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Prospective relations between resting-state connectivity of parietal subdivisions and arithmetic competence

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ABSTRACT

The present study investigates the relation between resting-state functional connectivity (rsFC) of cytoarchitectonically defined subdivisions of the parietal cortex at the end of 1st grade and arithmetic performance at the end of 2nd grade.

Results revealed a dissociable pattern of relations between rsFC and arithmetic competence among subdivisions of intraparietal sulcus (IPS) and angular gyrus (AG). rsFC between right hemisphere IPS subdivisions and contralateral IPS subdivisions positively correlated with arithmetic competence. In contrast, rsFC between the left hIP1 and the right medial temporal lobe, and rsFC between the left AG and left superior frontal gyrus, were negatively correlated with arithmetic competence. These results suggest that strong inter-hemispheric IPS connectivity is important for math development, reflecting either neurocognitive mechanisms specific to arithmetic processing, domain-general mechanisms that are particularly relevant to arithmetic competence, or structural 'cortical maturity'. Stronger connectivity between IPS, and AG, subdivisions and frontal and temporal cortices, however, appears to be negatively associated with math development, possibly reflecting the ability to disengage suboptimal problem-solving strategies during mathematical processing, or to flexibly reorient task-based networks. Importantly, the reported results pertain even when controlling for reading, spatial attention, and working memory, suggesting that the observed rsFC-behavior relations are specific to arithmetic competence.

1. Introduction

Early math skills are a robust predictor of academic success, employment, physical and mental health, arrest, and incarceration (Bynner and Parsons, 1997, 2006; Duncan et al., 2007). However, many individuals are 'functionally innumerate', lacking the basic numerical and mathematical skills to function effectively in modern society (DfES, 2005; NCES, 2007).

Behavioral research suggests a set of core foundational competencies that underlie development of math skills, specifically, the processing of nonsymbolic (i.e., sets of dots) and symbolic (i.e., Arabic digits) numerical magnitude (Bugden and Ansari, 2011; De Smedt et al., 2009; Halberda et al., 2008). A reliable set of neural substrates are associated with these foundational competencies. First, the intraparietal sulcus (IPS) supports the processing of numerical magnitude in typically developing individuals (Cantlon et al., 2006; Holloway et al., 2010; Piazza et al., 2007) and is structurally and functionally atypical in individuals with math learning disabilities (Mussolin et al., 2009; Price et al., 2007; Ranpura et al., 2013). A number of studies suggest that the right hemisphere IPS is particularly involved in the processing of nonsymbolic magnitudes while the left IPS develops specialization for processing symbolic magnitudes (Ansari, 2008; Holloway et al., 2010). Second, the left angular gyrus (AG) appears to play a role in the processing of symbolic numbers (Ansari, 2008; Holloway et al., 2010; Price and Ansari, 2011) and the retrieval of arithmetic facts from memory (Delazer et al., 2005; Grabner et al., 2009a). Thus, two circumscribed regions of the parietal cortex have been reliably identified whose function during nonsymbolic/symbolic magnitude processing (IPS) and symbolic/arithmetic processing (AG) appears to be related to math development.

While structural and functional integrity of these regions is associated with the development of math competence, focus on isolated cortical regions may be insufficient for linking brain function to cognition. Instead, attention must be paid to the connectivity between brain regions (Bressler and Menon, 2010). Task-independent,

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resting-state functional connectivity (rsFC) analyses can be advantageous over task-based functional connectivity for at least two reasons. Firstly, task-related connectivity patterns may be a product of incidental task demands (e.g., visual stimulation in a magnitude comparison task or response selection during mental arithmetic) that vary dramatically across experimental paradigms. rsFC, on the other hand, is thought to measure intrinsic connectivity of brain regions that have developed a functional relationship through a history of co-activation (Dosenbach et al., 2007; Fair et al., 2007). As such, rsFC can provide important insights into behaviorally relevant functional brain architecture independent of transient task demands. Secondly, individual differences in network connectivity during a task could be a function of intrinsic and task-specific behavioral differences in cognitive strategies, neural differences, or both. rsFC is particularly useful in avoiding these confounding factors, especially in the study of atypically developing individuals with learning difficulties, or even performance or test anxiety, when task administration might not be optimal. To the best of our knowledge, there is also no consensus on which numerical or mathematical task is optimal in capturing individual and group differences in functional brain organization.

A further advantage of rsFC is that being task-independent, it can be easily replicated methodologically and compared across studies. rsFC can provide important insights into the functional organization of the brain in ways that complement information yielded by investigating task-based functional connectivity (Cole et al., 2010; Fox and Raichle, 2007), and thus represents a potentially informative method to probe the neural mechanisms underlying math development. Recently, a large-scale analysis of task-based and resting-state fMRI data from over 400 subjects in the Human Connectome Project database, Shah et al. (2016) found systematic differences in group-mean functional connectivity between task and rest, but also across different tasks. Crucially, they also found preserved individual differences in functional connectivity during task and rest, and between different tasks (Shah et al., 2016). The utility of rsFC in elucidating possible biomarkers associated with reading difficulties has been demonstrated by several studies in individuals with (Schurz et al., 2015) and without dyslexia (Koyama et al., 2010, 2011, 2013; Zhou et al., 2015), suggesting a strong potential for rsFC studies to contribute to the understanding of typical and atypical development in alternative academic domains, such as math. These findings further support the validity of using rsFC measures as a complementary approach to task-based neuroimaging in the investigation of individual differences in behaviorally relevant functional connectivity.

Several studies have investigated task-based functional connectivity during numerical and mathematical processing (for a review see Moeller et al., 2015), indicating an important role for a network of frontal and parietal regions. Number related networks have also been identified using rsFC. For example, Abboud et al. (2015) used seed regions in the inferior temporal gyrus (ITG), derived from a number processing task to show rsFC between the right ITG and bilateral parietal and prefrontal cortices. In contrast, a letter-related region in the left ITG showed rsFC patterns with a left lateralized network of regions typically associated with language processing. Those results suggest that a functional network related to numerical processing can be identified using rsFC.

However, to the best of our knowledge, only four studies have examined the relation between rsFC and math development. Supekar et al. (2013) found that rsFC between the hippocampus and frontal and temporal brain regions predicted response to arithmetic tutoring in third grade children. In another sample of third grade children, Jolles et al. (2016b) found that rsFC between the IPS, prefrontal cortex, ventral temporal-occipital cortex, and hippocampus strengthened after arithmetic tutoring, and was correlated with individual performance gains. They also found that the rsFC of angular gyrus did not predict response to tutoring. Subsequently, Evans et al. (2015) showed that rsFC between regions in the fusiform gyrus, IPS, frontal, and prefrontal cortex predicted gains in math performance over a six year period. Most recently, Jolles et al. (2016a) reported hyper-connectivity between the IPS and bilateral frontal and parietal regions in children with mathematical learning difficulties. In sum, those studies which have investigated rsFC in the context of mathematical or numerical processing suggest an important role for multiple networks, often involving prefrontal, medial and inferior temporal, and parietal regions.

While the majority of neuroimaging studies investigating numerical and mathematical cognition refer to the IPS and AG as unitary cortical regions, cytoarchitectonic mapping studies suggest the IPS can be divided into hIP1, hIP2, and hIP3, and AG can be divided into anterior (PGa) and posterior (PGp) portions (Caspers et al., 2006; Choi et al., 2006), and that these subdivisions show distinct patterns of functional and structural connectivity (Uddin et al., 2010). Furthermore, a recent study suggests that these subdivisions are functionally heterogeneous during the performance of mental arithmetic (Wu et al., 2009). It is possible that treating the IPS and AG as unitary cortical areas masks nuanced patterns of functional connectivity that relate to math competence in differing ways. In summary, of the four studies relating rsFC to math performance, only two (Jolles et al., 2016a,b) used anatomically defined seed regions (left and right IPS), and no study to date has examined the relation between math achievement and rsFC of cytoarchitectonic subdivisions of key parietal regions.

To address this, the present study examines the relation between rsFC of cytoarchitectonically defined parietal subdivisions and the whole brain at the end of 1st grade, and calculation performance at the end of 2nd grade. We focus our analyses on subdivisions of the IPS and AG as two regions widely reported as being associated with the development of math competence (Ansari, 2016; Dehaene et al., 2003). We also further examine the extent to which our results are specific to arithmetic competence, given that the IPS is also involved in attention (Anderson et al., 2010) and working memory (Bray et al., 2015; Pessoa et al., 2002), and the angular gyrus is involved in reading and language (Church et al., 2011; Meyler et al., 2007; Price, 2000; Seghier, 2012). In so doing, this is the first study to our knowledge that investigates the prospective relation between intrinsic functional connectivity of anatomically defined parietal subdivisions and math achievement.

2. Methods

2.1. Subjects

The present study initially comprised 60 typically developing 1st grade children who were part of an ongoing longitudinal study on the development of reading skills, and for whom standardized measures of math achievement were available at the end of 2nd grade. Initial exclusion criteria included known and uncorrected visual impairment, hearing impairment of at least 25 dB loss in either ear, previous diagnosis of intellectual disability, history of neurological disorders including epilepsy, spina bifida, cerebral palsy, and traumatic brain injury, current or previous diagnosis of an autism spectrum disorder, parental report of significant symptoms of a severe psychiatric diagnosis including major depressive, bipolar, or conduct disorders, and treatment with any antipsychotic medication – with the exception of stimulant medications for attention-deficit hyperactivity disorder (ADHD). Two children in the current sample met the criteria for ADHD. No children met the criteria for oppositional defiant disorder, adjustment disorder, and mild depression.