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Neural signatures of phonological deficits in Chinese developmental dyslexia

Fan Cao[a,*], Xin Yan[a], Zhao Wang[b], Yanni Liu[c], Jin Wang[d], Gregory J. Spray[a], Yuan Deng[d,**]

[a] *Communicative Sciences and Disorders, Michigan State University, East Lansing, MI, USA*
[b] *Beijing Normal University, Beijing, China*
[c] *University of Michigan, Ann Arbor, MI, USA*
[d] *Institute of Psychology, Chinese Academy of Sciences, Beijing, China*

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ABSTRACT

There has been debate on whether phonological deficits explain reading difficulty in Chinese, since Chinese is a logographic language which does not employ grapheme-phoneme-correspondence rules and remote memorization seems to be the main method to acquire reading. In the current study, we present neuroimaging evidence that the phonological deficit is also a signature of Chinese dyslexia. Specifically, we found that Chinese children with dyslexia (DD) showed reduced brain activation in the left dorsal inferior frontal gyrus (dIFG) when compared to both age-matched controls (AC) and reading-matched controls (RC) during an auditory rhyming judgment task. This suggests that the phonological processing deficit in this region may be a signature of dyslexia in Chinese, rather than a difference due to task performance or reading ability, which was matched on DD and RC. At exactly the same region of the left dIFG, we found a positive correlation between brain activation and reading skill in DD, suggesting that the phonological deficit is associated with the severity of dyslexia. We also found increased brain activation in the right precentral gyrus in DD than both AC and RC, suggesting a compensation of reliance on articulation. Functional connectivity analyses revealed that DD had a weaker connection between the left superior temporal gyrus (STG) and fusiform gyrus (FG) than the two control groups, suggesting that the reduced connection between phonology and orthography is another neural signature of dyslexia. In contrast, DD showed greater connectivity between the left dIFG and the left inferior parietal lobule (IPL) than both control groups, suggesting a reduced segregation between the language network and default mode network in dyslexic children. We also found that connectivity between the left STG and the left dIFG was sensitive to task performance and/or reading skill rather than being dyslexic or not, because AC was greater than both RC and DD, while the connectivity between the left middle occipital gyrus (MOG) and left STG was sensitive to age, because both AC and DD were greater than RC. In summary, our study provides the very first neurological evidence of phonological deficits in Chinese developmental dyslexia and we successfully distinguished variations of brain activity/functional connectivity due to age, performance, and dyslexia by comparing AC, RC, and DD.

Introduction

Developmental dyslexia is defined as a specific and significant impairment in reading abilities, unexplained by deficits in general intelligence, learning opportunity, general motivation, or sensory acuity (Critchley, 1970). It is one of the most common neurological disorders which affects 5–17% of the population regardless of writing system (Stevenson et al., 1982; Shaywitz, 1996; Zhang et al.,1998; Ziegler et al., 2003; Sun et al., 2013). The phonological deficit has been the most popular hypothesis about the cause of DD (Bradley and Bryant, 1983; Rack et al., 1992; Pennington and Lefly, 2001). The phonological deficit refers to the impairments of processing and/or representing phonemes (Shankweiler et al., 1992; Shankweiler et al., 1995). The underspecified phoneme representations, or the unsuccessful retrieval of the phoneme representations, lead to poor development of the grapheme-phoneme correspondences that are essential to reading (Snowling, 1980; Muter et al., 1998). A number of studies have reported a phonological deficit in children with DD (Rack and Olson, 1993; Ramus and Szenkovits, 2008; Hulme et al. 2012; Castles, 2014).

There has been debate on cross-linguistic universality of the role

* Correspondence to: Michigan State University, 1026 Red Cedar Road, East Lansing, MI 48824.
** Correspondence to: 16 Lincui Road, Chaoyang District, Beijing 100101, China.
E-mail addresses: fcao@msu.edu (F. Cao), dengy@psych.ac.cn (Y. Deng).

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that the phonological deficit plays in reading difficulty. For example, would the phonological deficit still be the core cause of reading difficulty in languages that use logographic writing systems where no part of a character corresponds to a single phoneme of the syllable? There is evidence for the important role of phonological awareness in predicting reading achievement in Chinese children (McBride-Chang et al., 2008; Pan, 2011; Tong, 2011; Xue et al., 2013; Pan et al., 2015). Furthermore, there is evidence for impaired phonological awareness in Chinese children with reading difficulties in comparison to both age-matched controls and reading-matched controls (Ho, 1999; Ho, 2000; Ziegler and Goswami, 2005; Pan, 2014; McBride-Chang, 2015). However, visuo-orthographic and rapid naming deficits have also been suggested to be more dominant in Chinese dyslexic children than phonological deficits (Huang and Hanley, 1995; Ho, 2002; Ho et al., 2004; Tan et al., 2005). Using cluster analyses, researchers found that 50–57% of the dyslexic children sampled showed rapid naming deficits, 38.9–42% showed orthographic deficits, and only 15.3–29.3% showed phonological deficits (Ho, 2002; Ho et al., 2004). A recent study found that morphological awareness has a greater contribution to reading than phonological awareness in post-literate Chinese children, but pre-literate phonological awareness predicts post-literate morphological awareness, suggesting that phonological awareness influences reading via morphological awareness (Pan et al., 2015). Taken together, behavioral studies suggest a phonological deficit in Chinese dyslexia, however, phonological deficits seem to play a limited role in causing Chinese dyslexia and there appears to be other more salient deficits related with dyslexia in Chinese.

A number of neuroimaging studies to date have investigated brain mechanisms of DD using visual word/pseudoword tasks in alphabetic languages, with a consensus that there is reduced brain activation in the left temporo-parietal region and temporo-occipital region in participants with DD (Rumsey et al., 1997; Paulesu et al., 2001; Schulz et al., 2009; van der Mark et al., 2009; Tanaka et al., 2011; Kita et al., 2013). These abnormal brain activations are consistent with deficient phonological and orthographic processing in DD. Findings about the activation in the left IFG, however, are not consistent across studies with some reporting increased activation in DD (Shaywitz et al., 1998; Hoeft et al., 2007; MacSweeney et al., 2009) and others reporting decreased activation in DD (Brambati et al., 2006, Cao et al., 2006, Booth et al., 2007, Richlan et al., 2010; Wimmer et al., 2010). A meta-analysis study suggests that children with DD tend to show increased activation while adults tend to show decreased activation (Richlan et al., 2011). However, another study suggests that increased activation in the left IFG in children with DD was reading performance-related rather than dyslexia-related, because they found that children with DD did not show increased activation when compared to reading controls (Hoeft et al., 2007). Considerations should also be given to the difficulty of tasks used in different studies when one tries to explain the inconsistent findings at the left IFG. There seems to be over-activation when the task is simple, such as letter rhyming judgment (Shaywitz et al., 1998), and underactivation when the task is difficult, such as word rhyming judgment (Cao et al., 2006).

While extensive research has been done to examine the brain mechanisms underlying reading failure in English, the first fMRI study in Chinese dyslexia was only published in 2004 (Siok et al., 2004). Since that time, a handful of studies have been conducted to understand the brain mechanisms underlying Chinese reading failure. These studies found reduced brain activation in the left middle frontal gyrus (MFG) in a morphological task (Liu et al., 2013), a homophone judgment task (Siok et al., 2004), and a character decision task (Siok et al., 2004); reduced activation in the left IFG and bilateral temporo-occipital areas in a rhyming judgment and semantic judgment task (Liu et al., 2012), and a character decision task (Siok et al., 2004); reduced activation in left intraparietal sulcus in a font size judgment task (Siok et al., 2009); and increased activation in left IFG in a homophone judgment task (Siok et al., 2004). In comparison to English dyslexia studies, the main difference in the Chinese studies is that there is no report of reduced activation in the left temporo-parietal region, instead, there is a consistent report of reduced activation in the left MFG. In studies of normal adults reading, it is well documented that the left temporo-parietal region is associated with grapheme-phoneme correspondence (Pugh et al., 2000a, b; Booth et al., 2002; Pillay et al., 2014), which is more involved in English reading than in Chinese reading (Tan et al., 2003; Bolger et al., 2005; Tan et al., 2005), and more involved in transparent orthographies than opaque orthographies (Paulesu et al., 2000; Jamal et al., 2012). In contrast, the left MFG has been repeatedly found to be more involved in reading Chinese than English (Bolger et al., 2005; Tan et al., 2005; Nelson et al., 2009; Cao et al., 2013), more involved in opaque languages than transparent languages (Kumar, 2014), and more involved in inconsistent words than consistent words (Bolger et al., 2008), which is presumably associated with the coarse grain mapping. Therefore, the different findings in the dyslexia literature in Chinese and English seem to be consistent with the cross-linguistic differences in the normal reading literature. Another study directly compared Chinese dyslexic children with English dyslexic children in a word semantic task and found that dyslexic children in the two languages showed similar brain activation, both of which did not show language specialization as their own controls did – greater activation in the left MFG in the Chinese speaking children and greater activation in the left temporo-parietal region in the English speaking children (Hu et al., 2010). Taken together, both English and Chinese studies using visual word tasks suggest deficient orthographic and phonological processing in the brain in participants with DD, even though the specific regions in each language may be slightly different.

Neuroimaging studies on reading/visual word processing in participants with DD may not be as informative in testing the hypotheses of the causes of DD, because abnormal brain activation observed in visual word processing may be only a result of being DD rather than the cause of DD. Neuroimaging studies have also directly tested the phonological deficit hypothesis using spoken word tasks in participants with DD. Reduced activation was found in the bilateral STG (McCrory et al., 2000; Blau et al., 2010; Kast et al., 2011; Pecini et al., 2011; Paulesu et al., 2014), which is associated with phonological representation (Bookheimer and Dapretto, 1996; Fiez et al., 1996; Booth et al., 2002), the left inferior parietal region (Eden et al., 2004; Dufor et al., 2007; Kast et al., 2011), which is associated with phonological working memory (LaBar et al., 1999; Olesen et al., 2007), the left IFG (Ruff, Cardebat et al., 2002; Dufor et al., 2007; Heim et al., 2010; Kovelman et al., 2011; Pecini et al., 2011), which is associated with phonological manipulation (Fiez et al., 1996; Pugh et al., 1996; Booth et al., 2002), and the left fusiform gyrus (Desroches, 2010), which is associated with orthographic representations (Dehaene et al., 2001, 2004; Xue et al., 2006). These findings suggest phonological deficits, as well as orthographic deficits, can be detected in spoken word processing in DD. A recent study took a step further to suggest that DD is associated with deficient access to otherwise intact phonological representation (Boets et al., 2013), because they found that the neural robustness and distinctness to phonemes at the bilateral auditory cortices is intact in adults with DD, but the functional and structural connectivity between the bilateral auditory cortices and the left IFG, which is involved in higher-level phonological processing, is hampered. This finding is consistent with a previous behavioral study (Ramus and Szenkovits, 2008), however, more neuroimaging research is needed to support the intact but less accessible phonological representation hypothesis in DD. We planned to test this hypothesis in the current study by examining brain activation patterns at the STG and functional connectivity between the STG and dIFG in children with DD. Moreover, none of previous studies have examined the connectivity between phonology and orthography in DD during spoken word processing, even though one study found reduced brain activation in the orthographic region in an auditory rhyming task (Desroches 2010). Therefore, in the current