



Research in Perspective

Contributions of longitudinal studies to evolving definitions and knowledge of developmental dyscalculia

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ABSTRACT

In the last 20 years, longitudinal studies have demonstrated that it is important to attend to the stability of mathematical performance over time as a facet of dyscalculia, that the manifestation of mathematics difficulties changes with development, and that individual differences in cognitive profiles and learning trajectories observed in children with mathematics difficulties implicate differences between dyscalculic and non-dyscalculic subgroups. Intra-individual differences over time, and external factors related to children's learning environments, also contribute to performance trajectories; moreover, these factors may explain the inconsistent performance profiles observed among many students whose difficulty with mathematics emerges later or diminishes over time. Longitudinal studies on DD are also an important tool to elucidate why some children are more responsive to mathematics intervention than others.

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1. Introduction

Longitudinal studies make a unique contribution to our understanding of developmental dyscalculia (DD, or mathematics learning disability (MLD), terms we herein consider synonymous). Although both cross-sectional and longitudinal approaches are useful for describing concurrent cognitive profiles and correlates of DD within or across age groups, only longitudinal studies can reveal the trajectories of mathematics and related skills acquisition without potential confounds of cohort effects. Accordingly, longitudinal studies can delineate the timing of evolving relationships between associated skills at different periods of development, and whether children with

vs. without DD experience alternative pathways to mathematics achievement or delayed but shared pathways. Intervention studies, which are longitudinal by design, may show how students' learning environments affect these trajectories and which cognitive, social, or environmental determinants interact with intervention effects. Thus, longitudinal studies inform the development of theories of change in mathematics learning. Here we review some of the primary contributions longitudinal studies have made to recent efforts to define DD and how those contributions inform best practices for prevention and remediation of DD.

2. DD vs. other forms of mathematics difficulties

Defining DD is challenging (Box 1). When identifying if students qualify for special education services for mathematics instruction, knowledge of whether they have DD or another form of mathematics difficulty may be unnecessary; but this knowledge is essential for

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Box 1—Why is developmental dyscalculia so difficult to define?

- The term “developmental dyscalculia” (DD) does not refer to all forms of mathematics difficulty seen in childhood.
- Some children phenotypically show features of DD at some point of development, but their difficulties are not linked to a DD genotype; this is common among children with inadequate home or school learning environments linked to poverty.
- DD is considered a mathematics disorder, and mathematics encompasses a very broad range of cognitive abilities, skills, and strategies influenced further by innate, environmental, cognitive, and social factors.
- DD or some components of DD are likely to represent an extreme on a continuum of skills and abilities; therefore, it may be difficult to establish boundaries between typical development and DD, and knowledge of typical mathematics development and function can inform studies of DD. However, DD or some components of DD appear qualitatively distinct from other forms of low mathematics achievement, *limiting* the extent to which we can generalize findings from studies of typical mathematics development to the study of DD.
- Research on DD is increasing, but remains limited compared to research on other learning disabilities, so the knowledge base on which current definitions are based is still emerging.
- Existing research on DD has been fragmented. In view of the lack of universally accepted screening tools for DD or validated “core deficits”, researchers develop and use a range of measures in their studies. These measures vary even when addressing the same construct (such as “counting” or “magnitude comparison”); even standardized test norms vary across countries. Studies replicating previous findings using the same measures, and especially analyzing intervention effectiveness using the same educational programs, have been rare exceptions.
- Across research studies, educational media, and government reports, the terminology used when referring to DD is inconsistent. Math learning disability (MLD) has been used as synonymous with DD (as we do in this article), but also as distinct from DD when MLD is used to refer to the larger category of mathematics difficulties (MD), it is intentionally referring to all children who struggle with math. The emphasis on MD is understandable, given that all such children need our research and educational attention. However, not all these children have the severe, specific disability in math that we refer to herein as DD.

developing theories of *why* children struggle with mathematics and for establishing and testing treatment priorities. A constraint on the depth of our knowledge in this area stems from the paucity of research on DD, particularly relative to research on other learning disorders [12]. A related obstacle is the lack of universal classification criteria for DD, leading to inconsistent composition of DD samples across studies (as reviewed by Butterworth [9,10,11] and Murphy et al. [66]) that sometimes include children with milder or more transient forms of mathematics difficulties. Until recently, assessment-based cut-off scores used to define DD samples were also highly variable and nearly always applied dichotomously (unless contrasted with and without comorbidities; e.g., [75,40]; see Lander et al., this issue). A proposed trichotomous approach [61,26,66] compares children with persistently deficient (DD) or moderately low mathematics achievement (LA) in mathematics to each other

and to typically achieving (TA) peers. Group differences in cognitive profiles to emerge from this approach are not solely quantitative [13,17], and support the notion that DD and mathematics difficulties (MD) are both heterogeneous but are not synonymous [56,76]. However, the boundaries between DD and other forms of MD remain fuzzy, in part because their differences from each other are inconsistent across studies, absent in some studies or in some areas of function, and dependent on competencies being assessed and the ages at which assessments occur (Table 1). Longitudinal studies have enhanced awareness that multiple pathways may lead to DD [49], that DD is just one subset of MD [56], that MD linked to poverty and other poor learning environments may manifest as DD, and that high threshold cut-points can mask DD characteristics in research samples. The implication for clinical and educational practices is that individual and developmental variation should be considered when attempting to diagnose or rule out DD.

3. Diagnostic definitions of DD require a longitudinal perspective

Primary classification systems of developmental disorders, the ICD-10 and the DSM-IV, describe disorders of arithmetic skills in terms of a discrepancy between low arithmetical abilities and overall intelligence level and chronological age, and in particular focus on difficulty acquiring formal arithmetic operations. Although not stated explicitly, these diagnostic criteria require that learning difficulties are evident over a period of time. In view of empirically validated limitations of discrepancy based criteria [20], response-to-intervention (RtI, [38]) models have become favored for confirmatory diagnostics (e.g. [12,37]), but only a few studies have addressed the effects of educational interventions on the persistence of DD (Fig.1 A). Fuchs and colleagues [21] found that about one third of children initially meeting discrepancy criteria for DD no longer met the criteria after 16 weeks of intensive tutoring. However, prevalence rates of DD varied significantly depending on the test used to ascertain their mathematical achievement. This team has since demonstrated that response to intervention varies as a function of whether DD co-occurs with reading disability (RD) [22], depending on the type of intervention employed. For instance, among 3rd graders (8-year-olds) who received tutoring for number combination skills, those with DD but no RD showed greater gains on number combinations when tutoring included word problems, whereas children with DD and RD showed greater gains when number combination tutoring was not presented through word problems. Children with DD and RD showed greater gains when a strategy-use lesson was followed by daily practice, relative to students with DD only, for whom regular practice did not alter effect sizes. These and other findings from Fuchs' lab support the notion of DD $\pm$ RD as distinct subtypes of DD, as was proposed earlier by Geary [24].

Iuculano [39] showed different rates of response to an early intervention program developed in the UK for 2nd graders (6-year-olds) with significantly delayed numerical development. In addition to curriculum based monitoring assessments, these children completed a number sense battery designed to differentiate DD from LA [8]. Only children with LA benefitted from the standard intervention, making age-appropriate gains. However, their performance returned to the level observed in children with DD within three months following the end of the intervention. This means that even children with LA (that is, with less severe MD than in DD) fall behind without additional support and attention, and that children with DD are more resistant than those with LA to responding to at least some standard interventions.

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