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Left fronto-parietal white matter correlates with individual differences in children's ability to solve additions and multiplications: A tractography study

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ABSTRACT

Functional neuroimaging data have pointed to the activation of a fronto-parietal network during calculation tasks, the activity of which is modulated by arithmetic operation and arithmetical competence. As the cortical brain regions of this network are distant, it is crucial to investigate the white matter connections between them and to examine how these connections are related to different arithmetic operations and individual differences in arithmetical competence. By using diffusion tensor imaging (DTI) tractography in eighteen 12-year-olds, we tested whether white matter pathways connecting these distant regions were related to children's arithmetical competence and how this association was modulated by operation. For each child, we delineated the three subcomponents of the arcuate fasciculus, a bundle of pathways linking frontal and temporo-parietal regions that are commonly active during calculation tasks. Fractional anisotropy in the left anterior portion of the arcuate fasciculus was positively correlated with addition and multiplication, but not with subtraction and division, suggesting a specific role of this left anterior segment in the solution of those problems that are expected to be solved with fact retrieval. The observed correlation was not explained by age, intelligence and working memory. Follow-up control analyses using different types of reading measures revealed that the observed correlation only disappeared when measures that draw heavily on phonological processing, such as non-word reading, were controlled for, suggesting that the association between the left arcuate fasciculus-anterior and addition/multiplication reflects the involvement of phonological processing. These results are the first to demonstrate that individual differences in fronto-parietal white matter are associated with arithmetical competence in typically developing children of a very narrow age range and indicate that this association is modulated by arithmetic operation.

Introduction

Arithmetic is crucial in our daily life and represents an important part of the children's curriculum at school. At behavioral level large individual differences in learning arithmetic have been observed (Dowker, 2005). More recently, neuroimaging studies have started to unravel the neural correlates of these individual differences. Functional MRI studies in adults have revealed the activation of a fronto-parietal network during calculation tasks (Arsalidou and Taylor, 2011, for a review) and a similar fronto-parietal network has been observed in children (Kaufmann et al., 2011, for a review). Recent developmental fMRI data indicate that the activity in this network is modulated by arithmetic operation and individual differences in arithmetical competence (De Smedt et al., 2011). As the cortical brain regions of this network are distant, it is crucial to investigate the white matter connections between them and to examine how these connections are related to arithmetic operation and individual differences in arithmetical competence. Diffusion tensor imaging (DTI) is a powerful technique for studying these white matter connections and has been widely used to study brain–behavior relationships in children, particularly in the fields of reading (e.g., Beaulieu et al., 2005) and working memory (e.g., Nagy et al., 2004). DTI studies in arithmetic are scarce (but see Tsang et al., 2009; van Eimeren et al., 2008, 2010). To obtain more details about the neuro-anatomical correlates of arithmetic in children, the present study used DTI tractography to examine the association between fronto-parietal white matter and individual differences in children's arithmetical competence and how this association is modulated by operation.

Our specific attention to arithmetic is guided by different observations. First, arithmetic represents an important part of the children's curriculum at school and is a critical building block for subsequent mathematical skill development (Kilpatrick et al., 2001). By focusing on school-taught skills, such as arithmetic, the current study also adds to a growing body of data that include neural measures of school-

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taught performance, thereby contributing to the goals of the emerging field of Educational neuroscience (e.g., Goswami and Szucs, 2011). Second, a growing body of evidence points to deficits in arithmetic fact retrieval, or difficulties in direct retrieval of the answer from long-term memory, as a core deficit in children with mathematical learning disabilities or dyscalculia (e.g., Geary, 2004, 2010; Jordan et al., 2003). Lastly, most of the existing developmental behavioral (Geary, 2004, 2010; Jordan et al., 2003) and neuroimaging data (Arsalidou and Taylor, 2011; Kaufmann et al., 2011) about children's mathematical competence have focused on fact retrieval. As a consequence, the broad behavioral knowledge of arithmetic coupled with on the other hand, an understanding of the activation of the fronto-parietal network during arithmetic has provided ground for the current structural neuro-imaging research about arithmetic.

Over the last two decades, the development of fMRI has greatly increased our knowledge about the brain regions involved in arithmetic. In adults, the ability to solve arithmetic problems relies on a network of both frontal and temporo-parietal brain areas (Ansari, 2008; Arsalidou and Taylor, 2011; Dehaene et al., 2003; Kaufmann et al., 2011; Menon et al., 2000a; Zamarian et al., 2009). The involvement of frontal areas does not appear to be specific to arithmetic processing. These frontal areas are believed to relate to executive functions and have mainly an auxiliary role in the maintenance of intermediate mental operations in working memory (Christoff and Gabrieli, 2000; Fehr et al., 2007; Owen et al., 2005). By contrast, parietal regions such as the bilateral intraparietal sulci (IPS), left angular and supra-marginal gyri, appear to be more specifically related to arithmetic processing. The IPS are found to be important for manipulation of quantity representations (Arsalidou and Taylor, 2011; Dehaene et al., 2003; Menon et al., 2000a). The more language related areas, including the left temporo-parietal cortex (including the angular gyrus, supra-marginal gyrus and posterior temporal cortex) and the left inferior frontal gyrus (IFG), are engaged during the retrieval of verbally stored arithmetic facts (such as the multiplication tables) from long-term memory (Dehaene et al., 2003; Delazer et al., 2003; Prado et al., 2011; Rosenberg-Lee et al., 2011).

Adult fMRI data have shown that the activation in the above-mentioned fronto-parietal network during arithmetic is modulated by operation (e.g., Fehr et al., 2007; Prado et al., 2011; Zhou et al., 2007). More specifically, fMRI data have demonstrated a dissociation between subtraction and multiplication. On the one hand, it has been shown that the IPS is more related to subtraction compared to multiplication (Chochon et al., 1999; Fehr et al., 2007; Kawashima et al., 2004; Lee, 2000; Piazza et al., 2007; Schmithorst and Brown, 2004; Simon et al., 2002). On the other hand, multiplication tasks have been shown to rely more on left temporo-parietal regions linked to verbal processing (Chochon et al., 1999; Delazer et al., 2003; Ischebeck et al., 2007; Jost et al., 2009; Lee, 2000; Prado et al., 2011; Schmithorst and Brown, 2004; Zhou et al., 2007). In line with all these findings in healthy adults, lesion studies with brain-injured patients suffering from difficulties in arithmetic have demonstrated a double dissociation between subtraction and multiplication. In particular, lesions in the left perisylvian cortex resulted in impairments in multiplication but not in subtraction, whereas lesions to regions of the intraparietal cortex were associated with difficulties with subtraction but not with multiplication (e.g., Cohen et al., 2000; Dehaene and Cohen, 1997).

The engagement of different neural networks for different operations likely reflects the use of different strategies (Barrouillet et al., 2008; Campbell and Xue, 2001; Chochon et al., 1999; Grabner et al., 2009; Imbo and Vandierendonck, 2008; Lee, 2000). Additions and multiplications are usually solved by means of highly automated calculation, such as fact retrieval. The left perisylvian cortex (i.e. angular and supra-marginal gyri) is a key region for retrieval of memorized facts from long-term memory (Grabner et al., 2009). Accordingly the left angular and supra-marginal gyri have been put forward as important underlying neural substrates for addition and multiplication (Chochon et al., 1999; Lee, 2000; Rickard et al., 2000). In contrast, subtractions and divisions are more often solved by more quantity-based procedural strategies with the engagement of IPS and the superior parietal lobe (Chochon et al., 1999; Kazui et al., 2000; Lee, 2000).

At behavioral level large individual differences in learning arithmetic have been observed (Dowker, 2005). More recently, neuroimaging studies have started to uncover the neural basis of these individual differences. Menon et al. (2000b) compared a group of perfect performers with a group of non-perfect performers on an arithmetic verification task with simple addition and subtraction. The authors found less activation within the left angular gyrus for perfect performers compared with non-perfect performers. In contrast, Grabner et al. (2007) found that adults of higher mathematical competence recruited to a greater extent the left angular gyrus during multiplication than less competent adults. These findings fit well with results of adult training studies, where young adults were trained for arithmetic problems and subsequently were compared for trained and untrained problems (Delazer et al., 2003, 2005; Grabner et al., 2009; Ischebeck et al., 2006, 2007, 2009). These studies found that increased proficiency with trained problems was associated with decreased activation in frontal areas and IPS and increased activity in the angular gyrus. On the one hand, these training studies show that expertise is associated with a greater involvement of inferior parietal areas (e.g., angular gyrus), which reflects a shift from effortful calculation to result retrieval from memory. On the other hand, expertise is linked to a decrease of activation within frontal brain areas, which reflects a diminished reliance on working memory and attentional resources.

Compared with the number of published studies investigating the neural correlates of arithmetic in healthy adults and patients, relatively few investigations have been performed with children. Moreover, data from studies of arithmetic processing in children have been less consistent. Most of the existing developmental studies have examined brain activation only during small additions. Available findings from these studies suggest that like adults children activate a fronto-parietal network during calculation tasks (Ansari et al., 2005; Ansari and Dhital, 2006; Davis et al., 2009; Kawashima et al., 2004; Kucian et al., 2008; Meintjes et al., 2010, for a recent review see Ashkenazi et al., 2013). Predominantly activations in prefrontal and inferior parietal brain regions have been observed. However, direct comparisons between adults and children revealed significant differences in the level of activations in frontal and parietal cortices. In particular, with experience and learning, there is decreased dependence on the prefrontal cortex and greater reliance on posterior parietal regions, including IPS (Ansari and Dhital, 2006; Cantlon et al., 2006; Davis et al., 2009; Kawashima et al., 2004). To the best of our knowledge, only one fMRI study specifically investigated the effect of arithmetic operation on brain activity in children (De Smedt et al., 2011). These authors examined the brain response to addition and subtraction in children aged 10–12 years. Commensurate with adult data, subtractions activated a fronto-parietal network, including IPS. Different from the adults, however, the left hippocampus rather than the (left) angular gyrus was more active during addition than during subtraction. The authors suggested that this region would especially be important in arithmetic for those problems that could be expected to be solved by fact retrieval, at least in the early stages of learning to retrieve arithmetic facts. This is in line with data by Cho et al. (2011, 2012), who investigated neurodevelopmental changes associated with increased use of fact retrieval strategies in 7- to 9-year-old children. They demonstrated that increased use of retrieval strategies in young children was associated with greater activation of prefrontal (i.e. left ventrolateral prefrontal and bilateral dorsolateral prefrontal cortices) and hippocampal regions. Consistent with this, Rivera et al. (2005) reported that the fronto-parietal arithmetic network in children is subject to age-related changes due to a strategy shift from effortful procedures to memory-based problem-solving with age. In particular, their developmental data