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Developmental Dyscalculia: Nosological Status and Cognitive Underpinnings

Ricardo Moura, Suzane Garcia and Júlia Beatriz Lopes-Silva

Abstract

Mathematics is one of the main challenges faced by students throughout school life, with long-lasting impact on social life, including employability and incomes. The development of the research on numerical cognition occurred together with the study of math learning and its related deficits, in special developmental dyscalculia (DD). The present chapter explores the literature on DD in two levels. First, we discuss about the nosological status of the disorder together with considerations about its diagnosis. Afterward we review the main research findings regarding the cognitive underpinnings of DD, from numerical representations to domain general processes, including working memory and language.

Keywords: dyscalculia, learning disabilities, dyscalculia diagnosis, numerical cognition, learning

1. Introduction

Living in today's society requires well-developed mathematical competencies. As more cliché as this statement may sound, there is a robust scientific literature indicating that higher mathematical competencies are associated with higher employability and incomes [1–3], profitable financial decisions [4], and even better health outcomes [5]. Despite this well-established body of evidence, many adults and children, even from developed countries, struggle to perform simple arithmetic [6].

The reasons for failing at math are diverse and include socioeconomic [7, 8], educational [9], and emotional factors [10, 11]. Math is a complex and abstract discipline and depends mostly of formal instruction at school. Moreover, mathematical knowledge is also largely cumulative, so that newer, more complex, and abstract concepts depend on previous knowledge, which can either be acquired intuitively, like reciting the sequence of number words, or also formally at school. Therefore, we can say that a great part of the difficulties faced by children when learning or performing math activities are due to the complexity of mathematics itself. It is known that, compared to other disciplines, difficulty in learning math is already observed in children in the first years of school [12].

Some children, nevertheless, show persistent and important difficulties in learning math, which cannot be explained by socioeconomic, emotional, educational, psychiatric, or intellectual factors. In these cases the label developmental

dyscalculia (DD) is often applied, and difficulties encompass a broad range of mathematical tasks, like reading and writing numbers in different formats, comparing numbers and quantities, and performing the basic arithmetical operations [7, 13–16]. Some authors also indicate deficits in abilities concerning magnitude representation and the comprehension and use of symbolic codes to represent numerical information [17–19]. The estimates for prevalence of DD vary from 3 to 6% of school-aged children [7, 20, 21].

Despite the relative consensus about what are the difficulties that characterize DD, there is still some debate concerning the diagnostic criteria, neuropsychological underpinnings, and rehabilitation strategies. In the following sections, we will discuss in detail each of these three topics.

2. Nosological status

2.1 Diagnosis

Two main questions concern the diagnosis of DD. The first question is about the diagnostic criteria, and in the literature on the epidemiology of learning disabilities, three approaches are commonly reported. The discrepancy criteria are probably the most common in research studies and define math learning disability from the discrepancy between an average of above-average performance on general cognitive capacity (often the IQ) and the low performance on standardized math tests. The absolute threshold criteria is similar to the discrepancy criteria, but the disability is defined solely by the low performance in a standardized math test. The response to intervention criteria establish the diagnosis after investigating how the child responds to a set of psychopedagogical interventions. In this way, the persistency of the difficulty and not the discrepancy between capacity and performance is the main criteria for diagnosis.

The second main question concerns the definition on how low the performance in an achievement test must be in order to diagnose DD. The cutoff scores frequently used are 30th, 25th, 10th, and 5th percentiles. Higher cutoff scores (25th and 30th percentiles) are less conservative and, naturally, more prone to false positives. Lower cutoff score is more conservative when labeling children and less prone to false positive. Some authors argue that the sample of individuals labeled under higher cutoff scores is more heterogeneous, with their difficulties in math being more attributable to social, educational, and motivational factors and therefore are less stable over time [22]. On the other hand, the individuals whose performance falls into the more conservative cutoff scores are a more homogeneous group, and their difficulties are more probably associated to cognitive factors. Mazzocco [15] suggests that the individuals with performance under the fifth percentile must be identified as DD, and those with performance under the 30th percentile must be identified as “mathematics difficulties.”

2.2 Comorbidity and cognitive heterogeneity

The investigation of DD nosology also involves studying its comorbidities with other syndromes and how the cognitive profile varies among individuals. It is estimated that only 30% of the DD children are free of comorbidities [23]. The main comorbidities of DD are with developmental dyslexia and ADHD, with comorbidity rates of 40% for the first [24] and between 25 and 42% for the second [23, 25].

According to Rubinsten and Henik [26], different cognitive deficits can be the cause of difficulties in learning math, with comorbidities being mostly due

to a combination of deficits. For example, the pure cases (for which the label DD is applied) are due to a deficit in the abstract representation of number, in the cognitive level, and a deficit in the functioning of the intraparietal sulcus, in the neural level. The comorbidity of dyscalculia and ADHD would be explained by the co-occurrence of deficits in the processing of number and in attentional mechanisms. In turn, comorbidity with dyslexia is due to a single deficit in the angular gyrus that would cause a deficit in associating symbols (Arabic numbers, words) to a meaning. The cases of comorbidity would be referred as mathematics learning difficulties (MLD).

3. Cognitive mechanisms

Following the diversity of activities involved in math and the heterogeneity of manifestations observed in mathematics difficulties, the cognitive mechanisms are also diverse and related to basic numerical representations, working memory, visuospatial reasoning, and language. In the following, the literature on each of these mechanisms will be reviewed in more detail.

3.1 Nonsymbolic representations

Humans, like all other animals, are born with only a rudimentary, language-independent, system dedicated to grasping quantities from the environment [27]. Naturally, this system is not able to process numerical symbols, which are, from a phylogenetic perspective, a very recent cultural invention that demands enculturation in order to be assimilated by the human brain [28]. This inherited preverbal number knowledge operates in two forms, which are considered independent subsystems: the object-tracking system (OTS) and the approximate number system (ANS; [27]). The OTS represents small numerosities up to four with high accuracy and reaches its developmental plateau early in development. The ANS, in turn, is responsible for the representation of larger numerosities analogically and, therefore, with increasingly imprecision. One largely accepted model suggests that the ANS represents numbers in an approximate and logarithmically compressed fashion, according to the classical psychophysical laws of Weber and Fechner [29].

Since the last decade, the relationship between basic numerical representations and performance on mathematics has been in the spotlight for many research groups. A handful of evidence has indicated a positive relation between ANS accuracy and math performance [30–37]. Moreover, it has also been shown that children with DD are impaired even in simple tasks that tap ANS representations, such as estimating the numerical size of a set of dots and comparing two sets of dots [17, 38, 39].

A very well-established theory is that DD is the result of a deficit in the foundational representations of numbers [14, 26]. For some researchers, this deficitary representation of numbers lies in the ANS [17]. Other researchers, in turn, propose that the deficitary numerical system in DD is the numerosity coding, which is responsible for processing precise, but not continuous, numerical quantities, and in which the whole arithmetical thinking is based on. For a detailed discussion about these hypotheses, see Butterworth [14].

3.2 Symbolic representations

Basic numerical representations are not restricted to nonsymbolic representations. Actually, learning symbolic systems for representing numbers is a landmark

in the development of mathematical reasoning. As children learn to speak a sequence of numerical words, they are still devoid of any quantitative meaning [40]. Gradually, these number words are associated with nonsymbolic numerical representations [41, 42]. The mapping between a list of words and their respective numerical representations (meanings) will be established gradually as children become able to perform a range of new tasks. For example, they can use these numeric words to label a set of objects (say “six” when looking to six dolls at a glance). These activities only develop completely around the age of five, when children master the principle of cardinality [43].

Schneider and collaborators [44], in a meta-analysis study, found that the association with performance in arithmetic tests is stronger for symbolic comparison tasks than for the nonsymbolic ones. Furthermore, a finding consistently reported by studies indicates that children with DD exhibit weaker performance than controls in tasks requiring comparison of symbolic numbers, like Arabic numbers and number words [18, 38, 45–47]. According to a model proposed by Rousselle and Noël [18], DD can also occur due to a deficit in accessing nonsymbolic representations from numerical symbols (access deficit hypothesis).

3.3 Language

Language influences mathematics in different ways. Many mathematical tasks rely on verbal processing, such as learning the multiplication table, writing and reading numbers, and learning the Arabic code. According to Simmons et al. [48], the relationship between phonological awareness (often measured by a rhyme detection or phoneme elision tasks) and math learning is independent of measures of vocabulary and nonverbal reasoning, thus indicating a genuine verbal-numerical relationship.

Language skills also characterize an important landmark in the development of mathematical abilities. A special case is the ability to convert between numerical notations, often measured by tasks of number writing and number reading, and called number transcoding. Number transcoding is especially important early in school life, since it demands the understanding of basic lexical and syntactic components of Arabic and verbal numerals. As suggested by previous studies, understanding the place-value syntax of Arabic numbers and matching it with number words constitutes a significant landmark that young children must reach in order to succeed in mathematical education [49].

Some scientific evidence suggests that children master the numerical codes after 3 or 4 years of schooling. During the first year of elementary school (around 7-year-old), children still struggle to write and read Arabic numerals [50, 51]. Shortly after, in third and fourth grades (8- and 9-year-old children), most of these difficulties with Arabic numerals are already overcome [38]. This issue was further investigated by Moura et al. [52] in a study using more complex number transcoding tasks and investigating children with and without MLD. Results revealed significant number transcoding difficulties in children with MLD. These difficulties were more prominent in Arabic number writing, but the magnitude of this difference decreased with age, indicating that children with MLD tend to reach the performance of their typical achievers peers. Importantly, from the first to fourth school grades, most of the errors observed in children, regardless of their achievement in mathematics, are well explained by the syntactic complexity of numerals, as most errors were observed in numbers with more digits, and more syntactically complex (like 1002, 4015). A detailed analysis of transcoding errors suggested that children with MLD struggle with the syntactic structure of Arabic numerals, mainly with 3- and 4-digit

numbers, until the fourth grade, while typical achievers seem to overcome these difficulties around the third grade. Moreover, the acquisition of lexical primitives seems to be well developed in typical achievers by the first year of elementary school, while children with MLD show a small though significant proportion of lexical errors (e.g., writing *twelve* as 20).

Another important evidence for this interaction between numerical and verbal skills is the high comorbidity between DD and dyslexia. Epidemiological studies indicate that approximately 40% of dyslexic children also have deficits in arithmetic [24]. Some studies suggest comorbidity rates up to 70%, which may be overestimated because of diagnostic criteria and constructs evaluated by standardized arithmetic and reading tests [53]. Importantly, the comorbidity between DD and dyslexia is greater than would be expected by chance if the two entities were fully segregated independently. An influential hypothesis states that children with developmental dyslexia struggle with numerical activities that rely on verbal codes, such as number transcoding and learning arithmetic facts [54].

3.4 Working memory and attention

The association between mathematics skills and working memory and attention has been extensively reported in the literature. In fact, a high variety of numerical tasks including number transcoding, complex calculations, and problem solving require working memory resources and planning. According to Rubinsten and Henik [26], a relevant part of children with DD also present comorbid attention deficit hyperactivity disorder (ADHD) [21, 55].

Interestingly, a brain region that is considered crucial for numerical development, the intraparietal sulcus, is also involved in a range of nonnumerical activities, including attentional control and reasoning [56–59]. Recent studies propose that an important cognitive mark of DD is attentional control. Gilmore et al. [60] found that, due to strategies aiming to control for nonnumerical visual parameters, commonly used dot comparison tasks require inhibitory control mechanisms. Surprisingly, this executive function component is more strongly related to mathematics achievement than the numerical components of magnitude comparison tasks. Similarly, Szucs et al. [61] also proposed that children with DD have more difficulties in inhibiting irrelevant nonnumerical information than their typically developing peers.

3.5 Visuospatial abilities

Together with working memory, visuospatial abilities are one of the most critical abilities related to mathematics achievement, being associated mainly with performance in multidigit calculation, mainly in those requiring borrowing and carry-over procedures [62, 63].

Despite the evidence for a role of visuospatial skills in calculation, a pure visuospatial deficit in children with DD is perhaps less clear than the other cognitive skills discussed above, as there is no well-established visuospatial subgroup of DD. The co-occurrence of mathematics and visuospatial deficits were widely discussed in the context of the so-called nonverbal learning disability [64–66].

If, on the one hand, there is no consensus about a visuospatial deficit in DD, on the other hand, many studies found that children with DD present deficits in the visuospatial component of working memory [61, 67–73]. Importantly, the verbal component of working memory is frequently reported as preserved in these cases [61, 74].

4. Conclusion

Even though the study of the cognitive basis of numerical representations and mathematical performance is relatively new, a consistent body of scientific evidence has already been gathered, allowing important advances in the comprehension of the development of mathematical abilities and in the identification and remediation of mathematical difficulties. Nevertheless, this is a broad field of study and there are still several open questions. Currently, longitudinal and replication studies are especially relevant [75].

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