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Developmental Dyscalculia: A Cognitive Neuroscience Perspective

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Abstract

Developmental dyscalculia (DD) is considered a brain-based disorder usually caused by dysfunction of the parietal cortex. DD has been researched but the current available means of diagnosing and particularly of treating DD are still not clearly defined. The current review discusses the different suggested neurocognitive markers of DD subtypes and links them with suggested grounds for intervention programs.

Keywords: Developmental dyscalculia; Learning; Anxiety; Numerical distance

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Numerical knowledge is a central aspect of human intelligence. Specifically, mathematical skills are essential for productive functioning in our progressively complex, technological society, from estimating how much money may be spent on a vacation without overextending one's bank account to developing new computerized programs. As an example, intact numerical abilities are important for health numeracy [1] and contribute to full-time employment in adulthood [2]. High school achievement in mathematics predicts college acceptance and graduation, early-career earnings, and earnings growth [3]. Hence, mathematical skills may have an effect on social mobility and on poverty levels. This makes numerical abilities and disabilities an extremely important scientific field with potential application for solving problems in society and education.

Accordingly, individuals who experience severe difficulties in learning to count and calculate are at a great disadvantage in both academic and professional life. Individuals who exhibit severe calculation difficulties despite average intellectual abilities are formally eligible for a diagnosis of 'developmental dyscalculia' (DD) (ICD-10) [4]. Developmental dyscalculia [5-7], or mathematical learning disability (MLD) [8,9] is a circumscribed learning disability evident in the form of severe difficulties in learning to count and calculate despite good schooling and average intellectual abilities. DD is different than other learning disabilities such as dyslexia (i.e., severe difficulties in written language) and affects about 3 to 6% of the elementary school population [5,7,10-12]. Beyond the high rate of prevalence several other factors have led to the increasing awareness of dyscalculia as a major health problem. First, dyscalculia persists into adulthood if untreated. Secondly, children diagnosed with dyscalculia frequently develop associated emotional problems such as math anxiety, a persistent negative reaction to math, ranging from mild discomfort to extreme avoidance [13-18]. Hence, such emotional difficulties hamper students' mathematic performance and motivation. Finally, individuals who affected by DD are at a great disadvantage. That is, numerical difficulties result in significantly reduced educational and employment achievements, as well as increased costs involved in physical and mental health [19-22]. Some argue that, in western society, poor numeracy is a greater disadvantage than poor literacy [2,23]. Numerical difficulties are also manifested in several major clinical populations, including Dyslexia [24] and Attention-Deficit/Hyperactivity Disorder (ADHD) [25-27].

However, and despite the negative consequences of low numeracy, paradoxically, and compared to other cognitive abilities such as reading and attention, both intact and deficient development of numerical abilities are an unexpectedly neglected area by both clinicians and researchers. Consequently, neuroscientific research investigating DD is still in its infancy and our current understanding of DD–and thus our methods of diagnosing and treating DD–are very limited. Current assessment tools and theoretical frameworks are focused on the behavioral and pedagogical levels. For example, Von Aster and Shalev [24] recently described an important four-step developmental model of numerical cognition that enables predictions of dysfunctions in mathematical reasoning. Here we review scientific work that leads us to suggest that only when cognitive and neural factors are measured and not only behavioral symptoms, an easier and more precise diagnosis of DD can be accomplished.

Basic Numerical Skills and DD

Modern research has argued that mathematics rests on mental representations that developed in the course of evolution [28,29]. These core representations include a non-symbolic numerical system that represents the approximate numerical value of a collection of objects (i.e., *numerosity*). Non-symbolic approximation is a key evolutionary ability, which is believed to develop without formal teaching. Indeed, studies have found that infants [30-32] and even animals [33] display the ability to estimate quantities.

Non symbolic numerical knowledge is usually measured by comparison tasks, in which the participant is asked to identify the larger among two arrays of dots [34]. One major signature of non-symbolic core numerical representations that is present in human and non-human animals, is that comparisons are subject to a ratio (minimum/maximum) limit: accuracy falls and reaction time (RT) increases as the ratio of the numbers to be compared approaches one (i.e., the ratio effect) [28]. Similarly, the larger the distance between two numbers to be compared the faster the response, as first reported by Moyer and Landauer [35] (i.e., the Distance effect) [36]. The distance effect has since been replicated by many researchers under diverse conditions [37,38].

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The numerical distance effect has been found in children [39,40], and in primates [41]. Similarly, the ratio effect has been demonstrated in infants [42], in young children [43], and in animals [44,45]. Interestingly, both of these signature effects are compromised in developmental dyscalculia (DD); for the distance effect see [46-49], and for the ratio effect see [50,51]. Further research identified the neural tissues involved in ratio and distance effects. Specifically, the parietal lobes and in particular the intraparietal sulcus (IPS) serve the mental operations involved in these effects [52-58]. This accumulated body of results led to a widely accepted view suggesting that DD is a brain-based disorder, which means that the syndrome-defining cognitive impairment (i.e., deficient calculation skills) is linked to neural deficiencies residing in (intra) parietal brain regions. Specifically, it is suggested that DD involves a domain specific deficit in the capacity to estimate [5,7,9].

However, there is a growing awareness that the core deficit approach–which implies a single-deficit view of DD–is not enough to account for the complex and often heterogeneous clinical picture of the disorder [7,10,59].

Wilson and Dehaene [60] for example, proposed three theoretical subtypes of DD. A first subtype is the *number sense (numerical quantity) subtype* that is linked to deficiencies of brain areas around the intraparietal sulcus (IPS) [52-58]. A second possible DD subtype is the *spatial attention/executive subtype* (characterized by difficulties with solving number tasks requiring spatial and executive skills such as locating numbers on a number line, order perception and written calculation) [61], perhaps supported by the posterior superior parietal lobule (PSPL). Finally, the *verbal subtype* (regarded as deficient number fact retrieval, among others) may be linked with the angular gyrus (AG; a brain area in the Parietal Temporal lobe, located posterior and inferior to the HIPS) and perisylvian areas.

Few case studies and other evidence may support such a theoretical framework. For example, Delazer and Butterworth [62] described the cognitive abilities of SE, an acalculic patient with impaired cardinal numbers but spared ordinal spatial numbers. Specifically, SE, who suffered from a left frontal infarct, was unable to access the cardinal meaning of numbers (i.e., deficiencies in calculation tasks and an inverse distance effect in number comparison), yet was able to answer correctly "which number comes next?" questions, suggesting that the sequential meaning of numbers was preserved. The reverse dissociation was reported by Turconi and Seron [63]. They described a patient with right parietal lesion who was impaired in processing the order of words that denote ordinal information (i.e., numbers, letters, days and months) in various tasks, while showing better performance in processing quantity information. Together, these studies suggest that there are distinct brain and cognitive structures responsible for quantity and order or spatial processing

Similar to Wilson and Dehaene's theoretical model, Rubinsten and Henik [7] link the behavioral-cognitive deficits associated with DD with their potential neural foundations. They offer three alternative frameworks for the origins of DD. These frameworks can direct theoretical as well as empirical work, and help reveal the causal relationship between neuro-cognitive mechanisms and behavior. The first framework suggests that a single restricted biological deficit gives rise to a specific developmental disorder. However, as is the case with many developmental disorders, multiple problems are the rule and pure disorders apply to a minority of cases only. Hence, two other frameworks are suggested. The second framework suggests a variety of cognitive deficits, each producing a different mathematical deficiency, and as a whole they create the behavioral manifestations of MLD (disorder in mathematics due to cognitive deficits such as deficient working memory or attention). The third framework suggests that the neurocognitive damage that causes DD could produce other behavioral disorders that are unrelated to DD, namely co-morbidity (DD+ dyslexia). The major distinction between the two models (Wilson and Dehaene vs. Rubinsten and Henik) is that the classification of DD by Wilson and Dehaene is based on neurobiological foundations (i.e., impairment in IPS), while the classifications used by Rubinsten and Henik rest on behavioral/cognitive manifestations of dyscalculia.

Such theoretial frameworks may help in developing methodologies for diagnosis and rehabilitation that target the antecedents of numerical deficiencies as early as infancy. Indeed, several studies have shown the efficiency of intervention programs targeting the core deficit of numerical quantity processing [64,65]. Kroesbergen and Van Luit [66] analyzed a total of 58 studies in which interventions were performed on kindergarten and elementary school children who suffered from mathematical difficulties. Kroesbergen and Van Luit showed that most of the intervention studies trained basic mathematical skills (acquisition as well as automatization of the four basic mathematical operations - addition, subtraction, multiplication, and division), and training of these skills produced higher effect sizes than training basic number sense (i.e., estimations of quantities) and problem solving skills. In contrast Wilson and Dehaene [67,68] showed that intervention that is based on neurocognitive models and which is focussed on basic numerical skills may improve math achievement from an early age.

To summarize, there is a scarcity of studies that thoroughly investigate the neurocognitive sources of typical and atypical trajectories of numerical cognition [69] and as a result, there is a need for theory-driven and systematic brain imaging guided assessment and intervention studies of DD. Howevere, owing to the fruitful integration of theories from different disciplines in recent years, together with innovative methodologies and a successful alliance of scientists and participants, we may be at the cusp of very exciting discoveries. Specifically, showing the types of numerical neurocognitive systems (e.g., numerosity, magnitude, space, exceutive functions) that are accessible to higher math skills and knowledge would alert educators to certain antecedents of numerical cognition that should be explored and may carry implications for designing math-education curricula and identifying reliable markers of math performance during schooling. Currently however, DD cannot be officially diagnosed by biological markers. Instead, the diagnosis is based on behavioral criteria [24,70]. However, DD can be defined as neuro-developmental disorders with a biological origin and specific behavioural signs. That is, some causes of the behavioural signs, as well as cognitive symptoms of the condition, can, and maybe should be, specified neurobiolgically. For example, the ability to automatically associate written symbols with mental representations such as quantities or phonemes may lead to math difficulties [71,72]. Also, the Angular is involved with higher level cognitive functions and, among other things, enables the association between symbols and mental representations (e.g., mapping between arithmetic problems and their solutions, and mappings between written numerical symbols and the magnitudes that they represent) [73]. Such theoretical neural deficits are not conclusively proven, scientifically, but they can serve as a basis for testable predictions at both the behavioural and the biological levels. In other words, the core features of DD may be best understood in terms of deficits at the biological and cognitive [74]. Identification of risk profiles at the genetic, neurobiological, and cognitive levels, will make it possible to maximize the efficacy and efficiency of early interventions and reduce individual suffering as well as the enormous public health burden caused by developmental deficiencies in numerical knowledge.

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