. The results of the source reconstruction were then projected onto 3D MRI images, with varying colors used to represent differences in electromagnetic signal intensity.

Multivariate Pattern Analysis: Multivariate pattern analysis (MVPA) was conducted using the NeuroRA toolbox [?, ?], with a selected time window ranging from -0.2 s to 1 s relative to stimulus onset. Following EEG preprocessing, electroencephalographic data were extracted across all 62 channels for each participant, organized by channel, time point, and trial. For each participant, trials corresponding to the visual baseline, numerical color judgment, and quantity judgment tasks were labeled for use in Support Vector Machine (SVM) classification. To enhance the signal-to-noise ratio, data were averaged in groups of five trials. A five-fold cross-validation procedure and a leave-one-out approach were employed to train and test the dataset at each time point. In the five-fold cross-validation, the dataset was randomly partitioned into five equal subsets; each subset served as the test set exactly once, while the remaining four subsets were used to train the classifier. This process was repeated ten times to ensure stability, and classification performance was evaluated by averaging the results across the test sets. Decoding accuracy was calculated for each participant based on these classification results. For statistical analysis, a two-tailed t-test was performed at each time point to compare the participants' decoding accuracy against a 50% chance level. Cluster-based permutation tests were utilized to correct the t-values for multiple comparisons [?, ?].

3.1 行为结果

The mean and standard deviation for accuracy and reaction time (RT) are presented in . For the analysis of reaction times, trials with incorrect responses, RTs below 200 ms, and RTs exceeding three standard deviations from the mean were excluded before conducting a repeated-measures analysis of variance (ANOVA). The results indicated that the main effect of the math anxiety group was not significant ($F(1, 56) = 0.04, p > 0.05$). However, the main effect of task type was significant ($F(2, 112) = 12.80, p < 0.001, \eta_p^2 = 0.19$). Specifically, reaction times for the numerical magnitude judgment task ($M = 567.02, SE = 20.76$) were significantly longer than those for the numerical color judgment task ($M = 531.89, SE = 16.98$) and the non-numerical task ($M = 534.13, SE = 17.86$). A significant interaction between math anxiety and task type was observed ($F(2, 112) = 3.38, p = 0.038, \eta_p^2 = 0.06$). Further simple effects analysis revealed no significant inter-group differences across the three tasks ($ps > 0.05$). Within the high math anxiety (HMA) group, reaction times for the numerical magnitude judgment task ($M = 581.40, SE = 27.54$) were significantly higher than those for the numerical color judgment task ($M = 532.24, SE = 22.53, p < 0.001$) and the visual baseline task ($M = 525.42, SE = 23.13, p < 0.001$), while no significant difference was found between the visual baseline and numerical color judgment tasks ($p = 0.63$). For the low math anxiety (LMA) group, there were no significant differences in reaction times among the three tasks ($ps > 0.05$).

The analysis of accuracy rates showed that the main effect of the math anxiety group was not significant ($F(1, 56) = 1.05, p = 0.30$), whereas the main effect of task type was significant ($F(2, 112) = 9.13, p < 0.001, \eta_p^2 = 0.14$). Accuracy in the numerical magnitude judgment task ($M = 0.95, SE = 0.01$) was significantly lower than in the visual baseline task ($M = 0.97, SE = 0.01, p = 0.001$) and the numerical color judgment task ($M = 0.97, SE = 0.01, p = 0.005$). There was no significant difference in accuracy between the visual baseline task and the numerical color judgment task ($p = 0.74$). The interaction between math anxiety group and task type was not significant ($F(2, 112) = 0.07, p = 0.89$).

To further investigate the numerical distance effect within the magnitude judgment task, we performed a median split on the numerical distances (large vs. small). Repeated-measures ANOVAs were conducted using accuracy and reaction time as dependent variables; however, no significant interaction between math anxiety and numerical distance was found ($ps > 0.05$).

To confirm the participants' levels of math anxiety while performing the mathematical tasks, we measured state math anxiety for a subset of trials. An independent samples *t*-test on state math anxiety scores revealed a significant difference between the two groups ($t(56) = 2.62, p = 0.012$), with the HMA group reporting significantly higher state math anxiety ($M = 2.19, SE = 0.98$) than the LMA group ($M = 1.57, SE = 0.81$).

Table 1: Descriptive statistics of mean accuracy and reaction time for HMA and LMA groups across the three tasks. RT (ms) Mean, Standard Deviation;

Figure 2

Figure 2: Figure 2

Figure 3

Figure 3: Figure 3

Numerical Color Judgment.

3.2 单变量波幅分析

Results for the P3 component during the anticipation stage revealed a significant main effect of math anxiety ($F(1, 56) = 6.71, p = 0.01, \eta_p^2 = 0.11$). Specifically, the P3 amplitude for the high math anxiety group ($M = 1.28, SE = 0.33$) was significantly smaller than that of the low math anxiety group ($M = 2.49, SE = 0.33$).

There was a significant main effect of task type ($F(2, 112) = 3.25, p = 0.04, \eta_p^2 = 0.06$). No significant differences in P3 amplitude were found between the visual baseline task ($M = 1.91, SE = 0.25$) and either the digit color identification task ($M = 2.01, SE = 0.25$) or the numerical magnitude judgment task ($M = 1.74, SE = 0.23$). However, the P3 amplitude for the digit color identification task was significantly larger than that for the numerical magnitude judgment task ($p = 0.03$). The interaction between math anxiety group and task type was not significant ($F(2, 112) = 0.90, p = 0.41$).

Topographic maps and waveforms of the P3 component during the anticipation stage. Results for the N170 component during the stimulus stage showed a significant main effect of math anxiety ($F(1, 56) = 5.30, p = 0.03, \eta_p^2 = 0.09$), indicating that the N170 amplitude in the high math anxiety group ($M = -1.42, SE = 0.44$) was significantly smaller than in the low math anxiety group ($M = -2.85, SE = 0.44$). The main effect of task type was also significant ($F(2, 112) = 6.5, p = 0.002, \eta_p^2 = 0.11$). The N170 amplitude for the visual baseline task ($M = -2.42, SE = 0.38$) was significantly larger than those for the digit color identification task ($M = -2.02, SE = 0.29, p = 0.015$) and the numerical magnitude judgment task ($M = -1.96, SE = 0.28, p = 0.006$). No significant difference was observed between the digit color identification and numerical magnitude judgment tasks ($p = 0.42$). The interaction between math anxiety group and task type was not significant ($F(2, 112) = 0.23, p > 0.05$).

Topographic maps and waveforms of the N170 component. Results for the P2p component during the stimulus stage revealed a significant main effect of math anxiety ($F(1, 56) = 4.03, p = 0.0496, \eta_p^2 = 0.07$), with the high math anxiety group exhibiting a significantly larger P2p amplitude ($M = -0.01, SE = 0.39$) than the low math anxiety group ($M = -1.13, SE = 0.39$). The main effect of task type was significant ($F(2, 112) = 7.85, p = 0.001, \eta_p^2 = 0.12$). The P2p

Figure 4

Figure 4: Figure 4

amplitude for the visual baseline task ($M = -0.94, SE = 0.36$) was significantly smaller than those for the digit color identification task ($M = -0.40, SE = 0.26, p = 0.006$) and the numerical magnitude judgment task ($M = -0.36, SE = 0.25, p = 0.004$). There was no significant difference between the amplitudes of the digit color identification and numerical magnitude judgment tasks ($p = 0.63$). The interaction between math anxiety group and task type was not significant ($F(2, 112) = 0.52, p = 0.59$).

Topographic maps and waveforms of the P2p component.

3.3 多变量模式分析

Figure 5 [FIGURE:5] illustrates the decoding results for the high and low math anxiety groups across different tasks. In the two perceptual tasks (digit color judgment and visual baseline), the HMA group was able to distinguish between the visual baseline and digit color judgment tasks within a time window of 140-745 ms (see Figure 5a). In contrast, the LMA group was able to differentiate between these two tasks significantly earlier, within a window of 114-950 ms. Furthermore, the LMA group exhibited significantly higher decoding accuracy than the HMA group during the 224-260 ms, 520-550 ms, and 640-655 ms time windows.

Regarding the two numerical tasks (digit color judgment and quantity judgment), the HMA group was able to distinguish between the conceptual task and the perceptual task within the 885-905 ms time window (see Figure 5b). Conversely, the LMA group was capable of distinguishing between these two tasks as early as the 334-370 ms time window.

Additionally, the LMA group demonstrated higher decoding accuracy compared to the HMA group within the 495-540 ms time window. In summary, during the two perceptual tasks, the HMA group identified the distinction between digits and non-digits later and with lower accuracy than the LMA group. However, no such pronounced distinction between the groups was observed across the two numerical tasks.

3.4 HMA 符号数字识别损伤的机制探讨

[FIGURE:5] Results of the mediation analysis regarding the differences in decoding accuracy from multivariate pattern analysis revealed that the P3 amplitude during the anticipatory stage exerted a significant mediation effect only in the digit-color identification task (effect = -0.35, 95% CI [-0.77, -0.04]). Furthermore, both the total and direct effects of the model were non-significant, suggesting that the mediator P3 plays a full mediating role. To further investi-

gate this, we constructed a serial mediation model (PROCESS Model 6, Hayes, 2012) for both the digit-color and numerical magnitude judgment tasks, using math anxiety group as the independent variable, P2P amplitude as the dependent variable, and anticipatory P3 amplitude (M1) and N170 amplitude (M2) as mediators (Figure 5b). Bootstrap analysis with 5,000 resamples and a 95% confidence interval indicated that in the digit-color identification task, the mediation effect of Path 3 (Math Anxiety Group \rightarrow Anticipatory P3 \rightarrow N170 \rightarrow P2P) was significant (effect = -0.21, 95% CI [-0.54, -0.03]), whereas the mediation effects for Path 1 and Path 2 were non-significant. The simple mediation results suggest that math anxiety group negatively predicts N170 amplitude through the mediator P3. Compared to the LMA group, the HMA group exhibited significantly reduced P3 amplitudes in the digit-color identification task, which in turn increased their N170 amplitudes. This suggests that the difficulties HMA individuals face in digit recognition stem from changes in attentional resources during the anticipatory stage. The serial mediation results further indicate that the influence of the anticipatory P3 amplitude extends beyond digit recognition to affect subsequent conceptual processing.

Source localization analysis was further performed on the anticipatory P3 component in the digit-color identification task. The results revealed that the activated brain region was localized to Brodmann Area 40 (BA 40), specifically the inferior parietal lobule. This region is situated within the frontoparietal network, which aligns with our initial hypotheses (Figure 5c). This suggests that the low activity within the frontoparietal network in HMA individuals during the anticipation of symbolic digit-color identification may be related to the increase in their N170 amplitude, subsequently leading to an increase in P2P amplitude. In other words, cognitive or emotional control during the anticipatory stage influences the visual-perceptual processing of symbolic digits, which then results in difficulties during conceptual processing.

[FIGURE:6] Mediation effect of anticipatory P3 amplitude and source localization results in the color identification task. This study decomposed symbolic digit processing into two stages—visual digit recognition and numerical magnitude processing—to deeply explore the processing characteristics of HMA individuals across different cognitive components and to further reveal the neural mechanisms underlying their functional impairments. The results demonstrate that math anxiety simultaneously impacts both visual digit recognition and conceptual processing. Specifically, the HMA group differed significantly from the LMA group in both the N170 amplitude (representing visual symbolic representation) and the P2P amplitude (representing magnitude processing). Furthermore, multivariate pattern analysis revealed that, compared to the HMA group, the LMA group showed earlier differentiation and higher decoding accuracy between digits and non-digit symbols. Subsequent mediation analysis found that the anticipatory P3 amplitude fully mediated the relationship between math anxiety grouping and N170 amplitude in the digit-color identification task, and further mediated the variance in P2P amplitude. This component was localized to the intraparietal sulcus region. These findings reveal that cognitive/emotional

control during the anticipatory stage may be the neural basis for abnormal visual digit recognition in HMA individuals.

4.1 数学焦虑人群在数字视觉识别上的特点

The emergence and development of mathematics rely heavily on visual symbolic systems. Consequently, difficulties in the visual recognition of symbols may serve as the cognitive foundation for the poor performance of High Math Anxiety (HMA) individuals in symbolic numeracy and overall mathematical achievement. A critical question remains: do HMA individuals possess an independent impairment in the visual recognition stage?

First, although no significant behavioral differences were observed between groups, the N170 amplitude of the HMA group during digit recognition tasks was significantly smaller than that of the Low Math Anxiety (LMA) group. This suggests that the processing of symbolic digit recognition in HMA individuals may be affected even before explicit behavioral deficits manifest. Furthermore, although the digit color judgment task and the numerical magnitude judgment task targeted color and size respectively, N170 amplitudes did not differ significantly between these tasks. The consistency of the math anxiety effect across both tasks indicates that the neural response during the structural processing stage of digits is systematically inhibited in high-math-anxious individuals. The visual recognition of digits possesses a degree of automaticity; even when a task emphasizes semantic judgment, digits still enter early perceptual pathways in their visual form and are subject to the regulatory influence of anxious emotions.

However, mediation analysis suggested that the reduction in P3 amplitude during the anticipatory stage might be the cause of the decreased N170 amplitude in the HMA group. Subsequent analysis of covariance (ANCOVA) revealed that when the anticipatory P3 amplitude was included as a covariate, the inter-group differences in N170 amplitude were no longer significant in either the digit color judgment or magnitude judgment tasks. This indicates that the impairment in the visual recognition stage can be explained by the weakened P3 amplitude during the anticipatory phase. Thus, the HMA population may not suffer from an independent impairment in digital visual recognition, but rather a “conduction” impairment stemming from earlier stages.

The present study did not find behavioral differences between high and low math anxiety groups in symbolic or non-symbolic digit visual perception. We speculate that the low difficulty of the current behavioral tasks may have resulted in a ceiling effect, preventing the detection of inter-group differences. Future research should employ new paradigms, such as subliminal visual perception of digits, to further explore the behavioral characteristics of symbolic digit visual processing in HMA individuals. Additionally, our non-symbolic digit color judgment task utilized inverted digits; since participants can still perceive these as digits after a certain degree of mental rotation, we cannot entirely rule out the possibility that HMA individuals possess digit-specific visual processing defects.

Future studies must design new behavioral tasks to further investigate this issue.

4.2 数学焦虑人群数字概念加工的特点

Does the High Math Anxiety (HMA) group exhibit a specific impairment in numerical concepts? In the quantity judgment task, we found that the P2P amplitude of the HMA group was significantly higher than that of the Low Math Anxiety (LMA) group in both the color judgment and quantity judgment tasks. This result replicates previous findings (Núñez-Peña & Suarez-Pellicioni, 2014). It is possible that the HMA group implicitly processed quantity during the numerical color judgment task, thereby exhibiting a P2P amplitude similar to that observed in the quantity judgment task. Previous research has shown that passive viewing of numbers under adaptation paradigms can also activate the P2P component, with amplitudes showing no significant difference from those during active viewing (Hyde & Spelke, 2012).

Behaviorally, the reaction times of the HMA group were significantly longer during quantity judgment than during numerical color judgment, suggesting that neural-level abnormalities only translate into significant behavioral costs during numerical concept tasks. Previous studies have also identified significantly prolonged reaction times in small-ratio quantity judgments (Maloney et al., 2011). This may occur because, in simple perceptual tasks, although neural encoding (N170/P2P) is abnormal, the low demand for cognitive resources prevents these abnormalities from resulting in a significant behavioral cost (i.e., no difference in reaction times).

Numerical concept tasks are complex; in addition to visual input, they require the extraction of precise quantitative relationships. Consequently, the brain must recruit more time-consuming and effortful late-stage processing resources (as evidenced by MVPA results showing extremely late neural decoding), which leads to prolonged reaction times.

Mediation analysis revealed that the serial path disappeared during the numerical concept task, implying a qualitative shift in the mechanism of anxiety's influence when facing high-demand tasks. This suggests that simple linear conduction models are no longer applicable in this context. At higher cognitive levels of conceptual tasks, it is necessary to incorporate the independent impairment of the HMA group regarding numerical concepts; otherwise, it is difficult to explain the results solely through the conduction mechanism of emotional control during the anticipatory stage.

4.3 数学焦虑人群数字加工损伤的机制

When an individual perceives a digit, visual information is converted from the retina into neural electrical signals, transmitted via the optic nerve to the lateral geniculate nucleus (LGN), and subsequently projected to the primary visual cortex (V1) for basic feature processing, such as edges and orientations (Schaeffel,

2006). This information then travels to higher-order visual areas (e.g., V2, V4) for the further integration of shape and color cues. In the left fusiform gyrus, digits are identified as specific symbols, showing selective activation for numerical stimuli (Grotheer et al., 2016). Thereafter, the information is transmitted along the ventral pathway to the intraparietal sulcus (IPS), where it is linked to the numerical magnitude of the digit. The present study reveals that the negative emotions experienced by individuals with math anxiety when anticipating digits cause these digits to be treated as “threatening stimuli” from the outset. This is evidenced by a reduction in P3 amplitude during the anticipatory stage, which subsequently affects the digit identification stage (indicated by increased N170 amplitude) and interferes bottom-up with the entire “visual-to-quantity processing” pathway (indicated by increased P2P amplitude during quantity processing). Source localization traced the P3 amplitude during the anticipatory stage to the IPS region, suggesting that emotional control capacity plays a critical regulatory role in the numerical processing of anxious individuals. For high math-anxious (HMA) individuals, a failure of emotional control during the anticipatory stage leads to difficulties in symbolic digit identification. Our experimental findings align with the results of Lyons and Beilock (2012), which suggested that high reactivity in the frontoparietal network of HMA individuals during the anticipation of math tasks can mitigate impairments in math achievement.

However, the aforementioned mediational mechanism was only present in the digit color judgment task. In the quantity judgment task, neither the mediational effect of the anticipatory P3 amplitude nor the chain mediation effect reached significance. This suggests that quantity judgment tasks may rely on a different pathway, necessitating the hypothesis of an independent impairment in numerical concept processing for HMA individuals. We hypothesize that numerical processing in HMA populations relies on two pathways: the first is a “conduction impairment pathway” acting at the level of visual digit identification. Here, math anxiety impairs emotional/cognitive control during the anticipatory stage (decreased P3 amplitude), leading to inefficient early encoding and processing of digit symbols (N170); this pathway dominates tasks requiring rapid, automatic identification. The second is an “independent impairment pathway” acting at the level of numerical concept processing, which works in tandem with the conduction pathway during numerical conceptual tasks. This pathway dominates tasks requiring semantic retrieval and complex cognitive operations. A dual-pathway model combining these two pathways provides a more precise explanation for all findings in this study: in the digit perception task, we primarily observed the effects of the conduction pathway (significant chain mediation); in the numerical concept task, the effect of the independent impairment pathway was manifested as a significant prolongation of reaction times. Due to this independent impairment in quantity representation among HMA individuals, the conduction pathway becomes non-significant in numerical conceptual tasks.

Independent impairment at the level of numerical concepts may be the deep-seated cognitive root causing individuals with math anxiety to experience ex-

treme difficulty and avoidance behavior when faced with actual mathematical operations. Future work should focus on directly verifying this independent impairment of quantity representation. This could be achieved through cross-modal quantity tasks (to isolate visual input), neural representational similarity analysis (RSA), or computational modeling to directly quantify the quality, stability, and access efficiency of quantity representations and test whether they are independent of early visual ERP indices. Additionally, a limitation of this study is that general cognitive abilities and intelligence were not measured. Consequently, we cannot entirely rule out the possibility that the different behavioral patterns observed between the two groups stem from general cognitive processes, such as differences in visual attention or intelligence, rather than being specific to numerical processing. Future research should implement stricter controls for these irrelevant variables.

The findings of this study have important practical implications. On one hand, emotional interventions targeting the anticipatory stage of numerical processing (such as attentional bias modification or emotion regulation training) may serve as effective routes to reduce the impact of math anxiety. On the other hand, early, gamified training in number sense and spatial transformation abilities to intervene in the core quantity representation system could significantly enhance the learning efficiency of high math-anxious learners. This study deconstructs math anxiety from a vague “fear of difficulty” into specific, intervenable cognitive process deficits. It advocates for a shift from simply “telling students not to be nervous” to “helping the student’s brain prepare for and process mathematical information more efficiently,” providing a critical cognitive neuroscience foundation for personalized education and scientific intervention.

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Yao, Y., Zhou, H., Xu, T., Ge, X., Du, F., Wang, C., & Chen, F. (2023). Different impacts of long-term abacus training on symbolic and non-symbolic numerical magnitude processing in children. *Biological Psychology*, 178, 108514. <https://doi.org/10.1016/j.biopsycho.2023.108514> Neural Mechanisms of Symbolic Number Processing in High Math Anxiety: An ERP Study LIU Jie¹ YAO Xiaohuan¹ LIN Yuefan¹ YAN Peiqing³ HAN Shangfeng² (1 1 School of Psychology, Shenzhen University, Shenzhen 518060, China) (2 School of Psychology, College of Education / Center for Brain and Cognitive Sciences, Guangzhou University 510006, China)(3 Ronggui Xijiao Primary School ShundeDistrict, Foshan 528305, China)

Abstract

Math anxiety has been consistently shown to impair performance in numerical and mathematical tasks, but its impact on specific cognitive stages—particularly the visual perception of numerical symbols and the processing of numerical magnitude—remains poorly understood.

The present study investigated the neural mechanisms underlying symbolic number processing deficits in individuals with high math anxiety (HMA) using event-related potentials (ERP). A hierarchical task design was employed to dissociate distinct levels of numerical processing, including a visual baseline task (non-digit color judgment), a digit color judgment task, and a numerical magnitude judgment task. This design allowed for the separation of general visual processing, symbolic digit recognition, and abstract numerical magnitude processing.

Fifty-eight university students were selected from a larger screening sample based on their scores on the Shortened Mathematics Anxiety Rating Scale (sMARS), forming high math anxiety (HMA, $n = 29$) and low math anxiety (LMA, $n = 29$) groups. Participants completed the three experimental tasks while EEG was recorded. ERP analyses focused on the anticipatory P3 component elicited by task cues, the N170 component associated with early visual processing of digits, and the P2P component related to numerical magnitude processing.

Results showed that individuals with HMA exhibited significantly reduced N170 amplitudes during digit processing, suggesting weakened neural responses during early visual recognition of symbolic numbers. In contrast, the HMA group showed increased P2P amplitudes during numerical magnitude processing, indicating altered or less efficient neural processing of quantity representations. Although behavioral performance did not reveal robust group differences—likely

due to task simplicity and ceiling effects—neural measures clearly differentiated the groups.

Multivariate pattern analysis (MVPA) further demonstrated that individuals with low math anxiety could distinguish between digit and non-digit stimuli earlier and with higher decoding accuracy than those with high math anxiety. Specifically, the LMA group showed earlier and more reliable neural decoding of digit-related information, whereas the HMA group exhibited delayed and less accurate classification, indicating reduced efficiency in symbolic number discrimination.

Importantly, mediation analyses revealed that the anticipatory P3 amplitude fully mediated the relationship between math anxiety and both N170 and P2P amplitudes in the digit color judgment task. This finding suggests that deficits in anticipatory cognitive-emotional control contribute critically to downstream impairments in symbolic number processing. Source localization using sLORETA traced the anticipatory P3 activity to the inferior parietal region (Brodmann area 40), a key node within the frontoparietal control network. Reduced activity in this region may reflect impaired emotional regulation and cognitive control during the anticipation of numerical stimuli in individuals with high math anxiety.

Taken together, these findings suggest that symbolic number processing deficits in individuals with high math anxiety arise from a multi-level disruption that begins during anticipatory preparation and propagates through early visual recognition to later numerical magnitude processing. These results highlight the role of anticipatory emotional and cognitive control mechanisms in shaping numerical cognition and provide new neurocognitive evidence for understanding and potentially intervening in math anxiety.

Key words: Mathematical anxiety, Symbolic number, ERP, N170, MVPA

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