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The functional anatomy of single-digit arithmetic in children with developmental dyslexia

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ABSTRACT

Some arithmetic procedures, such as addition of small numbers, rely on fact retrieval mechanisms supported by left hemisphere perisylvian language areas, while others, such as subtraction, rely on procedural-based mechanisms subserved by bilateral parietal cortices. Previous work suggests that developmental dyslexia, a reading disability, is accompanied by subtle deficits in retrieval-based arithmetic, possibly because of compromised left hemisphere function. To test this prediction, we compared brain activity underlying arithmetic problem solving in children with and without dyslexia during addition and subtraction operations using a factorial design. The main effect of arithmetic operation (addition versus subtraction) for both groups combined revealed activity during addition in the left superior temporal gyrus and activity during subtraction in the bilateral intraparietal sulcus, the right supramarginal gyrus and the anterior cingulate, consistent with prior studies. For the main effect of diagnostic group (dyslexics versus controls), we found less activity in dyslexic children in the left supramarginal gyrus. Finally, the interaction analysis revealed that while the control group showed a strong response in the right supramarginal gyrus for subtraction but not for addition, the dyslexic group engaged this region for both operations. This provides physiological evidence in support of the theory that children with dyslexia, because of disruption to left hemisphere language areas, use a less optimal route for retrieval-based arithmetic, engaging right hemisphere parietal regions typically used by good readers for procedural-based arithmetic. Our results highlight the importance of language processing for mathematical processing and illustrate that children with dyslexia have impairments that extend beyond reading.

Introduction

Proficient mathematical cognition is the basis for many routine activities in our daily lives (e.g., keeping track of time or money) and a key factor in children's academic success. Arithmetic, the branch of mathematics concerned with addition, subtraction, multiplication, and division, is especially important in the early stages of math learning. As such, there has been a significant interest in the neural basis of normal mathematical cognition and numerosity (Menon, 2010; Nieder and Dehaene, 2009), as well as its disorders (for review, see Ashkenazi et al., 2013). A model of number processing that integrates brain imaging with behavioral and patient studies has been put forward as the "triple-code model" (Dehaene, 1992; Dehaene and Cohen, 1995; Dehaene et al., 2003). This model specifies that distinct brain regions are assigned to specific systems of representations of numerical information (quantitative, verbal, and visual systems), and their respective contributions vary depending on the task. For example, bilateral parietal cortices have been identified as a locus of quantity representation (Nieder and Dehaene, 2009), and have been shown to elicit greater activity when subjects solve arithmetic problems with more procedural demands such as subtraction (De Smedt et al., 2011) and division (Rosenberg-Lee et al., 2011). Other aspects of mental arithmetic, such as verbal representation of numbers and fact retrieval, have been associated with language functions (i.e., the verbal representation of numbers in the triple-code model) and are thought to be subserved by left hemisphere perisylvian language areas (Dehaene et al., 1999, 2003). Examples of brain imaging studies in support of this include the demonstration that addition of small numbers (Stanescu-Cosson et al., 2000) or well-rehearsed arithmetic facts such as multiplication (Chochon et al., 1999; Lee, 2000; Prado et al., 2007), both of which utilize verbal retrieval, elicit activity in language areas, including left hemisphere angular and inferior frontal regions (for review see Dehaene et al., 2003). Grabner et al. (2007) have shown that adults with higher mathematical competence have stronger activation of the left angular gyrus while solving multiplication problems, suggesting their stronger reliance on language-mediated processes for multiplication. Grabner et al. (2009) also showed stronger activation of the left angular gyrus while solving arithmetic problems for which participants reported using fact retrieval rather than procedural strategies.

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These studies demonstrate an important role for left hemisphere language areas in specific aspects of arithmetic and dovetail with earlier behavioral studies, which have revealed a relationship between phonological awareness (i.e., the ability to isolate and manipulate the sounds of words) and computation of arithmetic problems solved through verbal fact retrieval (i.e., small addition and multiplication, which are more likely to be retrieved), but not subtraction and division problems, which are typically solved through procedural strategies. Studies in typically developing children have identified a relationship between phonological awareness and later mathematical skill development (Simmons and Singleton, 2008). For example, Hecht et al. (2001) found that phonological awareness from a range of measures (including phonological memory and the rate of access to phonological codes) was the best long-term predictor of mathematical competency (measured by untimed computation and timed small-digit arithmetic) in the later elementary school years. De Smedt et al. (2010) found a positive correlation in fifth graders between phonological awareness skills (measured by a phoneme elision task) and speed and accuracy on an arithmetic verification task (in which subjects determine whether an arithmetic problem is correct or incorrect). Importantly, this relationship was found to be specific to arithmetic problems likely to be solved through retrieval mechanisms, suggesting an important connection between phonological awareness and arithmetic fact retrieval.

These findings have led to the idea that developmental dyslexia, a reading disability characterized by core weakness in reading and phonological awareness, is concomitant with weaknesses in arithmetic (De Smedt and Boets, 2010; Simmons and Singleton, 2008). Developmental dyslexia is a common learning disability, neurobiological in origin, that is characterized by poor reading that cannot be accounted for by low intelligence (Lyon et al., 2003; Peterson and Pennington, 2012). It is marked by difficulties in recognizing and decoding single words, the latter thought to be due to a deficit in phonological awareness. Many students with dyslexia are also diagnosed with math disability, and incidence rates of deficits in both have been reported to be as high as 50% (Lewis et al., 1994). Further, candidate susceptibility genes for dyslexia (e.g., ROBO1) appear to contribute to not only dyslexia but also its correlated phenotypes like math difficulties (Mascheretti et al., 2014). Interestingly, even dyslexic children with scores in the normal range in mathematics (assessed via standardized tests) show subtle deficits in arithmetic performance (Simmons and Singleton, 2008). For example, they demonstrate decreased accuracy and increased reaction times compared to controls on multiplication problems typically solved via verbal fact retrieval strategy (Boets and De Smedt, 2010). Also, the characteristic 'operation effect' seen in typically developing children and adults (Barrouillet et al., 2008; Delazer et al., 2003), in which addition and multiplication problems are solved more quickly than subtraction and division problems, is absent in these struggling readers. Boets and De Smedt (2010) suggest that dyslexic children are unable to implement the same time-saving strategies of verbally retrieving arithmetic facts from memory that are characteristic of typically developing children.

Differences in arithmetic fact retrieval have also been found in adults with developmental dyslexia compared to typical readers (Simmons and Singleton, 2008). For example, dyslexic college students exhibit slower reaction times compared to age-matched controls in solving small addition and multiplication problems, with intact performance on subtraction and measures of basic numerical and spatial processing, including symbolic number comparison and mental rotation (Gobel and Snowling, 2010). Another study of dyslexia in young adults reported slower reaction times compared to controls when solving single-digit arithmetic problems (De Smedt and Boets, 2010). These researchers also found a significant correlation between phonological awareness skills and the frequency of reported use of retrieval strategies during arithmetic and argue that individuals with dyslexia, despite years of experience, have subtle behavioral deficits isolated to simple arithmetic processing attributed to their weaknesses in language-based skills, specifically phonological awareness.

Together, these behavioral findings demonstrate that retrieval-based arithmetic skills rely on mechanisms related to phonological awareness, and that individuals with reading disability (who typically have deficits in phonological awareness) exhibit a weakness in retrieval-based arithmetic even without meeting diagnostic criteria for math disability. These observations lead to the prediction that left hemisphere perisylvian brain regions are compromised in children with dyslexia during the solving of arithmetic problems via retrieval. While the neural basis for reading and phonological awareness has been studied extensively in dyslexia using brain imaging technology (Linkersdörfer et al., 2012; Maisog et al., 2008; Richlan et al., 2013), there have been no such investigations into arithmetic problem solving in dyslexia. Interestingly, Prado et al. (2011) demonstrated direct anatomical convergence for brain areas involved in multiplication of small numbers and phonological processing of single words in typical adults, suggesting a shared neural representation for this type of retrieval-based arithmetic and language processing involving the retrieval of phonological codes. These language areas seem to be underutilized by children with weaknesses in arithmetic fluency (De Smedt et al., 2011) but have not been previously studied in children with impaired reading such as in dyslexia. A better understanding of the neural representation of numerical processing in dyslexia is of theoretical importance, as it provides insights into the neural basis for dyslexia's behavioral manifestations (which includes some weaknesses in specific aspects of arithmetic even in the absence of a formal diagnosis of math disability) and potentially provides an explanation for why a diagnosis of math disability occurs more often in children who are diagnosed with dyslexia than those who are normal readers (Barbaresi et al., 2005; Katusic et al., 2001; Lewis et al., 1994).

Here, we examined the neural basis of single-digit addition and subtraction in children with pure developmental dyslexia (i.e., impaired single word reading and phonological awareness skills while maintaining normal performance on a standardized measure of calculation compared to age-matched typical readers). Based on prior work (Grabner et al., 2007, 2009; Prado et al., 2011), we expected that brain regions involved in retrieval-based arithmetic such as multiplication, e.g. left angular gyrus (AG), middle temporal gyrus (MTG), and inferior frontal gyrus (IFG), would be affected in children with dyslexia during other retrieval-based arithmetic (e.g. addition of small numbers), such as the left angular gyrus (AG), middle temporal gyrus (MTG), and inferior frontal gyrus (IFG), would be affected in children with dyslexia during other retrieval-based arithmetic (e.g. addition of small numbers). On the other hand, we predicted that right hemisphere parietal regions underlying nonverbal representation would not be affected in children with dyslexia when performing primarily procedural-based arithmetic (subtraction of small numbers). We used a factorial design to test for the effects of arithmetic operation (addition versus subtraction), diagnostic group (dyslexic versus non-dyslexic), and their interactions.

Material and methods

Subjects

The subjects were a subset of a group of children participating in a larger study on reading, reading disability, and reading development (Evans et al., 2013; Krafnick et al., 2011, 2014; Olulade et al., 2013a,b). Subjects with developmental dyslexia had a documented history of their reading disability, and most attended a school that specializes in the teaching of children with learning disabilities. To be included in this study, the dyslexic children had to have a standard score of less than 92 (30th percentile) on either real word or pseudoword reading accuracy. This cut-off is consistent with prior studies (Bruck, 1992; Krafnick et al., 2014; Olulade et al., 2013a) and ensured that we would have a continuum of skills when the dyslexics were combined with the non-dyslexics for later correlation analysis. Non-dyslexic control subjects were recruited from within the same geographic region in