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Chapter 25

Developmental dyscalculia

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INTRODUCTION

Developmental dyscalculia (DD) is a learning disorder affecting the acquisition of school level arithmetic skills, and is characterized by poor arithmetic achievement in the context of normal IQ, schooling, and socioeconomic background. Prevalence estimates suggest that approximately 3–6% of the population suffers from DD (Shalev, 2007), making it roughly as common as dyslexia (a developmental disorder affecting the ability to read in the presence of otherwise normal development), and a high degree of comorbidity between DD and dyslexia is typically observed. The root causes of DD are, however, poorly understood, and research in the field has been hampered by widely varying operational definitions of the disorder, significantly divergent subject selection criteria across studies, and consequently, a high degree of heterogeneity in subject profiles. This chapter outlines the most commonly observed behavioral characteristics of DD, and brings together the results of the currently small group of neuroimaging studies which have investigated the neural bases of the disorder.

BEHAVIORAL CHARACTERISTICS

The most consistently, though not universally, observed behavioral difficulties in DD are slow and error prone learning and retrieval of arithmetic facts from memory, deficits which tend to persist throughout elementary school even in the event of focused intervention (Jordan and Montani, 1997). Additionally, DD is characterized by procedural deficits, such as the perseverant use of immature calculation, problem solving, and counting strategies and delayed progress from finger counting to verbal counting and fact retrieval, from first to second grade (Geary, 2004).

In addition to deficits of fact retrieval, counting, and calculation, several studies suggest that children with DD do not represent and access numerical magnitude information (an approximate or exact understanding of numerical quantity) in the same way as typically developing children do, lending support to the "defective number module" hypothesis of DD (Butterworth, 1999). For example, Geary et al. (1999) observed that children with DD showed lower accuracy than controls during number comparison, particularly so during visual compared to auditory presentation of stimuli. Furthermore, Landerl et al. (2004) found that DD children presented with poorer performance than controls on a range of basic numerical processing tasks including number naming, number comparison, verbal counting, and dot counting. Children with mathematical difficulties have also been shown to perform worse than controls in approximate calculation, a task thought to require manipulation of numerical magnitude representations (Jordan and Hanich, 2003), and adults with DD have been found to exhibit less interference from task-irrelevant numerical magnitude information during tasks requiring them to judge the physical size of Arabic digits (Rubinsten and Henik, 2005). Recent research also suggests that DD is associated with a stronger behavioral distance effect during comparison of both symbolic and nonsymbolic quantities (Mussolin et al., 2010) and for single and double digit numbers (Ashkenazi et al., 2009b).

In support of their contention that DD is primarily a deficit of accessing numerical magnitude information

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through Arabic numerals, Rousselle and Noel (2007) demonstrated that DD children were slower and less accurate than controls during symbolic number comparison but not during nonsymbolic comparison after controlling for processing speed and error rate.

In addition to research investigating numerically specific behavioral deficits in DD, an emerging body of work suggests impairments in spatial attention and spatial working memory may play a role in the etiology of the disorder (Ashkenazi et al., 2009a; Rotzer et al., 2009). However, the logic of a causal link between a generalized deficit in spatial attention or working memory and a domain-specific learning disorder in mathematics remains unclear.

In summary, behavioral deficits in DD center on poor learning and retrieval of arithmetic facts, and difficulties in learning and executing developmentally appropriate procedural strategies for counting and calculation. Recent behavioral research has revealed more basic deficits of numerical processing in DD, including number naming and number comparison. Some debate still exists as to whether DD stems from a deficit in accessing numerical magnitude representations through Arabic digits, or whether the representations themselves are impaired.

NEURAL CHARACTERISTICS

Structural imaging

Studies investigating brain structure in DD have revealed atypical organization of the intraparietal sulcus (IPS). Molko et al. (2003) carried out a morphometric analysis of Turner syndrome (TS) patients with mathematical deficits and revealed abnormal structural organization of the right IPS. In a second study, Molko et al. (2004) supported this finding with voxel-based morphometry (VBM) evidence that TS subjects showed decreased gray matter volume in the left superior temporal sulcus and right IPS. A more recent VBM study revealed reduced gray matter volume in the right IPS in DD children relative to controls (Rotzer et al., 2007).

These results are supported, to some extent, by Rykhlevskaia et al. (2009), who observed reduced gray matter in bilateral superior parietal gyri, intraparietal sulcus, fusiform gyrus, parahippocampal gyrus, and right anterior temporal cortex. It is possible, however, that the less focal results of this study were due to the very liberal selection criteria employed to operationally define DD (either a numerical operations or maths composite standardized score of less than 95). Despite the

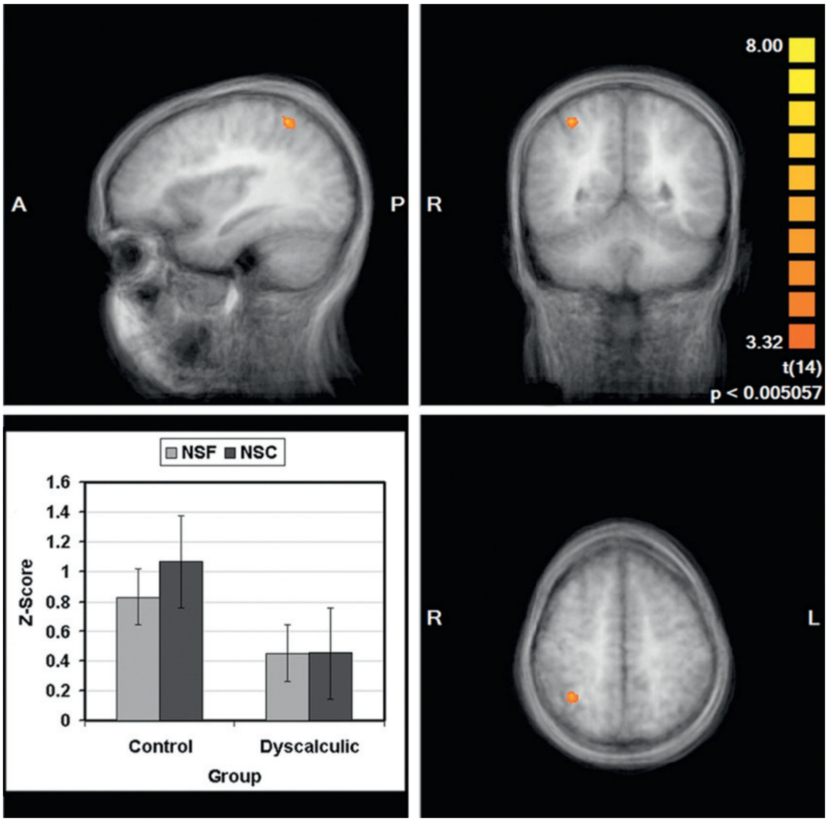

Fig. 25.1. A group x distance interaction in the right intraparietal sulcus during nonsymbolic numerical magnitude comparison. The bar chart shows a classic neural distance effect in typically developing children (i.e., greater activation for small distance (NSC) pairs than large distance (NSF) pairs), but no such distance effect in the dyscalculic children. From Price et al. (2007).

liberal subject selection criteria, this study represents the first attempt to investigate white matter tractography in DD using diffusion tensor imaging (DTI). The results suggest that long range fibers linking the right fusiform gyrus and temporo-parietal white matter were specifically impaired in the DD group.

Taken together these findings suggest that atypical structural development of parietal brain regions, and in particular the right IPS, may undermine the normal development of arithmetic abilities. It is important to note, however, that TS patients present with mathematical difficulties as part of a broader genetic syndrome, and this should be taken into account when generalizing the results of some of these studies to "pure" DD.

Functional imaging

As well as studies investigating the structural organization of brain regions thought to support numerical processing, neuroimaging research is increasingly focusing on how these regions function in DD subjects during the performance of numerical tasks. In a functional magnetic resonance imaging (fMRI) study, Molko et al. (2003) reported that while control subjects showed increased activation in the bilateral IPS as the difficulty of exact calculations increased, TS subjects did not show the same modulation of IPS activation, a pattern also observed in females with fragile X syndrome in calculation verification tasks (Rivera et al., 2002).

To date, only a handful of studies have investigated the neural correlates of numerical magnitude processing in children with pure DD rather than wider genetic syndromes. Kucian et al. (2006) investigated the neural basis of numerical magnitude processing in DD in an fMRI experiment using approximate and exact calculation conditions and a magnitude comparison task (i.e, comparing small sets of different objects). The results revealed similar activation patterns between groups, albeit generally weaker and more diffuse, for DD and control groups in all conditions. When Kucian et al. focused their analyses on a region of interest in the IPS, rather than the whole brain level, they found that DD subjects showed significantly weaker activation relative to controls in the left IPS, and a nonsignificant trend in the same direction in the right IPS, during approximate calculation and number comparison.

Using fMRI to investigate the neural correlates of nonsymbolic numerical magnitude processing in children with DD, Price et al. (2007) employed a numerical comparison paradigm which tested for the effects of numerical distance (distance between the two numbers being compared) on brain activation. This study revealed that when the two numerosities being compared were relatively close together compared to relatively far apart (e.g., 5–6 vs. 5–9), typically developing children showed greater activation in the right IPS and right fusiform gyrus. Children with DD, on the other hand, showed no such increase in brain activation in response to increasing numerical processing demands (Fig. 25.1) leading the authors to suggest that DD may be associated with the disruption of the brain circuitry supporting the representation of numerical magnitude. Furthermore, a recent fMRI study found that DD children did not show the same modulation of brain activation during a symbolic (Arabic numerals) number comparison task as typically developing children, who showed increased activation in the right IPS and left superior parietal lobes for comparisons with small relative to large numerical distances (Mussolin et al., 2009). These results fit well with recent DTI evidence suggesting that white matter tracts linking the right fusiform gyrus and parietal regions may be compromised in DD (see Rykhlevskaia et al., 2009 below), although the functional relationship between these regions requires further exploration.

In addition, an Event-related brain potential (ERP) study investigated numerical magnitude processing in DD children using symbolic number comparison (Soltesz et al., 2007). This study observed no significant differences in the distance effect at an early time window, but at a later time window the control group showed a nonsignificant distance over right parietal areas, while the DD group showed no such signs. Although nonsignificant, these qualitative differences, consistent with the data from Price et al. (2007) and Mussolin et al. (2009), support the possibility of a right parietal dysfunction in DD. However, a more recent re-analysis of the same data set using principal components analysis revealed a somewhat different pattern of results (Soltesz and Szucs, 2009). In the control group the distance effect was associated with greater negativities in left-hemisphere parietal electrodes, while in the DD group it was the right hemisphere parietal electrodes which showed greater negativity. Additionally, the DD group showed a distance effect in fronto-central electrodes while the control group did not. Thus, the implications of current ERP research for DD remain somewhat unclear and further investigations are necessary.

Although research investigating the neural bases of DD is still limited, the most common finding is that DD is characterized at the brain level by atypical structural properties of the right intraparietal sulcus, and atypical functional modulation of this region during basic numerical processing. DD children show atypical functional activation in the IPS during basic numerical processing whether the task requires the use of symbolic (Arabic digits) or nonsymbolic (sets of objects) stimuli, suggesting that the behavioral deficits in DD may stem not just from an impairment in accessing numerical magnitude representation through Arabic digits, but that the representation itself may be compromised.

CONCLUSIONS

Research on developmental dyscalculia is still in relative infancy when compared to work investigating dyslexia. Behavioral research has revealed a heterogeneous pattern of difficulties, but this variation may be in part attributable to the variation in subject selection across existing studies. Behavioral work has associated DD with deficits in basic numerical magnitude processing and numerical symbol use as well as calculation difficulties, and the still sparse neuroimaging work is beginning to point to an underlying deficit in the representation of numerical magnitude. Further research is required, however, in order to understand the precise nature of that deficit, and its functional relationship with the development of mathematical abilities.

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