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Research report

Children with mathematical learning disability fail in recruiting verbal and numerical brain regions when solving simple multiplication problems

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ABSTRACT

Greater skill in solving single-digit multiplication problems requires a progressive shift from a reliance on numerical to verbal mechanisms over development. Children with mathematical learning disability (MD), however, are thought to suffer from a specific impairment in numerical mechanisms. Here we tested the hypothesis that this impairment might prevent MD children from transitioning toward verbal mechanisms when solving single-digit multiplication problems. Brain activations during multiplication problems were compared in MD and typically developing (TD) children (3rd to 7th graders) in numerical and verbal regions which were individuated by independent localizer tasks. We used small (e.g., 2×3) and large (e.g., 7×9) problems as these problems likely differ in their reliance on verbal versus numerical mechanisms. Results indicate that MD children have reduced activations in both the verbal (i.e., left inferior frontal gyrus and left middle temporal to superior temporal gyri) and the numerical (i.e., right superior parietal lobule including intra-parietal sulcus) regions suggesting that both mechanisms are impaired. Moreover, the only reliable activation observed for MD children was in the numerical region when solving small problems. This suggests that MD children could effectively engage numerical mechanisms only for the easier problems. Conversely, TD children showed a modulation of activation with problem size in the verbal regions. This suggests that TD children were effectively engaging verbal mechanisms for the easier problems. Moreover, TD children with better language skills were more effective at engaging verbal mechanisms. In conclusion, results suggest that the numerical- and language-related processes involved in solving multiplication problems are impaired in MD children.

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1. Introduction

Several alternative accounts advance that mathematical learning disability (MD or dyscalculia) stems from a specific impairment in basic numerical processing. The "Core Deficit Theory" (Wilson & Dehaene, 2007) argues that MD is a deficit in the approximate number sense, whereas the "Numerosity Coding" theory suggests that the deficit lies in the ability to represent numerosities in a discrete and precise way (Butterworth, 2010). In support of a primary impairment in numerical processing, MD children show poor number acuity (i.e., the ability to compare collections of items based on their numerical quantity) compared to same age peers (Mazzocco, Feigenson, & Halberda, 2011; Moeller, Neuburger, Kaufmann, Landerl, & Nuerk, 2009; Piazza et al., 2010). Evidence from structural and functional neuroimaging studies also supports a core deficit in numerical processing. First, MD children have reduced gray matter in the right intra-parietal sulcus (IPS) (Rotzer et al., 2008), an area thought to be involved in the processing of both symbolic and non-symbolic numerical information (Ansari, 2008; Nieder & Dehaene, 2009; Piazza, Izard, Pinel, Le Bihan, & Dehaene, 2004; Pinel, Dehaene, Rivière, & LeBihan, 2001). Second, the majority of functional neuroimaging studies using non-symbolic tasks show abnormalities in IPS in MD children (Kaufmann et al., 2009; Price, Holloway, Räsänen, Vesterinen, & Ansari, 2007). Neurofunctional differences in MD children have also been observed in symbolic tasks. For example, in a single-digit comparison task, MD children exhibited weak involvement of bilateral IPS, with no modulation of activations due to the distance between the two digits (Mussolin et al., 2010). Such a modulation is typically present in adults and children without specific math impairments (Mussolin et al., 2010; Pinel et al., 2001). All together, these studies indicate that the quality of numerical representations supported by the IPS are crucial for math skill and may be central to math disability.

A small number of imaging studies comparing typically developing (TD) to MD children have further suggested that altered IPS processing might also underpin impaired performance in arithmetic tasks. A study examining addition showed that MD children had weaker activations in the bilateral IPS and middle and inferior frontal gyri for an approximate condition, whereas no group differences were observed for an exact condition (Kucian et al., 2006). The authors argued that the impairment in MD children may lie in the evaluation of numerical distance, but not in counting or fact retrieval mechanisms. In contrast to the wide age range studied in Kucian et al. (2006), Davis et al. (2009) tested exact and approximate addition problems within third graders. Stronger activations for MD children were observed in the right insula and precentral gyrus, suggesting the possible use of immature finger counting strategies to solve the task (Jordan & Montani, 1997). Davis et al. (2009) also showed greater activation for the MD children during approximate calculation in the right inferior parietal lobe; an area associated with processing spatial information (Pinel et al., 2001). In summary, studies on arithmetic are broadly consistent with the results on numerical processing, suggesting alterations in the parietal cortex in MD children.

As suggested by De Smedt, Holloway, and Ansari (2011), such an impaired system of numerical representations in the IPS could prevent MD children from moving toward more efficient retrieval strategies for solving arithmetic problems over the course of development. In TD children, operations such as single-digit addition and multiplication are thought to become familiar with schooling so that by adulthood these do not require computation but are retrieved from long-term verbal memory (Ashcraft, 1992; Groen & Parkman, 1972; Parkman & Groen, 1971). MD children, however, are less accurate and slower when retrieving the solutions to single-digit arithmetic problems (Geary, 1993; Geary & Hoard, 2001; Shalev & Gross-Tsur, 2001) probably because they use less efficient and immature calculation strategies (Jordan & Montani, 1997). This is consistent with the results of two recent neuroimaging studies. First, De Smedt et al. (2011) found that, in TD children, the IPS was more activated during larger addition problems (thought to mostly depend upon calculation mechanisms) than during smaller addition problems (thought to mostly depend upon retrieval). Conversely, the authors showed that MD children failed to modulate brain responses in the right IPS based on problem size, suggesting that they rely on numerical mechanisms even for small problems (and thus may fail to use retrieval mechanisms). Second, Ashkenazi, Rosenberg-Lee, Tenison, and Menon (2012) also manipulated arithmetic complexity to study the neural bases of single-digit addition in MD and TD children. The authors confirmed that MD children had reduced sensitivity to complexity in bilateral IPS and superior parietal lobules (SPLs), suggesting that all problem types engage calculation mechanisms. However, this paper also reported a weaker response to complexity for MD children in the left middle temporal gyrus (MTG). Because the left MTG could play an important role in retrieving verbally stored arithmetical facts (Prado, Mutreja, & Booth, 2014; Prado et al., 2011), these findings suggest that MD children might not be able to store arithmetic facts in memory as effectively as TD children. Indeed, a number of behavioral studies have highlighted the role of verbal competences, such as phonological awareness, as unique predictor of later mathematical performance, in particular for multiplication problems (De Smedt, Taylor, Archibald, & Ansari, 2010; Hecht, Torgesen, Wagner, & Rashotte, 2001). Because the problem and the correct answer need to be present simultaneously in short-term memory to be stored as long-term verbal representations (Geary, 1993), children struggling with the manipulation of numerical quantities would not be able to create such associations. It follows that the IPS impairments observed in MD might be associated with impaired representation of math facts in verbal regions of the MTG.

The aim of this study was to investigate whether MD children differ from typical children in their reliance on both numerical and verbal mechanisms when retrieving arithmetic facts. Although the neural bases of single-digit subtraction and addition have been compared between MD and TD children (Ashkenazi et al., 2012; De Smedt et al., 2011), we chose to examine single-digit multiplication because these problems are thought to be retrieved from verbal memory whereas subtraction and addition might rely more on calculation procedures (Fayol & Thevenot, 2012). We also manipulated