ACTA Vol. 5, No. 3, 2007, 120-130
NEUROPSYCHOLOGICA

NEUROPSYCHOLOGY OF NUMBER PROCESSING AND MATHEMATICAL DISORDERS: FROM THE PAST TO THE FUTURE

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Key words: *acalculia, developmental dyscalculia, cognitive neuropsychology*

SUMMARY

Research on mathematical disorders and their brain mechanisms has a long tradition. This paper presents the history of the search for the mechanisms of aquired acalculia from the perspective of clinical neuropsychology. The classic typologies of this disorder formed by Berger and Hecaen are discussed, as well as modern trends in the research on specific arithmetic difficulties in children. The latest general models of number processing (McCloskey, Dehaene, Butterworth, Zorzi) constructed within cognitive neuropsychology are included. Recently, new technologies of neuroimaging are being applied in research carried out within clinical and experimental cognitive neuropsychology. Neuroimaging technology (fMRI, PET) opens up opportunities to study the neural basis of number processing. On the other hand, these methods must be employed with care and the conclusions should be drawn within a broader, biopsychosocial context. Otherwise, there is the risk that a person with disorders will be reduced solely to an object of experiments. Furthermore, the neuroimaging results may lead merely to the development of "neurophrenology." Such tendencies in research raise questions about its methodological limitations.

INTRODUCTION

The psychology of number has a long tradition, but recent years have witnessed intensive development. There are many reasons for such rapid progress. First of all, the problem of numbering and magnitude representations is of interest for researchers from various sub-disciplines of psychology, including developmental and educational psychology, pediatric clinical psychology, clinical and cognitive neuropsychology, and other neurosciences. These disciplines have been in a stage of dramatic growth for several years now. Interesting experiments are produced by the collaboration not only of psychologists, but also neurologists and mathematicians.

PAST AND CURRENT TERMINOLOGY

The concept of acalculia was first introduced in 1919 by S. Henschen (cf. Butterworth, 1999), who used this term to describe disturbances of computational abilities after brain dysfunction. He noted that the neural correlates for calculation are different from the language areas (Rourke & Conway, 1997).

Developmental dyscalculia was first described by a Slovak researcher, L. Košč (1974). This was one of the most complete presentations of disorders influencing the learning of arithmetic in the early years of education. Moreover, he paid attention to the genetic components of developmental dyscalculia and to arguments for hereditary and congenital factors in these disabilities. He collected a large amount of data from neurological studies on many children with dyscalculia and stressed brain dysfunction in this disorder. Košč was the first clinical researcher dealing with children's problems to define developmental dyscalculia. Moreover, he did so in a very precise way. Today, his definition is cited by neuropsychologists and scientists in the field a s a pattern that remains helpful in selecting subjects for research, and in understanding the phenomenon of developmental dyscalculia. B. Rourke and J. Conway (1997) analyzed his definition and noted its three main points. The first of these is that normal intelligence is a necessary condition for diagnosing specific mathematical disabilities, i.e. developmental dyscalculia is not a form of mental retardation. The second is that the gap between the chronological age of the child and the level of mathematical skills should be significant for the diagnostician to be sure that she is dealing with developmental dyscalculia. Furthermore, she should exercise great care in this respect. More specifically, not every weakness in mathematics, even when more than slight, should be considered pathological. The third point of Košč's definition is that as a developmental disorder, dyscalculia should be distinguished from acquired forms of arithmetic disabilities occurring after brain damage in adults.

Currently, the notions of mathematical disorders, disabilities or difficulties are often used interchangeably. They refer to specific problems in mastering the ability to calculate and process numbers in children who otherwise develop well intellectually. However, many other terms are used in the literature to describe problems with learning mathematics in children with normal intelligence. These include:

- mathematical disorder (DSM-IV, 1994; ICD-10, 1997; Maerlender, 2002);
- mathematical disabilities (Geary et al., 1990; 1993; 2002; Alarcón et al., 1997; Ginsburg, 1997; Keeler & Swanson, 2001; Fuchs & Fuchs, 2002);
- mathematics disabilities (Lock 1996; Miller & Mercer, 1997);
- arithmetic disabilities (Marshall et al., 1999; Silver et al., 1999);

– specific arithmetic disabilities (Strang & Rourke, 1985a);
– specific arithmetical impairment (Strang & Rourke, 1985b);
– math learning disabilities (Garnett, 1998);
– mathematically disabled children (Geary et al. 1992);
– numerical disabilities (Dehaene & Changeux, 1993);
– mathematical difficulties (Jitendra & Hoff, 1996; Jordan & Montani, 1997; Jordan & Hanich, 2000; Hanich et al., 2001);
– specific arithmetic difficulties (Lewis et al., 1994);
– developmental dyscalculia (Košč 1974; Temple, 1989; 1991; Dehaene & Cohen, 1995; Hittmair-Delazer et al., 1995; Gross-Tsur & Manor, 1996; Shalev et al., 1997; Macaruso & Sokol, 1998; Butterworth, 1999; Geary & Hoard, 2001; Shalev & Gross-Tsur, 2001);
– profound developmental dyscalculia (Ta'ir et al., 1997).

The concept of disorder is often used in research pertaining to neurocognitive and medical sciences. This kind of research is focused on searching for explanations of brain mechanisms of mathematical problems. Disability is more often used by researchers who represent developmental and clinical psychology. The term difficulties is usually used by scientists describing the problem from a pedagogical or educational point of view, where what is most important is the mechanism of disturbances in learning arithmetic and their determinants. Many authors use these terms interchangeably, but define them precisely at the beginning of their research. Some of them (Ta'ir et al., 1997) are very strict in distinguishing the terms used. They propose the notion mathematical difficulties for children in the mainstream of learning, and developmental dyscalculia for children with severe organic brain dysfunctions. They emphasize the depth of disorders by using the term profound developmental dyscalculia. Other authors (Macaruso & Sokol, 1998) propose the term acquired dyscalculia for children with brain lesions, although they believe it should be used only when the child after a brain injury lost mathematical abilities possessed at a satisfactory level before the lesion.

The international classifications generally used and accepted in the EU and the US contain criteria to diagnose these disorders. There are two different terms used in relation to these disorders. In the fourth edition of the American Diagnostic and Statistical Manual of Disorders – DSM-IV (1994) we find mathematical disorder under number 315.1, and in the tenth version of the European International Classification of Diseases and Health Problems - ICD-10 (2000) we find specific disorder in development of arithmetic skills (F 81.2).

According to DSM IV (1994) mathematical disorders are identified on the basis of the following three diagnostic criteria:

– A. Mathematical skills, graded individually based on a standardized test, are significantly below the abilities normal for the chronological age of the child, her intelligence level and education level appropriate for the age.
– B. The disturbances described in Criterion A significantly interfere with achievements at school and every-day activities involving mathemati-

cal abilities.
- C. If a sensory deficit is present, the difficulties in mathematical ability are in excess of those usually associated with it.

According to ICD-10 (2000), specific disorders of arithmetical development are diagnosed based on the following indicators:
- Criterion A: the result of a standardized arithmetic test is significantly lower than the one expected based on the age and intelligence of the child (at least two standard deviations).
- Criterion B: the results of reading and writing tests are within the age-group range.
- Criterion C: difficulties in performing calculations are not due to incorrect method of teaching, learning or delay in intellectual development.
- Criterion D: difficulties in using numbers are not due to sensory disorders of seeing and hearing.
- Criterion E: difficulties in calculating are not a derivative of neurological and psychotic disturbances.

When compared, these two definitions and the associated diagnostic criteria for mathematical disorders exhibit many similarities. On the other hand, there are subtle differences between them. The operational definition described in DSM-IV (1994) is more practical, stressing the fact that mathematical disorders are connected not only with school achievements but also with other everyday activities. On the other hand, in ICD-10 (2000) the emphasis is on precise determinants of arithmetic disorders. These are helpful in distinguishing these specific problems from other mathematical difficulties having a different background. It is worth noting that these classifications use different terms for the same disorder. DSM-IV speaks of mathematical disorder while ICD-10 speaks of specific disorder in the development of arithmetic skills. Apparently, both terms are the same, but in fact the term used in ICD-10 is more precise, the term mathematical being broader than arithmetic. To be more specific, at the beginning of schooling mathematical education is restricted to knowing numbers, base-ten system counting, calculations, solving arithmetic problems, addition, subtraction, multiplication and division, while all these operations, even including fractions and decimals, are strictly connected with numbers and arithmetic. On the other hand, as other results of research and observations show, most children with arithmetic disorders have permanent problems in learning mathematics in further years of education, and then their difficulties concern algebra, geometry, trigonometry, probability and so on.

HISTORICAL DIRECTIONS OF RESEARCH ON MATHEMATICAL DISORDERS

We should begin with the prescientific period of seeking the localization of the functions in the brain. This stage is called the period of phrenology. Early theories of localization of counting function were based on the nineteenth-century phrenology widely known to psychologists. F. Gall and J. Spurzheim (Butterworth, 1999; Rourke & Conway, 1997; Walsh, 1998) studied the protrusions and sulci of the skull and the purported relations between them and behavior. They believed that protrusions indicated well-developed functions, while depressions indicated insufficient development of the involved areas and their functional counterparts. This was the way many functions were located, including the ability to calculate. Gall and Spurzheim discovered that in mathematicians the temporal area of the skull had a tendency to protrusion. Hence, they concluded that the organ of calculation is located in this area (see: Rourke & Conway, 1997).

The next period involved case studies of patients after brain damage. Clinical neuropsychology brought many interesting studies of adult patients with brain lesions and led to the discovery of several neuropsychological syndromes of acquired disorders, e.g. letter and number agnosia and acquired acalculia. In 1919 Henschen (see Kahn & Whitaker, 1991) was the first to conduct a statistical analysis of 305 cases of patients described in the literature plus 67 cases of his own patients. His analysis led him to identify a small subgroup of patients with profound problems with calculation without linguistic disorders. Based on this discovery he concluded that the neuronal substrate of counting is different from that of linguistic functions, and deficiencies leading to acalculia may be independent of aphasia (Rourke & Conway, 1997).

In the next stage, studies of acalculia were focused on the analysis of various types. Authors tried to systematize the symptomatology of these disorders. They distinguished typologies of acalculia, some of them still in use and confirmed by contemporary technologies of visualization of the active brain. In 1926 Berger (see: Rourke & Conway, 1997; Walsh, 1998; Geary, 1993) was the first to present a classification of acalculia. His classification involved two types:

- Primary acalculia is a counting disorder without other cognitive deficits of memory, attention, or visual perception. It is a result of a parietal lesion of the left hemisphere.
- Secondary acalculia is a disorder caused by linguistic disabilities, such as aphasia, or deficits of long-term or short-term memory. It is a consequence of letter and number agnosia and the result of bilateral occipital lesions of the brain, and of lesions in Broca's and Wernicke' s areas in the left hemisphere.

In 1961 Hecaen, Angelergues and Houiller (see Geary, 1993; Rourke & Conway, 1997; Walsh, 1998) proposed a classification involving three types of acalculia:

- 1) acalculia due to alexia and agnosia of letters and numbers: disorders of recognition of digits;
- 2) spatial acalculia: disorders of spatial organization of numbers, difficulties in calculation in writing with columns, inversions of arithmetical symbols (<, >) and multidigit numbers (27-72);

– 3) anarithmetria: inability to calculate despite a preserved ability to read numbers and the absence of visuo-spatial deficits.

This classification is still used and cited today, and referred to in handbooks of clinical neuropsychology (Walsh, 1998). Although it first emerged as a result of studies of adult patients with acquired acalculia, recently there have been attempts to confirm it via research on children with developmental mathematical disabilities (Geary, 1993), some of which have been successful.

CURRENT RESEARCH ON NUMBER PROCESSING

Current work on number processing can be organized into four major disciplinary perspectives:

– a) the neuropsychological perspective: from clinical disorders, such as aphasia, acquired acalculia in adults after brain damage, to less severe disorders, including dyslexia, dyscalculia and their developmental forms;
– b) the educational-clinical perspective: almost 100 years of research on developmental dyslexia and on difficulties in reading despite normal intelligence, and approximately 30 years of research on similar learning problems in other very important skills, such as arithmetic, including developmental dyscalculia;
– c) the neurocognitive perspective: the brain mechanisms of number processing and their neuronal substrates and computational representations;
– d) the neurodevelopmental perspective: an attempt to compare the brain mechanisms of number processing in adult and developing brains, and to explain the nature of development of number concept and numerical abilities.

The dynamic development of the neurosciences has led to discoveries regarding the neuronal bases of number processing. We are witnessing the vigorous development of clinical neuropsychology and even more rapid development of cognitive experimental neuropsychology, involving research on healthy volunteers with the use of new neuroimaging technology. In neuropsychological research on number processing the methods used include fMRI – functional magnetic resonance imaging (Dehaene, 2005), and NIRS – near infrared spectroscopy (Schroeter, 2005), or TMS – transcranial magnetic stimulation (Nieder, 2005). These techniques allow for observing and analyzing brain activation during number processing and finding the circuits which are the most engaged in magnitude representation. This is very important for discovering the brain mechanisms of number concept and explaining arithmetical disorders. The results obtained with these methods have made it possible to construct models of number processing. The most popular such models are the following:

- the general model of number processing and calculation by McCloskey, Caramazza, and Basili (1985);
- the triple code model by Dehaene (1992);
- the hypothesis of number module by Butterworth (1999);
- the computational modeling of numerical cognition by M. Zorzi (2005).

The first model is also called the abstract code model (ACM). It identifies three cognitive systems involved in numerical processing:

1) comprehension mechanisms;
2) generation/production mechanisms;
3) calculation mechanisms, which include three components:
   a) number facts;
   b) procedures;
   c) rules of calculation.

The center of this model is the abstract semantic representation module, which serves as mediator and communicator among the three systems. It transcodes one form of numerical representation at input (e.g. Arabic numerals) into another on output (e.g. number words).

While the ACM identifies three cognitive systems of number processing, the triple code model posits the existence of three codes on which number processing is based (Dehaene, 1992). These are:

- 1) an analogue magnitude representation, active in comparison of numbers and estimation of their magnitude;
- 2) a visual-Arabic number form (3+5=?);
- 3) auditory-verbal code ("three plus five is eight"). This model has no abstract representation, but rather a language-based representation (verbal code).

The "mathematical brain" proposed by B. Butterworth (1999) postulates the presence of an innate number module in the human brain. The role of this module is to categorize the world in terms of numerical categories. It operates automatically. Due to the number module even an infant can subitize, i.e. estimate the size of small collections of objects up to 4-5 in a set at a glance, without counting. This is the basis of arithmetic. This number module and the higher capacity to use mathematics can be developed through conceptual tools provided by culture and education. Butterworth (1999) argues that these tools can be systematized into four main categories:

- a) body-part representations;
- b) external representations (objects for counting, calculators);
- c) linguistic representations (i.e. numeral words – three, eleven, forty five);
- d) numerals (i.e. written symbols – 3, 11, 45).

For various reasons this number module sometimes fails to develop normally. Then there are difficulties in the estimation of number and further problems in learning mathematics. These could occur in the form of developmental dyscalculia. Hence, as Butterworth argues, the basis of this disorder is congenital, and connected with the number module and its development.

The computational modeling of numerical cognition proposed by M. Zorzi (2005) is based on a mathematical model of number processing and connected with the neural networks of numerical representations.

Another direction in the explanation of the brain mechanisms of number processing is to find neural substrates and circuits of numerical representations. The use of new neurophysiological technology, including the visualization of brain activity in vivo, could precisely indicate the neuroanatomical structures responsible for different kinds of number processing: calculation, number comparison, addition, multiplication, estimation, solving story problems with numbers. In some cases this seems to lead to neurophrenology, because such research discovers only the anatomical structures in the brain, but it is much more difficult to describe the mechanisms of the processes that are involved.

PERSPECTIVES

By analyzing current tendencies in the neurosciences, one can surmise their directions in the future. Concerning developmental dyscalculia the following tendencies in research can be identified:

- Modern techniques of neuroimaging could help to explain the brain mechanisms of the determinants of development and disorders of counting.
- The cooperation of research teams within international networks (for example the European network with many groups and associates named: Numeracy and Brain Development – NUMBRA) should make it possible to compare the results obtained in different cultures and languages.
- Associations, similarities and differences in the results from clinical and developmental research may allow new cognitive models of number processing to be constructed, including the brain mechanisms of computational representations in adults and children.
- It may prove possible to construct appropriate diagnostic and therapeutic tools based on the results of research within experimental cognitive neuropsychology, to produce methods strongly connected with their theoretical background. Most of the methods currently used are non-theoretical and even intuitive.
- Computerized diagnosis and therapy of developmental dyscalculia could open up the opportunity to develop economical, fast assessment of children with disorders even by their teachers, and offer them early help, which is very important in the remediation of the most developmental disorders.

LIMITATIONS OF THE RESEARCH

An unlimited fascination with the potential to measure neuronal function in real time during an experiment may lead the unwary researcher into various kinds of traps. First of all, there is the danger of reducing the human being with a particular kind of disorder to a disembodied brain that becomes the object of experimentation, and of seeing the results thus obtained as "neurophrenological" discoveries ("where" is more important than "what"). It should be stressed that even the most precise localization of counting representations, of their neuronal brain mechanisms, and the neuroanatomic structures responsible for number operations, is not sufficient for an appropriate description and explanation of number processing.

Secondly, separating laboratory results from practical applications (for example in the diagnosis and remediation of disorders) may be a limitation, which makes the spectrum of possible application of the obtained effects narrower, of interest only for theory and academic debates unrelated to clinical practice.

Thirdly, the nature and structure of mathematics, or even arithmetic, proves to be much more complicated than reading and writing, so the way of finding its components may be more complex. We are still at the beginning of this road. By way of comparison, the diagnosis of developmental dyslexia was once a much longer process, but now, since we have learned that visuo-spatial skills are not as crucial abilities for this disorder as once thought, the process of assessing reading disabilities is shorter, since phonological competences and naming speed are the most diagnostic functions. We hope that in the future we could assess mathematical disabilities in the same manner, that is, by examining merely the most crucial related functions. We do not yet know, however, what they are.

Where are we heading, then? The theory and practice of clinical work with developmental dyscalculia should be brought up to date with recent results and research tendencies. At the same time, it must fit in a broader perspective, and be linked with the results of previous research, so that it will not be the case that we are constantly crying "Eureka!" when we discover facts that have long been known.

ACKNOWLEDGEMENTS

This paper is a part of research project number 1H01F 079 26, entitled: Cognitive mechanisms of calculation disorders in children, funded by the Polish Scientific Research Committee and coordinated by the Marie Curie-Sklodowska University in Lublin, Poland, with the collaboration of University College London, Great Britain.

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RECEIVED: 18 March 2007
ACCEPTED: 10 October 2007