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Review

Drawing connections between white matter and numerical and mathematical cognition: A literature review

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ABSTRACT

In this review we examine white matter tracts that may support numerical and mathematical abilities and whether abnormalities in these pathways are associated with deficits in numerical and mathematical abilities. Diffusion tensor imaging (DTI) yields indices of white matter integrity and can provide information about the axonal organization of the brain. A growing body of research is using DTI to investigate how individual differences in brain microstructures relate to different numerical and mathematical abilities. Several tracts have been associated with numerical and mathematical abilities such as the superior longitudinal fasciculus, the posterior segment of the corpus callosum, inferior longitudinal fasciculus, corona radiata, and the corticospinal tract. Impairments in mathematics tend to be associated with atypical white matter structures within similar regions, especially in inferior parietal and temporal tracts. This systematic review summarizes and critically examines the current literature on white matter correlates of numerical and mathematical abilities, and provides directions for future research.

Contents

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1. Introduction

1.1. Neural correlates of numerical and mathematical competencies

A long history of research has explored the cortical regions supporting numerical and mathematical processing such as the ability to understand and manipulate numbers as well as the ability to do mental calculations such as addition or subtraction (Ansari et al., 2008; Dehaene et al., 2003). Both structural and functional neuroimaging techniques have been useful in constraining and informing our understanding of numerical and mathematical processing.

To date, research has primarily focused on the functional correlates of numerical and mathematical cognition, using methods such as functional magnetic resonance imaging (fMRI) and event-related brain potentials (ERPs). Comparatively less is known about brain structures underlying numerical and mathematical skills. Since connectivity between regions is integral to efficient cognitive processing (Johansen-Berg, 2010), understanding the role of structural connectivity in mathematical processing may further elucidate the neural mechanisms supporting numerical and mathematical abilities and individual differences therein. Diffusion tensor imaging (DTI) has proved to be a useful method of examining white matter integrity and exploring the relationship between brain microstructure and cognitive functions (Ben-Shachar et al., 2007; Johansen-Berg, 2010; Niogi et al., 2010; Olesen et al., 2003). Individuals who are skilled at math not only need efficient processing in grey matter areas, but also efficient communication between different cortical nodes of a network that support these processes (Ben-Shachar et al., 2007; Johansen-Berg, 2010). Consequently, investigating the connecting white matter structures can lead to a better understanding of individual differences and the networks involved in numerical and mathematical processing. Research on the white matter pathways underlying numerical and mathematical skills has begun to reveal some consistent findings, therefore allowing for a systematic review of the literature.

The aim of this review is to examine the current literature on the relationship between white matter integrity and mathematical skills, summarize common themes, and consider yet unanswered questions (See Table 1 for a list of terms and abbreviations used in the paper). In Section 1 we will first provide a brief overview of the literature on functional neuroimaging and mathematical skills to provide some context of the grey matter networks important for numeracy and mathematics. This background will help guide the discussion on which white matter regions may be related to the functional network. Next, we will introduce the technique of DTI, including a description of typical DTI measurements and how they are analyzed. Section 2 will review the currently published DTI studies that have explored the relationship between mathematical skills and indexes of white matter integrity. More specifically, we will review literature from typically developing children, adults, and atypically developing children. We will also compare and contrast these findings with the functional neuroimaging literature. Section 3 will explore some unanswered questions and future directions.

Table 1
Terms and abbreviations.

Terms	Abbreviation
Arcuate fasciculus	AF
Axial diffusivity	AD
Corpus callosum	CC
Corticospinal tract	CST
Diffusion tensor imaging	DTI
Fetal alcohol spectrum disorder	FASD
Fractional anisotropy	FA
Functional magnetic resonance imaging	fMRI
Inferior fronto-occipital fasciculus	IFO
Inferior longitudinal fasciculus	ILF
Intraparietal sulcus	IPS
Multiple sclerosis	MS
Radial diffusivity	RD
Region of interest	ROI
Superior corona radiata	SCR
Superior longitudinal fasciculus	SLF
Tract based spatial statistics	TBSS
Velocardiofacial syndrome	VCFS

1.2. A fronto-parietal network for numerical and mathematical processing

A network of fronto-parietal regions have been associated with numerical and mathematical processing (Fig. 1). The superior and inferior parietal lobules are commonly associated with numerical tasks such as numerical magnitude comparison (Ansari, 2008; Arsalidou and Taylor, 2011; Cohen Kadosh et al., 2008; Dehaene et al., 2003). Specifically, the intraparietal sulcus (IPS) has consistently been associated with numerical magnitude processing. In contrast, calculation tends to use a more widely distributed fronto-parietal network that includes parietal regions such as the superior and inferior parietal lobules and prefrontal regions including the middle and superior frontal gyri (for a meta-analysis of the neural correlates of numerical and mathematical processes, see Arsalidou and Taylor, 2011).

Calculation is a complex skill that is not process pure (Ansari et al., 2008) and requires many cognitive processes including attention, working memory, and processing speed in addition to math-specific skills. It has been hypothesized that activation in frontal regions supports domain-general processes such as working memory, attention, and response-selection, whereas parietal activation is more specific to representations of number and quantity (Ansari, 2008; Dehaene et al., 1999; Menon et al., 2000).

Converging evidence suggests that parietal circuits become increasingly specialized for number magnitude processing and calculation over the course of development (Ansari, 2008). A fronto-parietal shift is evident from childhood to adulthood for calculation; activation in the frontal cortex decreases with age while the left inferior parietal cortex becomes more engaged (Rivera et al., 2005a,b). The hypothesis of a fronto-parietal shift over development is congruent with the arithmetic training studies that show a shift in activation from the IPS and the inferior frontal gyrus for untrained problems to the angular gyrus for trained problems (Delazer et al., 2003; Ischebeck et al., 2006). Presumably task difficulty demands decrease over the course of learning and development, resulting in a smaller load on frontally-mediated, domain