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Numeracy Skills Disorders: Review of Causes and Neuropsychological Mechanisms of Dyscalculia

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The article presents a review of foreign studies on the numerical difficulties and numerical disorders. The main modern theories of the mechanisms underlying the difficulties and disorders of counting are reflected, various classifications of dyscalculia are compared, and the neuropsychological foundations of the brain organization of counting are analyzed according to foreign scientists. It is noted that in the world of psychological science, the issues of the causes and mechanisms of difficulties and disorders of counting are still insufficiently developed, and the results of empirical researches are contradictory. It is concluded that for further study of dyscalculia it is necessary to analyze the psychological structure of counting and its changes under the influence of learning, taking into account the structural and functional features of the brain organization of quantitative information processing.

Keywords: numeracy skills disorder, dyscalculia, mathematical learning difficulties.

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Нарушения счетных навыков: обзор причин и нейропсихологических механизмов дискалькулии

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Представлен обзор зарубежных исследований, посвященных нарушениям счета. Отражены основные современные теории механизмов, лежащих в основе дискалькулии, сравниваются различные классификации нарушения счетных навыков, анализируются нейропсихологические основы мозговой организации счета по данным зарубежных ученых. Отмечается, что в мировой психологической науке вопросы причин и механизмов трудностей и нарушений счета еще недостаточно разработаны, а результаты эмпирических исследований являются противоречивыми. Делается вывод, что для дальнейшего изучения дискалькулий необходим анализ психологической структуры счета и ее изменений под влиянием обучения с учетом структурно-функциональных особенностей мозговой организации процессов переработки количественной информации.

Ключевые слова: нарушения счетных навыков, дискалькулия, трудности обучения математике.

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Introduction

At various times many Russian and foreign scientists (V.A. Krutetsky, P.Ya. Galperin, V.V. Davydov, N. I. Nepomnyashchaya, J. Piaget, E. Thorndike, etc.) paid attention to the problem of mathematical abilities and searched for the most effective methods for helping children to master the elementary course of mathematics. An important place in the scientific literature on pedagogy, psychology, speech therapy and special education is occupied by the studies of numerical skills disorders and ways of their remediation (T.V. Akhutina, N.M. Polonskaya, A. Germakovskaya, R.I. Lalaeva, G. Kapustina et al.), as well as by the studies of computational skills disintegration resulting from local brain lesions and of restorative learning (A. . Luria, L.S. Tsvetkova, M.G. Khrakovskaya, etc.).

Despite the fact that the researches on numerical skills and their disorders occupy an important place in neuropsychology, the results obtained cannot be called exhaustive and there are several reasons for this. On the one hand, subtests involving numeracy skills are included in almost all neuropsychological batteries and tests of intellectual abilities. On the other hand, there are much fewer neuropsychological studies specifically focused on arithmetical operations and their disorders as compared to the studies of reading disorders despite the approximately similar severity of the effect on functioning during life span [5; 9; 24; 26]. At the same time, even fewer studies pay sufficient attention to the psychological structure of the numerical skills in connection with the solution of the question of the brain substrate of arithmetical operations. L.S. Vygotsky also noted that the problem of localization involves solving the question of the ratio of structural and functional units of the brain and insisted on the importance of understanding what is to localize in order to clarify the nature of localization [1]. The vast body of the Russian literature on the problem of numerical disorders was published in the middle or end of the last century, while modern Russian studies are represented by a very limited set of articles that pay relatively little attention to the brain mechanisms of the numerical information processing and the mechanisms of math disorders (Rysina N.N., Gribanov A.V., O.V. Stepkova, L.V. Selkina, Yu.V. Krasilnikova, S.U. Kondratiev, Tikhomirova T.N., Malykh S.B., etc.). That is why it seems important to us to present an overview of modern, mainly foreign studies devoted to the classification of dyscalculia, the causes and mechanisms of impaired acquisition of numerical skills and the brain organization of numerical information processing in general. Understanding the causes of difficulties in forming basic mathematical skills in children, such as the concept of numbers and the four basic arithmetic operations, as well as identifying the types and kinds of difficulties that can be detected in children when mastering the numerical skills, is important both for early identification of children at risk of developing dyscalculia and for the development of intervention programs to overcome the difficulties that have already arisen.

Neuropsychological analysis of the cerebral mechanisms of arithmetical operations

The numerical skills are a multi-component functional system based on an extensive chain with a large number of links [2; 5; 9]. It is often disturbed both in focal and diffuse brain lesions of various localization, for example, in diffuse axonal injuries resulted from traumatic brain injuries in children [26].

At the initial stage of research, the definition of the brain substrate for arithmetical operations was based mainly on observations of neurological and neurosurgical patients [2; 5]. Based on the data of brain pathology, scientists around the world associated the processing of numerical information primarily with the parietal lobes of the cerebral cortex. This picture is also generally confirmed by the methods of modern radiology. Studies conducted using neuroimaging methods indicate unambiguous involvement of the post parietal regions in the numerical information processing and arithmetical operations, mainly the intraparietal sulcus, angular gyrus and supramarginal gyrus, which is part of the inferior parietal lobule. In addition, the processes of arithmetical operations and calculating involve the prefrontal, occipitotemporal areas of the brain and the hippocampal region [9; 24].

With the expansion of the methodological possibilities of studying the brain organization of counting, primarily due to the methods of EEG, fMRI, PET and other modern technologies, a large number of studies of children with dyscalculia or, more broadly, with mathematical disorders (MD) was added to the traditional studies involving neurosurgical patients [28], as well as healthy adults [19]. Until recently, the majority of-studies of this kind have focused on exploring the differences in the structure of gray matter [3; 13; 28]. And only in the last few years scientists have begun to pay attention to the problem of intracerebral connections, and there are studies, including longitudinal ones, concerned with differences in white matter of the brain in children with MD and in typically developing peers [23; 24].

Modern studies using neuroimaging emphasize the connections going from the parietal lobes to the left frontal lobes in the case of presenting the subject with more complex tasks [9]. In Russian neuropsychology, the connections between mathematical abilities, including the ability to proceed with arithmetical operations and solve problems, with the frontal lobes of the brain have already been obtained on the basis of local brain lesions [2], and modern studies of brain processes using neuroimaging technologies have only once again confirmed the findings of our scientists.

An important discovery of modern neuroimaging research is the objective confirmation of the fact that the organization of brain networks involved in performing arithmetic operations is dynamic, heterochronous, and the areas of brain activity responsible for performing mathematical tasks shift from one neural subsystem to another as learning progresses. Thus, in a groundbreaking study by Rivera and co-authors, healthy right-handed participants (children from 8 years old and adults) were asked to determine whether the arithmetic calculations presented to them were correct. In adult participants carrying out calculations in their heads, there was greater activity of the left parietal cortex, including the supramarginal gyrus and the anterior part of the intraparietal sulcus adjacent to these areas, together with the lateral sections of the occipitotemporal cortex. In children, the activation pattern was significantly different. Thus, they showed greater activity in the prefrontal cortex and anterior cingulate cortex. The authors of the study explain this activation pattern by the fact that children needed more attention resources and working memory to achieve the same productivity of calculations in the mind as adults. The fact that the younger participants had greater activation of the hippocampus and dorsal basal ganglia zones as compared to the older ones was connected by researchers with the fact that young participants rely more on the resources of both declarative and procedural memory in the process of calculations [27]. That is, there is a certain pattern of development in the organization of brain connections as a person masters the numerical skills which changes with age and competence of the actor. As more and more competence in calculations is acquired, the focus of activity shifts from the frontal lobes and medial temporal lobes to the parietal and occipitotemporal divisions, showing a comparative decrease in the need for working memory resources to perform the necessary calculations as the process is automated and symbolic designations are mastered, greatly facilitating work with mathematical information [4]. These data could be generalized more broadly to show that in the study of the brain organization of numerical skills, it is legitimate to separate the already obtained arithmetic facts and the use of newly acquired math knowledge, since in the process of calculations in the first case, the left angular gyrus is more activated (when extracting facts from memory), and in the latter case, the frontal lobes and the interstitial furrow is more activated [16; 18].

The key point is that almost all math or numerical processes are directly related to the parietal lobe of the brain, especially the intraparietal sulcus, and to their connections with the left frontal lobe, which suggests that these areas are the most important for processing numerical information and performing arithmetical operations.

Causes of dyscalculia

Despite the fact that performing calculations and other mathematical tasks involves the same brain areas, different researchers interpret these connections and their functional orientation differently, trying to identify one or more fundamental deficits that lead to mathematical difficulties. Accordingly, they distinguish different types of dyscalculia based on the alleged cause of mathematical difficulties.

Some researchers believe that the basis of the mathematical difficulties is a specific, often innate, 'core' deficit associated with a disturbance of processing information about quantity in the brain. Others are of the opinion that in addition to specific problems with the representation of quantity, calculations difficulties are also associated with disturbances of such processes as visual-spatial information processing, the ability to reject irrelevant stimuli and defects in working memory. Still, others find it more correct to speak not about a single deficit specific to mathematical difficulties, but rather about several areas of the brain specific to numerical skills. Let's take a closer look at each of their concepts.

The recently widely used model of the "triple code" processing of numerical information (The Triple Code model), first proposed by Dehaene in 1992 [14], designates three important domains responsible for mathematics. These include the numerical representation of quantity (which can include the "number sense" associated with the activation of the intraparietal sulcus), visual-spatial numerical representations (posterior upper-parietal regions) and auditory-verbal representations (extraction of mathematical information from memory) associated with the angular gyrus and areas near the Sylvian sulcus.

Another theory of the origin of arithmetical operation disorders currently widespread in Western neuropsychology is the theory of damage to the system in the brain responsible for the ideas of quantity (magnitude representation theory), according to which the relationship between a numeric symbol and the quantity that this symbol represents is disrupted or not developed in a dyscalculic person [9; 31].

The cerebral substrate of magnitude representation is considered to be the region of the intraparietal sulcus [9]. Now there is a large amount of data in the literature that the intraparietal sulcus is responsible for representations of the quantitative value (magnitude) of a numeric symbol [15; 25], equally as an analog value or as a discrete representation that encodes the number of elements in the set. This is proved by the activation of the zone of the intraparietal sulcus during the processing of information about the number of objects in the set [12]. Moreover, when the functioning of the intraparietal sulcus is disrupted by magnetic stimulation, the ability to evaluate discrete quantities is affected [11; 20].

Patterns of brain activity in 4-year-old children and adults show the involvement of areas in the parietal lobes of both hemispheres in response to changes in the number [10].

The fact that the intraparietal sulcus is involved in both simple and complex calculations is interpreted by representatives of this theory as confirmation of the fact that the basic idea of quantity is always involved, even with a simple extraction from memory of well-acquired knowledge about the addition and subtraction of numbers within a dozen [34]. According to the magnitude representation theory proponents who suggest the ability to represent of quantity to be the most important marker of the ability to calculate, this is consistent with the well-known “problem size effect”, in which solving arithmetical tasks within a dozen takes the longer time the greater the value of the number was involved, even if these are well-known arithmetical operations [33]. Thus, researchers who are adherents of this theory assume that typically developing people, even when extracting mathematical facts from memory, cannot but simultaneously use their knowledge about the composition of a number (number bonds). If such a connection has not been established, the ability to perform arithmetical operations is necessarily damaged [9]. This interpretation is confirmed by the activation of the intraparietal sulcus, which is associated with the magnitude representation, when arithmetical operations are performed [9].

Adherents of the magnitude representation theory talk about several mechanisms, or deficits, in the representation of quantity, which lead to difficulties in performing arithmetical operations. The so-called theory of the approximate number system (ANS) is being developed. According to this theory, there is a special mechanism in the brain that allows you to quickly compare several sets (for example, in tasks about where there are more points — on the right or on the left). It is this mechanism that is disrupted in people with dyscalculia. Also, people with mathematical disorders have a decreased ability to estimate the number of elements in small sets roughly, “by eye” (the so-called “subitizing”). Normally, people can say without counting how many dots they were presented with if the number of the stimuli presented is less than 3 or 5. This ability is severely damaged in people with dyscalculia. It is interesting that all these abilities are associated with the activity of the intraparietal sulcus, and the activation of the intraparietal sulcus during neuroimaging studies with participants involved in performing arithmetical operations is considered by adherents of this theory as confirmation of its validity.

However, it is noted in the literature that the intraparietal sulcus can be associated not only with the magnitude representation. This allows the development of theories explaining the origin of dyscalculia by other causes. Thus, a number of researchers associate dyscalculia with visual-spatial functions, in particular, visual-spatial working memory and problems of inhibition of irrelevant stimuli (inhibitory control), which are also associated with the cerebral cortex, including the intraparietal sulcus [31].

Thus, Szucs et al. concluded after their study that the magnitude representation theory was not confirmed. Instead, it was argued that the central problem in dyscalculia sufferers is disruption of visual-spatial immediate and working memory, as well as inhibition control impairment with impaired ability to suppress interfering influences. It is noted that both of these functions are associated with the functioning of the intraparietal sulcus [31]. Based on the data obtained in their study, scientists put forward a very interesting hypothesis for further verification. They suggest that 'pure' dyscalculia can be characterized by a specific disruption of the visual-spatial short-term memory together with a specific disruption of the processes of inhibition, key to the visual-spatial central executive, which leads to a decrease in working memory. The researchers suggest that an intervention aimed at improving these functions in children with dyscalculia will help shed light on this issue. In conclusion, the researchers express their idea that, apparently, the mechanisms of processing spatial information themselves remain intact in children with discalculia, but access to them is slowed down due to memory impairment/inhibition impairment [31].

Interestingly, if this assumption is true, then in order to identify such problems with mathematics in children it will be necessary to develop a more subtle methodological apparatus, since this hypothesis assumes that neither the visual-spatial functions themselves, nor the visual or visual-spatial memory are significantly damaged. The rejection of irrelevant stimuli in other modalities may also be unaffected, or only slightly affected. But there is a deficit at a much more subtle level — these are difficulties in using visual-spatial memory (speed and regularity of access). That is, the ability to work in the mental '"space' of short-term visual-spatial memory is damaged in the sense of the possibility of a quick and consistent change of frames (while showing resistance to interfering influences).

It should be noted that in Russian neuropsychology, it was true acalculia (unlike frontal and optical ones) that was associated with a deficit of visual-spatial representations and occipital-parietal areas of the cerebral cortex [2]. Having considered the mechanisms underlying the arithmetical operations disorders, let us consider the types of dyscalculia most often identified in the literature.

Dyscalculia classification

There are many classifications of counting difficulties in foreign literature, especially in relation to children's dyscalculia.

Kosc [22] describes six types of dyscalculia characterized by the following disorders: ability to verbalize mathematical terms and connections (1); ability to manipulate symbols/mathematical objects (2); ability to read numbers (3); ability to write numbers (4); ability to understand mathematical ideas (5); ability to perform mathematical operations (6).

Badian [6] found that dyscalculia sufferers often have spatial difficulties associated with numbers, primary anarithmia (primary difficulties in performing arithmetical operations), defects in attention and serial organization, but quite rarely dyslexia and dysgraphia when reading and writing numbers.

Geary [17], having analyzed studies on both developmental dyscalculia and acquired deficits in the field of arithmetical skills, based his classification of arithmetical operations disorders on the type of errors. He identified three types of dyscalculia. The first type, according to this classification, includes disorders characterized by difficulty in retrieving arithmetical facts from memory, including difficulties in remembering tabular values (such as the multiplication table). Moreover, he pointed out that children belonging to this type are also more likely to suffer from comorbid reading disorders (1). The second type includes difficulties of a procedural nature, such as the inability or difficulty in mastering the techniques of arithmetic operations, such as, for example, knowledge of the possibility of 'exchanging' units when using column subtractingor strategies used in addition (2). The third type includes counting disorders associated with difficulties in understanding and using visual-spatial relations to represent and interpret numerical information (3). The first two types of dyscalculia correlate with dysfunctions or lesions of the posterior cortical parts of the left hemisphere or subcortical structures, and the last type is associated with disorders of the posterior parts of the right hemisphere [17].

Rourke [29] distinguished between two types of developmental dyscalculia: 1) dyscalculia associated with speech problems (dyslexia), impaired understanding of instructions and verbal tasks and with a reduced amount of verbal memory (left hemisphere); 2) dyscalculia associated with spatio-temporal difficulties with disruptions of order and rearrangement of numbers (right hemisphere).

Karagiannakis [21; 30] (2014) identified four types of dyscalculia. Thefirst type involves dyscalculia resulting from a presumed damage in systems of internal magnitude representation, such as the approximate number system (ANS), object tracking system (OTS), symbolic representation, encoding of numerical information. The second type includes dyscalculia associated with memory disorders (working and semantic). The third type includes dyscalculia observed as a result of dysfunctionality of thinking due to a disruption of controlling functions. The fourth type is associated with visual-spatial functions [21].

In the modern Russian literature that we have analyzed, including articles published in the last 10-15 years, most authors do not offer their own classifications of dyscalculia. As a rule, in the reviewed works the authors distinguish between secondary and primary dyscalculia, as well as congenital and acquired. The main attention is paid to the classification proposed by Kosc back in the 70s of the last century (R. I. Lalaeva, A. Germakovskaya, S. Y. Kondratieva, N. N. Rysina, A.V. Gribanov, A. A. Plotnikova)

As can be seen from the above works, the types of dyscalculia identified by different scientists differ both in the principle underlying the classification and in the types distinguished on the basis of a similar principle. Analysis of various classifications of dyscalculia shows that the identification of various types of arithmetic operations disorders is often of external nature, based on phenomenology and clinical manifestations, without taking into account the mechanisms underlying the deficiency. In our opinion, the typology of mathematical difficulties should be based on structural and functional differences that cause one or another type of mathematical difficulties, and should take into account the principles of consistency in the structure of higher mental functions [2].

Conclusions

The analysis of studies devoted to the problem of identifying the mechanisms and causes of arithmetic operations disorders and arithmetic learning difficulties leads to the conclusion that the empirical results are contradictory and suggests that these issues are insufficiently developed. With a similar effect on functioning and quality of life, the problems of dyscalculia are less studied than the problems of dyslexia. The success of new research methods has led to the agreement of most scientists regarding the brain substrate of quantitative information processing, with the greatest involvement of the parietal and frontal regions. However, there is no such unity regarding the causes of arithmetical operations disorders and difficulties in mastering numerical skills, as well as the designation of types of dyscalculia. Most of the classifications of dyscalculia presented in the literature are based on their clinical manifestations rather than on a psychological analysis of the systemic dynamic organization of arithmetical operations and without taking into account the structural and functional differences in brain organization characteristic of a particular subtype of dyscalculia. Meanwhile, these issues are of primary importance for special education and developmental training of children with numeracy difficulties as well as for rehabilitation of children and adults following brain damage of both traumatic and non-traumatic genesis. Future research should focus on clarifying the causes of dyscalculia basing on the analysis of the psychological structure of arithmetical operations and its changes under the influence of learning, taking into account the structural and functional characteristics of the brain organization of quantitative information processing.

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