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Psychophysiological Mechanisms of Math Anxiety: Review of Current Research

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Mathematical anxiety (MA) negatively affects all aspects of activities related to manipulating numbers, both in education and in everyday life. MA is negatively associated with mathematical self-efficacy, subjective value of mathematics, attitude, and interest towards mathematics. Individuals with pronounced MA have a lower need for cognitive load and reflective thinking. Among the predictors of MA, cognitive, personality, and social aspects can be identified. The question of the brain mechanisms of MA remains relevant. The review provides an analysis of studies on the neurophysiological correlates of mathematical anxiety using modern psychophysiological methods: electroencephalography, magnetic resonance imaging (MRI). The results of studies using these methods are inconsistent. When studying MA, attention is paid to brain structures associated with the processing of both emotional information and cognitive processes. The analysis of the literature has shown that when implementing corrective measures, it is important to consider the lack of a unified theoretical approach, which raises questions about the causes of MA.

Keywords: math anxiety; causes of mathematical anxiety; psychophysiological methods; EEG; magnetic resonance imaging (MRI).

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Психофизиологические механизмы математической тревожности: обзор современных исследований

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Представленные в статье материалы посвящены проблеме математической тревожности (МТ). МТ негативно влияет на все стороны деятельности, связанные с манипулированием числами как в обучении, так и в повседневной жизни человека. Актуальным остается вопрос о мозговых механизмах МТ. Авторы ставили целью провести обзор исследований нейрофизиологических коррелятов математической тревожности с помощью психофизиологических методов: электроэнцефалографии (ЭЭГ) и магнитно-резонансной томографии (МРТ). Результаты исследований с их использованием неоднородны. При исследовании МТ внимание уделяется тем мозговым структурам, которые связаны с обработкой как эмоциональной информации, так и когнитивных процессов. Результат проведенного обзора продемонстрировал, что у лиц с высокой МТ обнаруживаются значимые различия во всех измеряемых показателях ЭЭГ. У испытуемых с высокой МТ активируется больше зон, ответственных за переживание негативных эмоций (страх и боль) при решении задач, числовая информация воспринимается как угроза и вызывает напряжение. Теория механизма недостаточного торможения описывает цикл обратной связи МТ: МТ вызывается математической задачей, после чего возникает страх, занимающий часть рабочей памяти, поэтому ее объема не хватает для решения математической задачи, что приводит к неправильному решению. Рабочая память во многом определяет успешность обучения в целом и математике в частности. МРТ-исследования демонстрируют участие мозговых зон в корреляции высокой МТ и распределения внимания. Также в МРТ-исследованиях показано, что при предъявлении сложных математических заданий, независимо от МТ, активируются зоны мозга, ответственные за когнитивный контроль и регуляцию негативных эмоций. У людей с высокой МТ повышается активность регионов мозга, ответственных за выполнение числовых операций при использовании стратегии когнитивной переоценки, что проявляется в повышении эффективности решения математических задач и снижении негативных переживаний. На основе проведенного обзора делается вывод об отсутствии единой теории МТ и необходимости проведения комплексных психофизиологических исследований с учетом когнитивных и эмоциональных компонентов математической тревожности.

Ключевые слова: математическая тревожность; причины математической тревожности; психофизиологические методы; ЭЭГ; магнитно-резонансная томография (МРТ).

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Introduction

Mathematical anxiety (MA) is a negative emotional reaction characterized by avoidance, as well as feelings of unease in situations related to mathematical cognition and thinking. In other words, MA can be defined as a negative affective reaction of an individual to situations involving numbers and calculations, accompanied by feelings of tension and anxiety that hinder the manipulation of numbers and the solving of mathematical problems in a wide range of situations. MA can also be defined as a robust experiencing of negative emotions associated with broad range of situations that require the use of numbers. The difficulties some individuals face performing mathematical operations negatively impact their subjective well-being and, consequently, their socio-economic status, posing a significant challenge to contemporary Russian society. However, which psychophysiological mechanisms are involved in the formation of MA and to what extent remains a topic of discussion. As long as this issue remains unresolved, it is impossible to effectively identify the causes of MA and to carry out corrective and compensatory measures. Thus, identifying the psychophysiological mechanisms of MA is not only an academic problem but also an acute issue justified by the demands of society: math competencies are a necessary condition for academic and professional success in the modern high-tech world. MA is negatively associated with the development of math competencies, leading to adverse consequences in career choice, limiting opportunities for employment and professional activity. This review aims to discuss the psychophysiological methods used to study the phenomenon of MA, as well as to analyze the main findings from research conducted using these methods.

MA is distinct from general anxiety or test anxiety, as well as it has specific psychophysiological and behavioral manifestations [1]. It is discussed that MA correlates with general anxiety; genetic differences contributing to general anxiety also contribute to genetic differences in MA, meaning that if a person has high anxiety, they are likely to exhibit high MA as well [40]. However, individuals who do not have high general anxiety can still display MA. Supporting this fact, data has shown that various indicators of MA correlate more strongly with each other than with constructs of general and mathematical anxiety [8]. In one study, it was found that MA arises as a response to numerical rather than textual representations of a problem [25].

Psychophysiological Methods for Measuring MA

MA Questionnaires are often used to assess MA [14;17;20;34]. However, as reported by F. Demedts and co-authors, this method of measurement is associated with a number of problems. Questionnaires require participants to recall how they feel in various situations, which involves retrospective assessment [15]. Here we encounter distortions in self-reports related to the peculiarities of memory. Additionally, the ability to self-report on one's behavior in specific situations is not available to all age groups, such as young children.

Measuring MA with psychophysiological methods is possible, as well as MA is rooted in physiological mechanisms of stress response. When MA occurs, a variety of reactions associated with the hypothalamic-pituitary-adrenal (HPA) axis and the release of glucocorticoids are activated [28;33]. Thus, MA has a well-defined physiological basis, allowing its psychological manifestations to be correlated with physiological reactions. Compared to survey methods, psychophysiological registration has several advantages, such as objectivity and the ability to directly measure MA in a modeled situation. The choice of registration methods can be based on the goals of the research. For measuring MA in educational settings such as schools and universities (i.e., in situations with high ecological validity) it is convenient to use methods that do not interfere with the everyday educational activities of respondents. Techniques may include the registration of skin galvanic response, heart rate, etc. In laboratory-based studies it is possible to use other methods: multichannel electroencephalography, magnetic resonance imaging, functional near-infrared spectroscopy, etc. In the next sections, we will take a closer look at the main psychophysiological methods used in MA research.

Electroencephalography (EEG)

Electroencephalography (EEG) is a non-invasive method for studying the functional state of the brain by recording its bioelectrical activity. Indicators such as event-related potentials, measures of rhythmic brain activity, source localization of electrical activity, and connectivity metrics are examined in EEG analysis.

Event-related potentials are measured brain activity that occur in response to sensory, cognitive, or motor events. The waveforms of event-related potentials consist of a series of positive and negative voltage deflections associated with a set of basic components. Some components of event-related potentials are denoted by abbreviations (e.g., the negative result associated with an error — ERN), while most components are labeled with a letter (N/P) indicating polarity (negative/positive), followed by a number indicating either the delay in milliseconds or the ordinal position of the component in the waveform. The components of event-related potentials analyzed in MA research include: P2, P3, N450, and ERN. Differences in N450, a negative wave of the event-related potential that occurs in the 450 ms period after stimulus presentation, are explained within the framework of Eysenck's attention control theory: individuals with high MA demonstrate reactive (post-hoc) control, while those with low MA exhibit proactive (anticipatory) control [39]. More negative ERN amplitude has been shown in individuals with high MA during numerical tasks, indicating specificity in error monitoring [38]. It has also been demonstrated that individuals with high MA exhibit higher P300 event-related potential during mathematical tasks compared to those with low MA. The P300 component is a positive wave that peaks around 300 milliseconds after stimulus presentation [13]. The P300 component in individuals with MA also varies depending on decisions regarding purchases [19]. Another EEG study highlighted the important role of the P600/P3b component: this component has a higher amplitude and later onset in mathematically anxious individuals [38]. Individuals with high MA, regardless of their success in solving tasks, demonstrate higher P300 amplitude when anticipating a math problem.

EEG studies of event-related potentials have shown greater amplitude of event-related potentials during math problem-solving in students with high MA compared to those with low MA. This difference was observed across various types of math tasks [30]. This result is interpreted as an increase in working memory load.

A widely used approach involves source localization of the brain's bioelectrical activity recorded by electrodes during EEG recording. This approach allows for the identification of zones (sources) of current brain activation. Studies utilizing source localization methods (particularly sLORETA) indicate that individuals with high MA activate regions such as the insula and amygdala. The insula is involved in pain responses, while the amygdala is associated with emotional experiences (fear, stress, anxiety). Specifically, EEG studies have shown that individuals with high MA activate more areas responsible for experiencing negative emotions (fear and pain), whereas those with low MA show greater activation in regions responsible for working memory function—such as the anterior cingulate cortex, insula, and supplementary motor area [22]. These findings support theories explaining MA as a precursor to pain and align with fMRI research showing that individuals with MA activate regions associated with pain sensations during problem-solving, as well as studies demonstrating that MA is linked to activation of centers responsible for experiencing negative emotions [27;41].

Another informative EEG-indicator is the rhythmic activity of the brain. The EEG rhythm is a regular (having a fixed frequency) type of electrical activity corresponding to a certain specific state of the brain and associated with particular cerebral mechanisms. The main EEG rhythms are linked to various mental states. Studies have shown an increase in gamma-range activity in individuals with high MA: the power of gamma oscillations increases in frontal leads [26]. A comparison of responses to numerical and textual information in people with high and low MA demonstrates that individuals with high MA exhibit higher gamma activity when perceiving numerical information compared to textual information, while no such differences were found for individuals with low MA. According to the authors, these results indicate that people with high MA perceive numerical information as a threat [10]. Additionally, studies have found differences between highly anxious and low-anxiety individuals in the alpha range [2]. Alpha activity is traditionally associated with wakefulness in a calm state, and thus the differences may reflect a variance in the ability to relax among those with high versus low MA.

Psychological traits, including MA, are related to the structural features of brain networks, particularly the number of “weak” pathways for information transmission within the network. The theory of the insufficient inhibition mechanism describes the feedback cycle of MA: MA is triggered by a mathematical problem [5;6;18]. This induces fear in the individual, occupying part of their working memory, which is insufficient for solving the math problem, leading to incorrect solutions. Functional connectivity analysis shows that individuals with low MA have more structured cortical networks with increased connectivity in areas related to working memory, such as the frontal cortex. In contrast, the brains of individuals with high MA exhibit a more dispersed and unstructured network, supporting the notion of working memory impairments [22]. Furthermore, an EEG study on cognitive fatigue during math problem-solving did not reveal differences in neural correlates of cognitive fatigue between individuals with high and low MA [42]. It should also be noted that MA can be predicted with 93.75% accuracy based on features of the electroencephalogram (EEG), using the machine learning method NBTree [21].

Magnetic Resonance Imaging (MRI), Functional MRI (fMRI), Diffusion MRI (dMRI)

When studying MA, special attention is paid to those brain structures that are associated with the processing of emotional information and working memory. Neurocognitive research using fMRI has shown that MA is linked to abnormal activity in the right amygdala [11;31]. Working memory is considered one of the important determinants of successful learning and mathematical cognition [24]. According to Baddeley’s model, working memory includes three components: (I) a visuospatial component, which serves as a storage for visual and spatial information; (II) a verbal component necessary for storing verbal information; (III) a central executive component involved in regulating, manipulating, and processing information [9]. Children with low levels of the visuospatial component of working memory suffer the most from MA when learning math [36].

MRI studies using morphometry have shown that high MA is negatively correlated with the volume of gray matter in the left intraparietal sulcus, which is responsible for attention distribution [16]. A study using functional magnetic resonance imaging (fMRI) showed that when employing a cognitive reappraisal strategy, individuals with high MA exhibit increased activity in brain regions responsible for performing numerical operations (Dorsal PFC/supplementary motor cortex, Inferior frontal cortex/frontal operculum, Medial prefrontal/temporal lobe, Temporo-parietal junction, Left anterior prefrontal cortex). At the behavioral level, this is reflected in an increase in correctly solved tasks and a simultaneous decrease in negative experiences related to math stimuli [32].

In another fMRI study it was revealed that when anticipating a complex math task, negative emotions arise in both individuals with high and low MA, and brain activity during this does not depend on a person's level of MA. It was also shown that when anticipating a complex math task, regardless of MA, areas of the brain responsible for cognitive control and regulation of negative emotions (such as the anterior cingulate cortex) are activated [23].

Using fMRI, differences in functional connectivity within and between the dorsal attention network (DAN), ventral attention network (VAN), and default mode network (DMN) were demonstrated in physics students with high and low MA while solving physics tasks [35].

A study using diffusion magnetic resonance imaging (dMRI) revealed a positive correlation between scores on the Abbreviated Math Anxiety Scale (AMAS) and the degree of microstructural connectivity in the left arcuate fasciculus (AF), the body of the corpus callosum (CC), right cingulum, and left inferior longitudinal fasciculus (ILF) in men. In women, a positive correlation was found between AMAS scores and the degree of microstructural connectivity in the genu of CC, right ILF, and bilateral fornices; a negative correlation was observed between AMAS scores and the degree of microstructural connectivity in the left cingulum and right cingulum [29].

Conclusion

The literature analysis revealed a methodological problem in studies of the brain mechanisms of math anxiety (MA), which raises questions about the causes of MA and complicates the selection of psychological and pedagogical interventions and their effectiveness.

Firstly, this is due to the complexity of the phenomenon of MA itself. MA is a distinct psychological construct with cognitive, personal and social predictors. For example, MA can arise in individuals with high anxiety and high cognitive abilities, as well as in low-anxiety individuals with deficits in specific cognitive functions.

Secondly, the results of studies using psychophysiological methods (EEG, MRI, fMRI, dMRI) demonstrate a wide range of data due to the specificity of each of the mentioned methods. On the one hand, data regarding the involvement of cognitive characteristics, such as working memory and attention control, in the formation of MA have been obtained. On the other hand, a link between MA and emotional experiences and feelings of pain has been identified.

The analysis conducted allows for a more detailed plan for further research aimed at identifying the brain mechanisms of MA. The first stage involves conducting a study using EEG, which will include participants with varying levels of MA and general anxiety. The experimental design will incorporate cognitive abilities significant for MA (working memory, solving arithmetic tasks, academic grades in math disciplines, etc.). EEG will be recorded in a resting state and during experimental tasks, allowing us to subsequently use analysis based on graph theory. The goal of our research is to specify the psychophysiological mechanisms of MA using EEG, particularly in identifying the activation of brain regions and parameters of functional connectivity. In the future, we plan to expand the study by including other psychophysiological methods.

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