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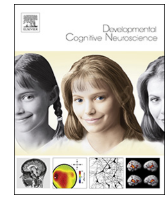

Alterations in white matter pathways underlying phonological and morphological processing in Chinese developmental dyslexia

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ABSTRACT

Chinese is a logographic language that is different from alphabetic languages in visual and semantic complexity. Thus far, it is still unclear whether Chinese children with dyslexia show similar disruption of white matter pathways as in alphabetic languages. The present study focused on the alteration of white matter pathways in Chinese children with dyslexia. Using diffusion tensor imaging tractography, the bilateral arcuate fasciculus (AF-anterior, AF-posterior and AF-direct segments), inferior fronto-occipital fasciculus (IFOF) and inferior longitudinal fasciculus (ILF) were delineated in each individual's native space. Compared with age-matched controls, Chinese children with dyslexia showed reduced fractional anisotropy in the left AF-direct and the left ILF. Further regression analyses revealed a functional dissociation between the left AF-direct and the left ILF. The AF-direct tract integrity was associated with phonological processing skill, an ability important for reading in all writing systems, while the ILF integrity was associated with morphological processing skill, an ability more strongly recruited for Chinese reading. In conclusion, the double disruption locus in Chinese children with dyslexia, and the functional dissociation between dorsal and ventral pathways reflect both universal and specific properties of reading in Chinese.

1. Introduction

Dyslexia is a neurodevelopmental disorder affecting 3–7% of school-age children, that is characterized by a specific difficulty in reading acquisition not solely accounted for by mental age, visual acuity problems, or inadequate schooling (World Health Organization, 2011). Neuroimaging research has revealed that children and adults with dyslexia showed anomalies in the frontal, temporoparietal and occipitotemporal regions of the left-hemisphere (Fiez and Petersen, 1998; McCandliss and Noble, 2003; Pugh et al., 2001; Richlan et al., 2010). In a recent meta-analysis of 28 functional neuroimaging studies, researchers reported both overlap and differences in dyslexic brain activations between deep and shallow orthographies, suggesting that the dyslexic brain shows both biological unity and orthographic specificity (Martin et al., 2016).

In the past decade, diffusion tensor imaging (DTI) studies have suggested that there is a decrease of fractional anisotropy (FA) in the left temporoparietal and inferior frontal regions in children and adults with dyslexia (Carter et al., 2009; Deutsch et al., 2005; Keller and Just, 2009; Klingberg et al., 2000; Niogi and McCandliss, 2006; Odegard et al., 2009; Richards et al., 2008; Rimrodt et al., 2010; Steinbrink et al., 2008; Vandermosten et al., 2012a). Less is known, however, about the anatomical white matter tracts that are exactly underlying these regions. Considering the most consistent temporoparietal region, for example, some researchers attribute the disruption to the anterior-posterior segment of the arcuate fasciculus (Gold et al., 2007; Klingberg et al., 2000; Nagy et al., 2004), while others attribute it to the corona radiata with an inferior–superior orientation (Beaulieu et al., 2005; Niogi and McCandliss, 2006), and yet others to the corpus callosum (Ben-Shachar et al., 2007). In a meta-analysis of DTI studies that used a voxel-based approach, researchers reported a well-replicated cluster in the left temporoparietal region ($x = -29$, $y = -17$, $z = 26$)

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(Vandermosten et al., 2012b). However, a more recent meta-analysis reported no reliable FA difference between children and adults with dyslexia and controls (Moreau et al., 2018, in press). Both meta-analyses relied exclusively on voxel-based studies, which have important limitations. Temporoparietal tracts are notoriously difficult to disentangle using voxel-based analysis (VBA). DTI tractography offers the possibility to reliably reconstruct the major fiber tracts in native space (Catani and Thiebaut de Schotten, 2008). It respects inter-individual variability and helps avoiding the problems brought by normalization and reference systems usually encountered in the VBA-approach (Jones et al., 2007; Ramus et al., 2018; Shen et al., 2007). Since this approach typically involves manual or semi-automatic segmentation, it is time-consuming and requires a priori anatomical hypotheses. Until now, only a few studies explored white matter anomalies in children and adults with dyslexia using fiber tractography methods (Vandermosten et al., 2012a, 2015; Yeatman et al., 2012; Zhao et al., 2016). These studies suggest that tracts in both the dorsal (AF and/or SLF) and ventral (IFOF and ILF) pathways are the main candidate neuroanatomical markers for dyslexia. More specifically, findings of reduced FA in the left AF (dorsal pathway, phonology related) are the most consistent across dyslexia studies (Carter et al., 2009; Deutsch et al., 2005; Klingberg et al., 2000; Rimrodt et al., 2010; Steinbrink et al., 2008; Vandermosten et al., 2012a). In contrast, findings of reduced FA in the left IFOF/ILF (ventral pathway, semantic/orthography related) are relatively scarce (Steinbrink et al., 2008; Vandermosten et al., 2015) and have not been replicated in some studies (e.g. Vandermosten et al., 2012a; Zhao et al., 2016). Thus, the most consistent deficit in children and adults with dyslexia in alphabetic languages seems to be in the left dorsal pathway. The correlation between AF integrity and phonological skill is also consistent with the important role of the phonological deficit in dyslexia in alphabetic languages (Vellutino et al., 2004). As an ideographic language, the division of labor between phonology and semantics in Chinese reading is more equitable (Yang et al., 2013; Zhao et al., 2014). This may suggest that not only the phonology-related dorsal pathway but also the semantic/orthography-related ventral pathway is important in Chinese reading. Thus, in the present study, we investigated both dorsal and ventral pathways in Chinese children with dyslexia.

What are the cognitive deficits underlain by the disrupted fiber-tracts? Reading is built on spoken language (Perfetti and Sandak, 2000) and consists of a series of complex cognitive processes, from decoding visual (orthographic) to auditory (phonological) information and to accessing conceptual (semantic) representations (e.g. Fiez and Petersen, 1998; McCandliss and Noble, 2003; Ramus, 2004). According to the dual route theory of reading, word reading can be achieved through two discrete routes: the grapho-phonological or indirect route for regular or novel words that transforms visual words into their auditory counterparts via grapheme-to-phoneme correspondences; the lexicosemantic or direct route for exception or frequent words that corresponds to a direct association between the visual form of the word and its meaning (Coltheart et al., 2001). Accordingly, researchers proposed that reading recruits two distinct neural routes in the left hemisphere: a dorsal phonological route and a ventral orthographic route (Jobard et al., 2003; Schlaggar and McCandliss, 2007). DTI studies have suggested that this functional dissociation is instantiated by the dorsal and ventral white matter pathways. The left AF in the dorsal route was found to be associated with phonological processing (Saygin et al., 2013; Vandermosten et al., 2012a; Yeatman et al., 2011), while the left IFOF and ILF in the ventral pathway have been found to be important for orthographic processing (Epelbaum et al., 2008; Vandermosten et al., 2012a; Zhao et al., 2016). Alternatively, other studies have suggested a semantic (Duffau et al., 2005; Han et al., 2013) and phonological (Vandermosten et al., 2015; Welcome and Joanisse, 2014) involvement of the left IFOF. Therefore, it remains unclear whether the ventral pathway is a purely orthographic processing route or whether it also participates in other cognitive processes.

All these findings were obtained in alphabetic languages. It remains a highly debated issue to what extent the neural basis of dyslexia differs across different languages and cultures (Perfetti et al., 2006; Pugh, 2006; Siok et al., 2004; Ziegler, 2006). As is well established, Chinese is a logographic language that differs from alphabetic languages in visual-orthographic and semantic properties (Shu et al., 2003). Firstly, Chinese writing is reputed for its visual complexity (constituted by strokes with different shapes and directions) and orthographic complexity (position and composition rules for different radicals) (Chen and Kao, 2002; Shu et al., 2003). Visual-orthographic skills have been found to be particularly important for reading development and dyslexia in Chinese children (Ho et al., 2004; Li et al., 2012). Secondly, morphology in Chinese differs from many other languages (Packard, 2000). Morphemes are the smallest unit of meaning. In Mandarin Chinese, there are about 7,000 morphemes, but only 1,300 syllables (Chao, 1976). Thus, more than five morphemes or characters share the same syllable, which results in a large number of homophones and homographs (Packard, 2000). A reader must be able to distinguish between the homophones and homographs that share the same syllable, but with different morphemes/meanings. Morphological awareness becomes increasingly important in reading development as children grow older (Shu et al., 2006). As mentioned above, previous studies on the IFOF and ILF in the ventral pathway have emphasized their role in orthographic processing and in semantic processing, but the evidence remains limited and ambiguous. No direct evidence is available on whether the integrity of the left ventral pathway is associated with orthographic and semantic processing skills in children with dyslexia.

In summary, although white matter disruptions in dyslexia have been found in alphabetic writing systems, it remains unclear whether Chinese children with dyslexia would show a similar disruption pattern. In the current study, by using state-of-the-art white matter tractography methods in each child's native space, we examined for the first time white matter microstructure in a group of Chinese children with dyslexia and their age-matched controls. The first aim of this study was to systematically examine the differences between Chinese children with and without dyslexia in the key white matter pathways, specifically in the dorsal (AF) and ventral (IFOF and ILF) pathways. Furthermore, we aimed to investigate the associations between the disrupted tracts and the reading-related cognitive skills, including phonological, orthographic and morphological processing skills. Based on previous studies in alphabetic languages (e.g. Vandermosten et al., 2012a) and the complex properties of Chinese language (e.g. Shu et al., 2003), we expected that Chinese children with dyslexia might show disruptions in both the left AF in the dorsal pathway (similar with alphabetic languages), and the left IFOF/ILF in the ventral pathway (more specific to Chinese). Furthermore, we hoped to clarify the respective functional roles of the dorsal and ventral pathways: FA values along the dorsal pathway might be particularly correlated with phonological processing skills (similar with alphabetic languages), while FA values along the ventral pathway might be more correlated with orthographic and morphological processing skills (more specific to Chinese).

2. Method

2.1. Participants

40 Chinese children participated in this study. There were 18 children with dyslexia (11 boys and 7 girls) and 22 control children (11 boys and 11 girls) with a mean age of 11.1 years old. Table 1 shows that the two groups were well matched in sex ($\chi^2(1) = 0.482$, $p = 0.537$), age, and nonverbal IQ ($ps > 0.05$). All the children were recruited from primary schools in Beijing. Their nonverbal IQ was in the normal range (C-WISC overall performance IQ score ≥ 80; Gong and Cai, 1993). All participants were native Mandarin speakers and had normal or corrected-to-normal visual acuity. Informed written consent was obtained from both the parents and their children. Ethical approval for the