



Editorial

Developmental dyscalculia: Fresh perspectives

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ABSTRACT

This issue of Trends in Neuroscience in Education offers some fresh perspectives on developmental dyscalculia. Here we present an overview of different theoretical approaches to identifying and defining developmental dyscalculia, and a consideration of critical measurement and experimental issues. We note a series of important caveats that must be applied when interpreting the existing research base. While there is currently no generally agreed upon *functional* definition of developmental dyscalculia (DD), the papers collected here represent the wide range of educational and research issues that must be considered when applying neuroscience techniques to the study of developmental disorders of number.

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1. Introduction

Mathematical skills are increasingly important if individuals are to thrive in today's technologically-oriented society. However, evidence suggests that many adults in developed societies possess quite immature mathematical abilities. A 2011 Department for Business, Innovation and Skills survey in the United Kingdom found that 49% of the adult population could only attain standards comparable to 11 year-old children in mathematics (whereas 14.9% achieved such standards in literacy). Furthermore, 23.7% of adults reached only the standards typical for 9 year-old children (compared to 7.1% for literacy). As may be expected from these figures, research on mathematical learning problems lags well behind research on literacy problems, and takes longer to affect educational instruction. For example, during the period of 1985–2006 nearly 5 times as many research papers were published on 'dyslexia' compared to 'dyscalculia' [51]. Hence, it is not surprising that there is *no* generally agreed upon *functional* definition of developmental dyscalculia (DD). In fact, conditions which may or may not be equivalent to DD are labelled by many different names (Box 1). Here we provisionally define DD at the widest possible *phenomenological* level. We define it as persistently weak mathematical performance of developmental origin, related to the weakness of some kind(s) of cognitive function(s) and/or representation(s); appearing when *concurrent* motivation to study mathematics and access to appropriate mathematics education is normal. Research suggests that most individuals who are weak in mathematics do *not* have DD. Here, we will consider DD at the levels of behavioural phenomena, cognitive functions and neural underpinnings, pointing to important controversies in research.

1.1. Behavioural phenomena (operational definition)

At the level of *behavioural phenomena* DD is usually defined operationally as a condition where mathematical achievement is (much) lower than average. Criterion validity is typically provided by

standardized mathematical tests. However, mathematics is a collection of various competences, and is not a well-defined skill as in the case of reading. Consequently, the content of different standardized tests of mathematics can differ markedly. For example, some tests may rely on the interpretation of verbal problems, while others rely on calculations with Arabic digits. Test content *always* differs when tests are aimed at different age groups. Thus, different standardized tests do not necessarily measure the same 'kind' of mathematics and/or the same kinds of skills supporting mathematics. This variability affects diagnosis. Further, there is no agreement on the particular threshold or 'cut-off' test score under which a child should be defined as having DD.

If DD is a specific weakness of mathematics, then false positive diagnoses can only be avoided by testing whether other functions are indeed preserved [48]. However, there is no agreement on the kind of non-mathematical control variables which should be selected (e.g. intelligence and/or reading), nor on whether discrepancy between intelligence scores and mathematical test outcomes should be considered [51]. Indeed, while mathematical problems often appear on their own [61,69], they are also frequently co-morbid with other learning problems [43], especially with reading and spelling problems [46,59]. These discrepancies raise important questions concerning whether co-morbid states of DD are as typical (or even more typical) forms of the disorder than 'pure' DD [44]. It is also important to establish whether co-morbid states represent profiles with qualitatively different mathematical impairments relative to pure states; whether they rely on the co-occurrence of independent cognitive impairments; and whether they rely on causal relations between impairments. The theoretical issue of whether co-morbidity is seen as core to the disorder or it is allowed in the definition at all obviously has strong implications for defining DD.

1.2. Prevalence

These uncertainties concerning which behavioural phenomena should be considered central to DD naturally make it difficult to establish prevalence rates for DD. Prevalence studies have used highly

Box 1—Terms used to describe conditions which may or may not be equivalent with DD.

Dyscalculia
 Developmental Dyscalculia (DD)
 Arithmetic-related learning disabilities (AD)
 Arithmetical disability (ARITHD)
 Arithmetic Learning Disability (ALD)
 Mathematical Disability (MD)
 Mathematics Learning Disability (MLD)
 Mathematical Learning Difficulty (MLD)

variable cutoff criteria, ranging from the 3rd to the 25th percentile, and studies differ in whether they have relied on control variables, in which control variables were selected, or whether control variables were considered at all. When control variables are thought to be important for the definition of DD, then prevalence estimates are affected by the intercorrelation of criterion and control variables. Prevalence estimates from 17 studies range between 1.3% and 10.3% (-2 SD to -0.68 SD below the mean in terms of a normal distribution). The mean of these estimates is about 5–6%, and there seem to be no consistent gender differences in DD (see review in [17]; especially Table 1 and Fig. 1). Experimental studies examining the functional basis of DD often ignore prevalence estimates and use very liberal cutoff scores, sometimes selecting children below the 35th (-0.38 SD) and 45th (-0.12 SD) percentiles as representative of low-achievement mathematics groups (see Table 1 in [51]). Such cut-offs include children within the normal range of performance. The extreme variability of children included in different samples means that it is difficult to compare experimental results across DD studies. Hence, in order to be able to differentiate between qualitatively different cognitive profiles, some researchers have classified children fitting various levels of cutoff criteria into different groups (e.g. [25,51]).

1.3. Cognitive functions

This variability with regard to criterion validity (testing instrument, cut-off score and control variables) contributes to the uncertainty about which cognitive function(s) and/or which mental representation(s) is/are affected in DD. One debate concerns whether there are qualitative differences in the cognitive profiles of children with DD [68]. DD may originate from the impairment or weakness of a single cognitive representation or function [64]; it may result from weakness in a constellation of multiple representations/functions, or indeed, it may be an *umbrella term*, denoting mathematical weakness of unrelated and/or variable functional origins [36]. Theories in adult cognitive psychology and cognitive neuroscience typically follow a modular view, preferring to identify a single function underlying a condition like DD. On the other hand, developmental researchers have shown that mathematical weakness appears in many forms. Hence, search for a single underlying cause of DD may not be an optimal strategy. As long as the underlying factors behind the various kinds of mathematical weaknesses are not understood, it is simply not possible to decide whether various weaknesses stem from the same underlying condition.

The literature offers a wide range of cognitive functions which may be impaired in DD. A popular view is that DD is the consequence of the deficit of a core amodal [49] magnitude representation often called the ‘number sense’ [15]. There are various versions of this ‘core deficit’ hypothesis [7,55]. Other researchers relate DD to impaired links between the magnitude representation and number symbols [14,62]; or to suboptimal automatic activation of the magnitude representation [63]. Yet others link DD to impairment in verbal and visual working

memory [6,23,24,31,53,54,77], impairment in spatial processing [60,61], impairment in attentional function [3,30,77], impairment in inhibitory function [5,6,20,77] and impairment in phonological ability [78]. All these different cognitive functions seem to play important roles in mathematics, and hence can be plausibly related to DD.

It has also been proposed that the field should distinguish between *subtypes* of DD depending on children's different mathematical profiles, which may be related to different cognitive impairments. For example, some children show weakness in mathematical fact retrieval (which provides shortcuts in both simple and complex arithmetic; [69]), while others show immature procedural/strategy choices, and others appear to have inefficient visuo-spatial manipulations [1,22,79,80]. Rubinsten and Henik [64] suggested that the term ‘Mathematical Disabilities’ should be used as an umbrella term, while the term ‘DD’ should be reserved for core deficits of the number sense. This suggestion raises the question of whether DD should be conceptualised as representing a quantitative extreme of the cognitive skills associated with mathematical achievement (the tail of the normal distribution), or whether it represents a discontinuous *qualitative* difference between DD and typically developing children.

1.4. Heritability

DD is of *developmental* origin, that is, it is not acquired through mental or physical events experienced by an individual who had age-appropriate mathematical skill during an earlier period of life. Rather, DD seems a deficiency of cognitive development that is inherent to an individual. One suggestion is that such an inherent deficiency has a genetic basis [37,72]. However, even the best-built genetic system needs crucial environmental input to achieve its potential. Hence, it is difficult to exclude the possibility that DD is the result of environmental factors which were not forthcoming at the appropriate time earlier in developmental history. Such factors, for example motivational and emotional factors and/or inadequate teaching, may be absent at the time of diagnosis, but may have contributed to DD *in the past*. That is, inherent developmental problems do not necessarily require genetic explanations but may result from (unknown) suboptimal past environmental inputs.

On the other hand, DD shows familial aggregation, which may be attributed to genetic factors [72]. However, besides genetic factors familial cultural and parental attitudes towards mathematics can probably also explain some familial aggregation effects [76]. In fact, a study of twins found that 49% of monozygotic twins (who share all of their genes) and 32% of dizygotic twins had DD, which points to moderate genetic influence [44]. Similarly, a large-scale twin study concluded that mathematical achievement is influenced moderately by *both* genetic and environmental factors, and that mathematical weakness is the quantitative extreme of the distribution of these factors rather than some kind of discontinuous qualitative difference [38]. Importantly, genetic explanations do not provide evidence for the heritability of an isolated number-specific factor. Various basic cognitive abilities, like overall memory capacity or speed of processing, may be under genetic influence, and all these factors can in turn influence mathematical development. Therefore, in principle, heterogeneous genetic influences on more than one cognitive factor may affect mathematical performance.

1.5. A developmental perspective

A critical issue in developmental disorders is how to define ‘age-appropriate’ mathematical skill (see e.g. [18,28]). Is a diagnosis of DD meaningful if a child has age-appropriate mathematical skills until age 7, but later shows signs of learning disability, even though there is no indication of mental/physical trauma [47]

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