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Review / Derleme

From Numerical Perception to Mathematics Anxiety: Insights from Neuroimaging Evidence

Sayı Algısından Matematik Anksiyetesine: Nörogörüntüleme Bulguları Işığında Bir Bakış

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ABSTRACT

This review examines the role of numerical perception in the development of mathematical abilities and the neural underpinnings of mathematics anxiety in light of neuroimaging findings. Numerical perception relies on cognitive systems such as the core number system and the symbolic representation system, and is localized in the brain's fronto-parietal regions. Individual differences in mathematical performance are influenced not only by general cognitive factors but also by domain-specific factors such as numerical processing and mathematical concept knowledge. As numerical skills develop, emotional factors such as mathematics anxiety also begin to influence performance. This condition is thought to impair performance by limiting working memory through negative emotional responses that arise during numerical tasks. Neuroimaging studies have shown functional and structural alterations in the amygdala, insula, and fronto-parietal networks in individuals with high mathematics anxiety. However, these neural alterations associated with this condition have been found to be modifiable through interventions such as education, practice, and emotion regulation. A better understanding of the relationship between mathematics anxiety and number processing may contribute to the development of practice- and education-based application strategies aimed at enhancing numerical performance.

Keywords: Number perception, Mental number line, Arithmetic, Mathematics anxiety, Numerical practice, Functional magnetic resonance imaging (fMRI).

ÖZET

Bu derleme çalışmasında sayı algısının matematiksel yeteneklerin gelişimindeki rolü ve matematik anksiyetesinin nöral temelleri nörogörüntüleme bulguları ışığında incelenmiştir. Sayı algısı, çekirdek sayı sistemi ve sembole erişim sistemi gibi bilişsel alt yapılara dayanır ve beynin fronto-paryetal bölgelerinde temsil edilir. Matematik performansındaki bireysel farklılıklar; genel bilişsel faktörlerin yanı sıra sayı işleme ve matematik kavram bilgisi gibi özel bilişsel faktörlerden etkilenir. Sayısal beceriler geliştikçe, matematik anksiyetesi gibi duygusal faktörler de performans üzerinde etkili olmaya başlamaktadır. Bu durumun sayısal görevler sırasında ortaya çıkan olumsuz duygusal tepkiler nedeniyle çalışma belleğini sınırlayarak performansı olumsuz etkileyebileceği düşünülmektedir. Nörogörüntüleme çalışmaları matematik anksiyetesi yüksek bireylerde amigdala, insula ve fronto-paryetal ağda işlevsel ve yapısal farklılaşmalar olduğunu göstermiştir. Bununla birlikte; bu durumla ilişkili nöral farklılaşmaların eğitim, pratik ve emosyonel düzenleme müdahaleleri ile değişebileceği bulunmuştur. Matematik anksiyetesi ile sayı işleme süreçleri arasındaki ilişkilerin daha iyi anlaşılması, sayısal performansı artırmaya yönelik pratik ve eğitim temelli uygulama stratejilerinin geliştirilmesine katkı sağlayabilir.

Anahtar kelimeler: Sayı algısı, Zihinsel sayı doğrusu, Aritmetik, Matematik anksiyetesi, Sayısal pratik, İşlevsel manyetik rezonans görüntüleme (iMRG).

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Introduction

The development of the core systems related to number perception in the brain is critical for the acquisition of mathematical abilities. Individual differences observed in mathematical performance are shaped by the efficiency of the cognitive systems involved in numerical processing. On the other hand, mathematics anxiety encompasses emotional factors that may lead to differences in mathematical achievement. Existing neuroimaging studies in the literature have not yet provided clear and consistent findings regarding the neural mechanisms underlying mathematics anxiety. In this review, we adopt an integrative perspective by synthesizing neuroimaging evidence on numerical processes together with emotional and cognitive control mechanisms implicated in mathematics anxiety, while also considering the roles of development, education, and practice.

Numerical perception

Numerical perception is a fundamental system encompassing cognitive processes such as distinguishing quantities and understanding the concepts of more or less. It is based on a biological foundation shared in simpler forms by different animal species (1,2). Research has shown that even young children can differentiate changes in numerical magnitude (3). A study with children under the age of two showed that looking time decreased during repeated presentations of sets with a fixed number of dots. When the number of dots changed, looking time increased significantly (4). Accordingly, it can be suggested that the capacity for numerical perception exists prior to the acquisition of counting skills.

The existence of a basic number sense can be observed early in development and appears to be relatively independent of formal education and cultural background. Studies in this area provide striking evidence for the universality of non-symbolic numerical perception. In a cross-cultural study, participants were asked to categorize sets of dots. They were able to use the number of dots, the surface area covered, or a combination of both to form categories. Regardless of age, educational level, or cultural background, participants predominantly relied on the numerical properties of the dots when forming categories (5). In another cross-cultural study, the Munduruku, an Amazonian indigenous group living in Brazil, were examined to determine whether numerical perception is independent of spoken language. Among the group members, words existed in their language for quantities from 1 to 5; but for quantities above 5, approximate representations were used. Despite this, group members were able to distinguish the larger set of dots in comparison tasks with success rates similar to French controls. Moreover, group members performed as well as controls in simple arithmetic tasks requiring the approximate summation of dot sets, but they showed lower performance in calculation tasks requiring exact results (6). The fact that numerical magnitudes are processed similarly across different developmental stages, cultures, and living conditions suggests the presence of a shared representational system for numerical perception in the brain. On the other hand, the cognitive processing of complex arithmetic tasks may be more dependent on the linguistic features of the culture in which one is raised.

In numerical perception, quantities are considered in two groups: non-symbolic and symbolic. Non-symbolic quantities represent sets composed of various units, such as dots. Thus, deciding in real time which of two sets of dots is larger constitutes non-symbolic numerical perception. The brain mechanisms involved in non-symbolic numerical perception are referred to as the “core number system.” The core number system encompasses two different systems and their associated neural structures: the “exact number system” which allows for precise and immediate perception of small quantities and the “approximate number system” which enables estimation (7). It is known that a system called “subitizing” is used particularly for distinguishing small quantities between 1 and 4 (8,9). In

this system, a small number of objects are tracked and marked with a cue (e.g., fingers, symbols), allowing them to be recognized rapidly and accurately without the need for counting (10).

On the other hand, symbolic quantities are expressions of quantities associated with number symbols. As the quantity increases, instant perception becomes difficult and the core number system becomes insufficient. For example, knowing the exact number of units in a set of dots requires counting. Prior to formal schooling, quantities are associated with number words (e.g., "one," "two," "three"), typically through informal learning within the family environment, and are later learned in relation to their corresponding number symbols (e.g., "1," "2," "3") through formal education (11). The brain regions involved in representing quantities through their associated number symbols are referred to as the "symbolic representation system" (Figure 1).

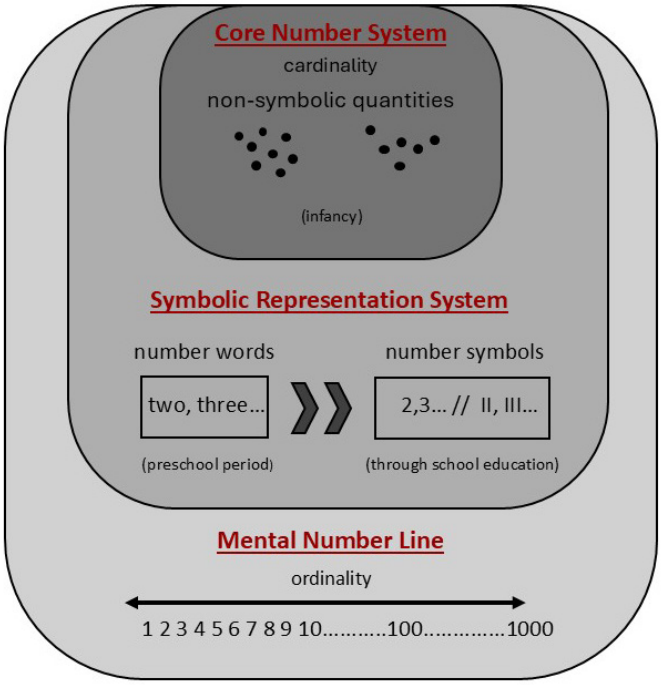


Figure 1. Developmental Model of Numerical Perception (13).

Two fundamental characteristics, distance effect and magnitude effect, underlie decision processes in both non-symbolic and symbolic numerical perception (12,13). According to the magnitude effect, increasing the size of numerical quantities makes it more difficult to distinguish them from each other. According to Weber's Law, in order to perceive a difference between two numerical magnitudes, this difference must be proportional to the magnitudes themselves (12). As numbers increase, the neural representation fields overlap more and reduce representational precision (10,12). Consequently, distinguishing between 6 and 8 is perceived as an easier task than distinguishing between 26 and 28. Findings from studies in monkeys and humans indicate that the magnitude effect corresponds to neural tuning in the intraparietal sulcus (IPS) in accordance with Weber's Law (14). In the distance effect, the discriminability of numerical quantities is facilitated by the relative distance between their magnitudes. As magnitudes get closer, overlapping neural representations reduce precision and make discrimination more difficult (10,12). Thus, distinguishing between 3 and 5 is perceived as more difficult than distinguishing between 3 and 17.

The quantitative properties of numerosities provide information about "cardinality" and answer the question "how many?" (15). The development of numerical perception is thought to begin with the core number system and continue with the acquisition of the symbolic representation system during schooling (11). Another important perceptual feature built on the cardinality of numbers is "ordinality," which represents positional or sequential information and answers the question "which one?" (15). Lesion studies have shown that, depending on the location of the damage, patients may lose either cardinal or ordinal aspects of numerical processing. Delazer and Butterworth (16) found that a patient with a left frontal lesion preserved ordinal-related abilities such as comparing non-symbolic quantities, ordering numerical quantities, and counting. However, the patient failed in tasks requiring the use of cardinal information, such as symbolic representation and calculation. Conversely, Turconi and Seron (17) reported that a patient with lesions in the right parieto-occipital junction and the left posterior parietal area had roughly preserved numerical quantity representations but impaired ordering processes. These findings may indicate that cardinal and ordinal prop-

erties of numerical quantities are related yet separable cognitive processes.

Mental Number Line and the SNARC Effect

The ordinal information which reflects the relative positions of numerical quantities, is thought to be represented along an imaginary "mental number line" (15,18). The mental number line describes a spatial plane in which smaller quantities are represented on the left and larger quantities on the right, reflecting the close relationship between space and numerical magnitude (19). However, the orientation of the mental number line can be influenced by the reading and language characteristics of the culture. Accordingly, the representation of numbers from left to right (small numbers on the left, large numbers on the right) along the mental number line applies to cultures with left-to-right writing and reading direction. In a study by Dehaene, Bossini, and Giraux (20), Iranian participants whose writing system is right-to-left showed that the representation of numerical magnitudes along the mental number line was oriented from right to left (small numbers on the right, large numbers on the left), consistent with their reading direction.

Behavioral research supporting the brain representation of the mental number line focuses on two main areas (10,18). The first concerns studies on the distance effect of numerical quantities. In these studies, participants are presented with two numerical values and asked to decide which is larger. Findings show that as the numerical distance between numbers decreases, the response time required to distinguish them increases (21). Conversely, it becomes easier to identify the larger number as the distance between numbers increases and this reduces response time (12).

Some of the knowledge regarding the close relationship between space and numerical magnitude comes from research on the "spatial-numerical association of response codes" (SNARC). In a study by Dehaene, Bossini, and Giraux (20), participants were asked to compare presented numbers to a fixed reference value using response buttons under their right and left hands. One group responded by pressing the right-hand button for larger numbers and the left-hand button for smaller numbers. The other group responded in the opposite way, pressing the left-hand button for larger numbers and the right-hand button for smaller numbers. The results showed that participants responded more accurately and faster with the left-hand button when the number was smaller than the reference, and with the right-hand button when the number was larger. The SNARC effect refers to the phenomenon in which smaller numbers are linked to the left-hand spatial field and larger numbers to the right-hand spatial field, reflecting the spatial organization of quantities according to numerical distance (20).

The cognitive systems involved in processing numerical quantities at different levels in the brain enable rapid judgments such as "9 is larger than 5, 3 is between 2 and 4, or 12 + 15 cannot equal 96" (22). The representation of numerical magnitudes along the mental number line supports automatic and efficient processing, which facilitates understanding of relationships in abstract arithmetic and lays the foundation for acquiring mathematical concepts (15,23). The successful establishment of cognitive subsystems involved in processing numerical quantities at different levels is crucial for the development of mathematical skills.

Neural Bases of Numerical Skills

Numerous studies aiming to elucidate the neural foundations of numerical processes have identified the parietal cortex as a key brain region involved (24). Single-cell recording studies in the parietal area have demonstrated the presence of neurons sensitive to numerical quantity representations (25). Moreover, patients with lesions in the parietal cortex have been reported to exhibit acalculia, a loss of numerical processing ability (26).

A neuroimaging study investigating the functional organization of the parietal cortex assessed various cognitive tasks including comprehension, pointing, language, eye movements, attention, and calculation. The results showed that deep regions of the IPS are selectively activated during calculation tasks (27). Furthermore, IPS activation has been found

to be influenced by the difficulty level of the calculation problem and the strategy employed for solving it (28). Bilateral IPS is known to be a core area engaged in the representation of both symbolic and non-symbolic numerical quantities (22). In a functional magnetic resonance imaging (fMRI) study examining task-related functional brain activity, Ansari, Lyons, Eimeren, et al. (29) demonstrated that the left IPS represents numerical quantities independent of stimulus format (symbolic or non-symbolic), whereas the right IPS is particularly sensitive to symbolic numerical processing. A study using transcranial direct current stimulation (tDCS), which modulates neural activity, to investigate IPS lateralization in number perception found that numerical information is represented in bilateral IPS, but representations associated with number symbols are lateralized to the right IPS (30). The IPS is consistently activated in the brain during the processing of numerical magnitudes (13). Structural and functional differences in the IPS have also been reported in neurodevelopmental conditions such as dyscalculia, which involves impairments in learning mathematics (31–33).

Several models have been proposed to understand numerical magnitude processing. Among them, the most well-known is the "Triple Code Model" proposed by Dehaene, Piazza, Pinel, et al. (34). In this model, the IPS, angular gyrus, and superior parietal regions are thought to subserve different cognitive functions related to mathematics and number processing. Specifically, the bilateral IPS is involved in numerical magnitude representation, the left perisylvian areas and left angular gyrus in verbal representation, and bilateral superior parietal regions in visuospatial representation. The model emphasizes the central role of the parietal cortex in numerical processing, while frontal regions are primarily engaged in supportive executive processes during calculation (34). Prefrontal areas are activated during arithmetic operations, especially calculation tasks that demand higher-order cognitive functions (28,35,36) (Figure 2).

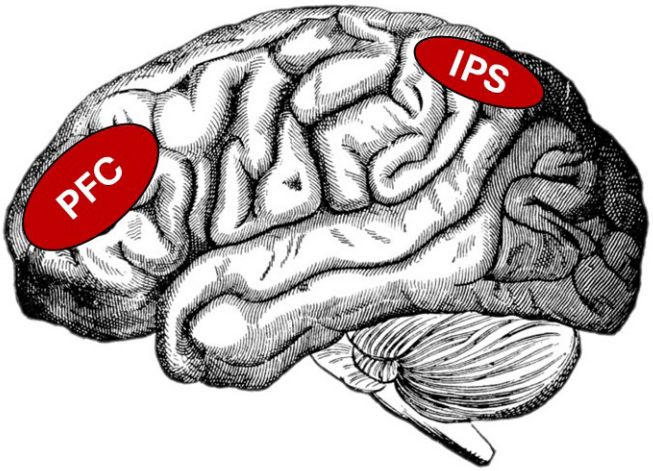


Figure 2. Core Brain Regions Involved in Numerical Cognition. IPS: Intraparietal Sulcus, PFC: Prefrontal Cortex.

Subsequent research has shown that the frontal cortex, along with many other brain regions, plays important roles in numerical processing. Single-cell recording studies in primates have identified neurons in the frontal regions that are sensitive to numerical quantities, similar to findings in the parietal cortex (37). In a single-cell recording study in monkeys conducted by Nieder and Miller (38), neural responses to numerical magnitudes were first observed in IPS neurons and subsequently in prefrontal cortex neurons, which may suggest a direction of information flow in numerical processing.

Although arithmetic constitutes a complex cognitive process, it fundamentally relies on numbers and requires the perception of numerical quantities and comprehension of their interrelationships. Meta-analyses of functional neuroimaging studies involving both adult and child participants have shown overlapping brain mechanisms for numerical perception and arithmetic (35,39). Accordingly, brain regions involved in numerical perception are similarly engaged during calculation. Several studies report that numerical processing in the brain is supported by a network extending across fronto-parietal regions (39,40). Moreover, the functional connectivity strength of the fronto-parietal network has been associated with individual differences in arithmetic performance (41). Diffusion tensor imaging (DTI) studies, which assess white-matter microstructural integrity, have demonstrated significant positive

correlations between arithmetic performance and the integrity of the superior longitudinal fasciculus, which provides structural connectivity among posterior parietal, prefrontal, and occipitotemporal regions within the number processing (31,42–44).

Although the fronto-parietal network plays a primary role in numerical calculation and mathematical cognition, other brain regions also contribute to numerical processing. In numerical perception studies, insular activation has been observed during quantity comparison tasks, particularly as a function of task difficulty (45,46). The insular cortex also functions as an initiator of control signals during arithmetic problem solving via the salience network (47). Similarly, the cingulate cortex, another key region of the salience network shows activation associated with cognitive control during numerical comparison (48). Developmental studies in number perception and mathematics learning have also highlighted the number form area (NFA) in the fusiform gyrus as an important brain region involved in numerical processing (49,50). In a study including both children and adults, the increase in NFA activation during numerical processing in adults reflected developmental differences (50). In line with this, Nemmi, Schel, and Klingberg (49) found that functional connectivity between the NFA and IPS increases with age.

In summary, numerical and arithmetic processing is supported by a distributed network centered on frontal and parietal regions that is formed through interconnections among multiple brain areas (51). Each brain region within this network reflects its role in arithmetic processing, encompassing both domain-specific cognitive processes and domain-general cognitive processes. Based on collective findings in the literature, determinants of individual differences in mathematics performance can be broadly categorized into these two classes (52). Domain-general cognitive processes refer to general cognitive abilities that influence performance across a wide range of tasks, including working memory, attention, executive functions, inhibitory control, language, cognitive flexibility, and spatial skills. In contrast, domain-specific cognitive processes involve individual characteristics that selectively affect performance in numerical and mathematics tasks, such as mathematical concept knowledge, quantity comparison performance, numerical magnitude processing ability, specific learning difficulties (e.g., dyscalculia), or mathematics anxiety.

Mathematics and Mathematics Learning

Behavioral studies have established that individual differences in numerical discrimination reliably predict later mathematical achievement (53,54). Furthermore, understanding the ordinal relationships of numerical quantities is considered a strong indicator of mathematics performance (55,56). However, it is not possible to make conclusions about mathematical achievement based on a single factor alone. Across the general population, there is considerable variability in mathematical performance. Some individuals perform exceptionally well on numerical tasks, while others struggle and exhibit lower performance (52).

Mathematical performance can be influenced by factors such as age, education, and practice. Studies have shown that educational interventions or practice can lead to functional and structural changes in brain networks (57). Short-term practice involving complex arithmetic problems has been shown to improve behavioral performance and alter brain activation patterns (58,59). Practicing numerical problems enhances proficiency in arithmetic solutions and can change the strategies employed. Neuroimaging studies have shown that activation shifts from the IPS toward the supramarginal gyrus/angular gyrus as arithmetic expertise increases (58–60). These neural activation changes are particularly associated with changes in arithmetic strategy use. As arithmetic knowledge becomes more automatic through practice, reliance on procedural calculation strategies tends to decrease, whereas the use of retrieval-based strategies may increase. However, when tasks are more complex (e.g., 18 – 9 + 7) or involve larger numbers (e.g., 56 – 39), active calculation strategies are typically required. In contrast, simple tasks with small numbers (e.g., 3 + 4) are generally solved using retrieval-based strategies. A neuroim-

aging study investigating the neural foundations of arithmetic reported that frontal areas are more active during calculation-based strategies in complex numerical tasks, whereas parietal regions such as the angular gyrus show higher activation when retrieval-based strategies are used in simpler tasks (61).

Mathematical problem-solving abilities become more specialized with age, and this is accompanied by changes in the neural systems associated with numerical processing. Age-related maturation in neural mechanisms is reflected in functional specialization in regions such as the left posterior parietal cortex and occipitotemporal cortex involved in numerical cognition (62,63). In early childhood, greater frontal activation is observed during numerical tasks, likely reflecting increased demands on cognitive processes such as attention and working memory. As arithmetic skills become more automatic with age, frontal activation tends to decrease and parietal regions become increasingly engaged (45,62). In a neuroimaging study, Vogel, Goffin, and Ansari (64) found that activation in the left IPS increased alongside greater sensitivity to symbolic number representations during development. The developmental or age-related shift in arithmetic-related brain activity from frontal to parietal regions is referred to as the "fronto-parietal shift theory" (45,62). However, recent evidence suggests that developmental changes in numerical processing may be more nuanced than a simple linear shift across brain regions (50). Furthermore, hippocampal activation observed during the consolidation of arithmetic knowledge in early childhood is gradually replaced by activation in parietal systems such as the angular and supramarginal gyri as automatization progresses (65). These findings indicate that, although largely dependent on developmental stage and age, increases in arithmetic knowledge through learning and practice are accompanied by widespread functional changes in the brain.

Mathematics Anxiety

Beyond numerical and learning-related processes, emotional factors also play a critical role in shaping mathematical performance. One of the most extensively studied affective influences in this context is mathematics anxiety. This condition refers to negative emotional responses such as tension, fear and stress experienced by individuals before (66) or during (67) numerical tasks, as well as worry about performance or task failure (68). Anxiety during numerical tasks can lead individuals to avoid career paths or academic activities requiring the use of numerical skills (69).

Although mathematics anxiety shares similarities with other forms of anxiety, such as test anxiety or trait anxiety, high correlations are frequently observed between their respective measurement tools (68). Therefore, studies examine mathematics anxiety separately from other anxiety-related factors (68). Mathematics anxiety selectively affects performance on numerical tasks (70). Maloney, Ansari, and Fugelsang (71) examined the relationship between mathematics anxiety and numerical magnitude processing in two behavioral experiments. In the first experiment, participants with high and low mathematics anxiety were asked to judge whether numerical values ranging from 1–4 and 6–9 were smaller or larger than a fixed reference value of 5. In the second experiment, the task and sample were modified, and participants had to decide which of two presented numerical values was larger. Reaction times for correct responses were compared across groups, and the results showed that people with high mathematics anxiety exhibited a more pronounced numerical distance effect. Specifically, in the first experiment, reaction times increased as numbers approached the reference value of 5. In the second experiment, high mathematics anxiety participants demonstrated longer reaction times when the numerical distance between numbers decreased.

Some studies have examined the relationship of mathematics anxiety with numerical magnitude perception, arithmetic performance, and reading ability separately. Maldonado Moscoso, Castaldi, Arrighi, et al. (72) demonstrated that high mathematics anxiety was associated with lower sensitivity to numerical magnitudes and poorer arithmetic performance, but reading performance was unaffected. Additionally, people with high mathematics anxiety exhibited increased physiological arousal during complex arithmetic tasks but showed no such response to

neutral verbal stimuli (73). These findings suggest that mathematics anxiety is a task-specific factor related to arithmetic success rather than an indicator of general task performance.

Research has also shown that people with high mathematics anxiety have reduced working memory, and this effect is particularly pronounced in calculation-based tasks (74). The negative impact of mathematics anxiety on numerical performance increases when arithmetic tasks become more complex and working memory demands are higher (75,76). According to Hopko and Ashcraft (77), anxious thoughts during task performance in people with high mathematics anxiety can interfere with working memory, which in turn leads to performance declines. Therefore, studies on mathematics anxiety consider not only different types of anxiety (e.g., state anxiety, test anxiety) but also cognitive functions (e.g., attention, working memory).

Neural Bases of Mathematics Anxiety

Research on the neural bases of mathematics anxiety remains limited, and existing findings are not yet fully consistent. Mathematics anxiety may reflect both shared anxiety-related processes and mathematics-specific task demands (73). In this respect, mathematics anxiety appears to differ from more general forms of anxiety, such as test or trait anxiety, by additionally engaging neural systems specifically recruited during numerical processing, rather than reflecting purely domain-general anxiety mechanisms.

In the first functional neuroimaging study in adults, groups differing in mathematics anxiety but with similar working memory and trait anxiety performed arithmetic and word tasks (66). Results indicated that mathematics anxiety elicited activation in brain regions associated with emotional processing, particularly the posterior insular cortex and midcingulate cortex, before the arithmetic task (66). Another fMRI study by the same team found that stronger frontoparietal activation before the arithmetic task was associated with greater activation of subcortical regions such as hippocampus, caudate nucleus, and nucleus accumbens during task performance in people with high mathematics anxiety (78). This suggests that activation of brain regions related to cognitive control before arithmetic tasks may be associated with motivational behavior during arithmetic performance, potentially compensating for arithmetic difficulties despite mathematics anxiety (78).

The default mode network (DMN) is a large-scale brain network that is typically active during rest, particularly when attention is not consciously directed toward external stimuli or goal-directed tasks. Pletzer, Kronbichler, Nuerk, et al. (79) reported that when arithmetic performance was matched across mathematics anxiety groups, reduced deactivation of the default mode network during numerical processing was observed in the high mathematics anxiety group. This implies that people with high mathematics anxiety may require greater cognitive resources to regulate emotional responses in order to perform successfully on numerical tasks. In line with this, Atabek, Şavklıyıldız, Orhon, et al. (80) reported heightened activation in the prefrontal cortex during mathematical thinking in the high anxiety group. Based on these results, the researchers suggested that people with high anxiety may require greater engagement of cognitive control regions during arithmetic tasks (80). Moreover, when tDCS was applied over the dorsolateral prefrontal cortex, a region involved in emotional regulation, mathematics anxiety decreased and performance improved in people with high mathematics anxiety (81). In contrast, the same procedure produced the opposite effects in the low mathematics anxiety group. Following these results, some researchers have argued that increased cingulate cortex and amygdala activation related to anxiety during arithmetic tasks may limit the processing capacity of prefrontal regions involved in attention and working memory, thereby slowing and reducing the accuracy of decision-making (82).

Several studies have also investigated the neural mechanisms of mathematics anxiety in younger populations who are still in formal education. In a neurodevelopmental study with children, groups differing significantly in mathematics anxiety scores but similar in IQ, trait anxiety, working memory, math-

ematics, and reading achievement were compared using fMRI (83). The findings showed that high mathematics anxiety was associated with functional differentiations during arithmetic tasks, characterized by hyperactivation of the basolateral nucleus of the right amygdala and deactivations in the posterior parietal cortex and prefrontal regions (83). In the study, multivoxel pattern analysis, which decodes distributed patterns of neural activation, revealed that basolateral amygdala activity could reliably distinguish high versus low mathematics anxiety groups. Moreover, high mathematics anxiety was associated with increased connectivity between the right amygdala and ventromedial prefrontal regions known to be involved in anxiety, as well as decreased connectivity with posterior parietal regions associated with numerical processing (83). Beyond functional differences, a structural neuroimaging study by Kucian, McCaskey, O'Gorman, et al. (84) found that higher mathematics anxiety was linked with reduced gray matter volume in the amygdala, a key region for processing negative emotional responses.

Mathematics anxiety also negatively affects performance on tasks that require mathematical conceptual knowledge and abstract reasoning, in addition to arithmetic calculations (85). In studies examining mathematical conceptual knowledge, participants evaluate the truth of statements regarding the fundamental principles of arithmetic operations (e.g., that the order of numbers in an addition can change without affecting the result). Resting-state connectivity, reflecting spontaneous brain activity measured in the absence of a task, between the insular cortex and the IPS was associated with task performance in an fMRI study examining mathematical conceptual knowledge in high and low mathematics anxiety groups (86). Specifically, greater success on conceptual knowledge tasks in people with high mathematics anxiety was linked to reduced resting-state connectivity between the insula which is involved in emotional processes and the IPS.

Task difficulty further modulates anxiety-related neural activity, with the insula initiating control signals during challenging arithmetic tasks (87). In a brain imaging study of mathematics anxiety, Pizzie, Raman, and Kraemer (88) used difficult arithmetic tasks to investigate calculation processes and found that high-anxiety individuals exhibited reduced IPS activation at the onset of complex arithmetic problems. Cognitive-behavioral techniques, known to be effective in situations where anxiety is prominent, have been shown to reduce anxiety and improve numerical processing performance in people with high mathematics anxiety. When these techniques were applied to the high mathematics anxiety group, increases in arithmetic performance were accompanied by corresponding rises in IPS activation related to arithmetic (89).

Practice can modulate the neural impact of mathematics anxiety. Supekar, Iuculano, Chen, et al. (90) demonstrated in children that eight weeks of cognitive arithmetic training increased mathematics performance and reduced mathematics anxiety. The training aimed to improve problem-solving skills in mathematics by teaching conceptual knowledge and efficient calculation strategies. Following the training, right amygdala hyperactivation decreased in the high mathematics anxiety group, and this reduction predicted decreases in mathematics anxiety levels. Furthermore, the increased bilateral amygdala connectivity observed in the high mathematics anxiety group before practice normalized after training to levels similar to those of the low mathematics anxiety group (90). These findings suggest that supporting cognitive processes in numerical tasks may improve arithmetic performance and modulate neural activations in people with high mathematics anxiety. Similarly, Altınok (91) extended these findings to adults, showing that eight sessions of structured numerical practice over four weeks enhanced arithmetic success in participants with high mathematics anxiety and led to differential activation changes between groups in the hippocampus, superior temporal gyrus, and supplementary motor area.

Overall, existing findings suggest that the link between arithmetic performance and emotional processes in mathematics anxiety is not yet fully understood. Anxiety during mathematics tasks can lower

arithmetic performance, while poor performance can trigger negative emotions and lead to avoidance of math. In general, higher mathematics anxiety is linked to poorer arithmetic performance (92). The limited neuroimaging findings available suggest that the emotional dimension of mathematics anxiety is primarily linked to neural mechanisms in the amygdala (fear perception) and insular cortex (pain/threat perception) (93). In this framework, these emotional mechanisms may interact with numerical processes and cognitive control systems, thereby influencing arithmetic performance, such as response speed or accuracy, in individuals with mathematics anxiety. On the other hand, impairments in numerical processing caused by emotional factors in mathematics anxiety may be diminished through interventions such as emotion regulation and numerical practice (93). Reducing the anxiety experienced by people with high mathematics anxiety can enhance their numerical processing skills and positively affect arithmetic performance.

Conclusion

This review comprehensively examined the impact of mathematics anxiety on numerical cognition and mathematical skills, as well as the neural foundations of these processes revealed through neuroimaging. Mathematics anxiety is not merely a cognitive variable dominated by emotional factors; it may also affects numerical performance at the neural level. Structural and functional neuroimaging studies indicate that it is associated with neural alterations in subcortical structures such as the amygdala and insula, as well as in regions within the fronto-parietal network. Nevertheless, studies on mathematics anxiety across age groups that accounts for emotional and cognitive factors are limited and methodologically insufficient. Differences in neuroimaging findings may partly stem from variability in study designs, such as whether studies focus on the anticipation of mathematical tasks or on active calculation and number processing, which are likely to engage distinct neural networks. Additional sources of variability may include differences in task demands, sample characteristics, and analytic approaches across studies. Future research on the relationship between mathematics anxiety and mathematical performance may help clarify the underlying mechanisms and support the development of novel interventions.

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