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Similar alterations in brain function for phonological and semantic processing to visual characters in Chinese dyslexia

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Abstract

Dyslexia in alphabetic languages has been extensively investigated and suggests a central deficit in orthography to phonology mapping in the left hemisphere. Compared to dyslexia in alphabetic languages, the central deficit for Chinese dyslexia is still unclear. Because of the logographic nature of Chinese characters, some have suggested that Chinese dyslexia should have larger deficits in the semantic system. To investigate this, Chinese children with reading disability (RD) were compared to typically developing (TD) children using functional magnetic resonance imaging (fMRI) on a rhyming judgment task and on a semantic association judgment task. RD children showed less activation for both tasks in right visual (BA18, 19) and left occipito-temporal cortex (BA 37), suggesting a deficit in visuo-orthographic processing. RD children also showed less activation for both tasks in left inferior frontal gyrus (BA44), which additionally showed significant correlations with activation of bilateral visuo-orthographic regions in the RD group, suggesting that the abnormalities in frontal cortex and in posterior visuo-orthographic regions may reflect a deficit in the connection between brain regions. Analyses failed to reveal larger differences between groups for the semantic compared to the rhyming task, suggesting that Chinese dyslexia is similarly impaired in the access to phonology and to semantics from the visual orthography.

Keywords

Chinese dyslexia; Orthography; Phonology; Semantics

1. Introduction

Developmental dyslexia refers to a significant reading difficulty that cannot be accounted for by a deficit in general intelligence or inadequate education. Estimates of dyslexia prevalence in children in Mainland China range from 4.5% to 8.0% (Zhang, Zhang, Yin, Zhou, & Chang, 1996). Studies on developmental dyslexia in alphabetic languages suggest a central deficit in mapping of orthography to phonology (Bradley & Bryant, 1978; Gabrieli, 2009; Hulme & Snowling, 1992; Hultquist, 1997; Pugh et al., 2001; Shankweiler, Liberman, Mark, Fowler, & Fischer, 1979; Shaywitz, 1998) and this deficit has been suggested to be of a universal biological origin: Dysfunction of left posterior occipito-temporal and temporo-parietal brain regions as well as frontal regions (Hoeft et al., 2006, 2007; Paulesu et al., 2001; Shaywitz et al., 2002). Compared to alphabetic languages, the cognitive and neural basis of dyslexia in Chinese is less understood.

The cognitive processes in reading are closely tied to the characteristics of the writing system. Unlike alphabetic orthographies, Chinese orthography is often described as logographic for several reasons. First, the relationship between orthography and phonology is less systematic in Chinese than in alphabetic languages. Although the phonetic radical of the Chinese character can indicate its phonology, fewer than 50% of Chinese characters have a pronunciation corresponding to the pronunciation of the phonetic radical in that character. Second, compared to the unsystematic mapping between orthography and phonology, the orthography to semantics mapping is relatively systematic (Ho, Law, & Ng, 2000). Third, the meanings of Chinese characters are often suggested by their visual configurations (Wang, 1973). Last, the mapping from phonology to both orthography and meaning is one-to-many in Chinese. In other words, a single pronunciation can be written in many different ways and can have many different meanings. Because of this one-to-many mapping, accessing semantics from phonology is unreliable without contextual cues. The direct connection between orthography and semantics is, therefore, more reliable for accessing meaning in Chinese (Cao et al., 2010).

One of the most critical questions for Chinese dyslexia is that whether the main deficit is in orthography to phonology mapping as in alphabetic languages. In terms of this question, different opinions exist. Because of the logographic nature of Chinese characters, some have suggested that dyslexia in Chinese should be marked with larger deficits in semantic processing than in orthography to phonology mapping (Shu, McBride-Chang, Wu, & Liu, 2006; Wu, Shu, & Wang, 2004). However, some other studies have shown that phonological skills predict reading acquisition in Chinese (Ho & Bryant, 1997; Shu, Peng, & McBride-Chang, 2008; Siok & Fletcher, 2001) and Chinese children with dyslexia have phonological deficits (Ho et al., 2000). In addition, other studies have reported orthographic deficits in Chinese children with reading disability (Ho, Chan, Lee, Tsang, & Luan, 2004; Ho, Chan, Tsang, & Lee, 2002). Ho et al. (2004) even argued that orthographic-related difficulties may be the crux of the problem in Chinese developmental dyslexia (Ho et al., 2004). In summary, behavioral studies are not consistent on whether dyslexia in Chinese is marked by larger deficits in semantic processing than in orthography to phonology mapping.

Neuroimaging studies on Chinese dyslexia also failed to determine whether dyslexia in Chinese is marked by larger deficits in orthography to semantics mapping than in orthography to phonology mapping. As with studies on alphabetic languages, functional neuroimaging studies of Chinese dyslexia have reported brain abnormalities in posterior occipito-temporal regions and anterior frontal regions (Siok, Niu, Jin, Perfetti, & Tan, 2008; Siok, Perfetti, Jin, & Tan, 2004; Siok, Spinks, Jin, & Tan, 2009). Studies on Chinese dyslexia have reported reduced activation in bilateral occipito-temporal regions rather than unilateral left occipito-temporal region, possibly due to the visual complexity of characters (Siok et al., 2004, 2009). In addition, studies have reported brain abnormalities in left middle frontal gyrus (Siok, et al., 2004, 2008, 2009), which has rarely been reported to show abnormalities in alphabetic dyslexia. However, the abnormal activation in left temporo-parietal regions consistently found in dyslexia in alphabetic languages has rarely been reported in Chinese dyslexia, with only one recent study (Hu et al., 2010) reporting reduced activation in angular gyrus. Among these above neuroimaging studies on Chinese dyslexia, only one (Siok et al., 2004) has investigated both phonological and semantic processing of characters. Using a homophone judgment task and a character decision task, this study found reduced activation in left middle frontal gyrus for both tasks in children with dyslexia. They interpreted this as reflecting a deficit in orthography to semantics mapping as well as in the orthography to syllable mapping. However, this study did not directly compare the phonological to semantic task, and therefore could not determine relative deficits in Chinese dyslexia.

The goal of the current study was to investigate whether dyslexia in Chinese is marked by larger deficits in semantic processing than in orthography to phonology mapping by using functional magnetic resonance imaging (fMRI) during a phonological task involving rhyming judgments and a semantic task involving association judgments. The two tasks were matched in stimuli characteristics so that direct comparisons could be made between the two tasks. It is also important to know whether the abnormal brain regions underlying the main deficit in Chinese dyslexia correlate with each other because correlated brain abnormalities could indicate a deficiency in the connection between brain regions suggesting a network level problem rather than independent deficits in isolated brain regions. Because Chinese characters place large demands on visuo-orthographic regions, we were particularly interested in posterior occipito-temporal regions and how these are correlated with prefrontal regions implicated in controlled retrieval and selection of posterior phonological and semantic representations. Previous functional and effective connectivity studies on alphabetic dyslexia have indicated a deficit in the connectivity between left posterior occipito-temporal regions and prefrontal brain regions (Cao, Bitan, & Booth, 2008; Horwitz, Rumsey, & Donohue, 1998; Quaglino et al., 2008; van der Mark et al., 2011). However, no studies have investigated connectivity between prefrontal regions and occipito-temporal regions in Chinese dyslexia. Previous studies suggest that Chinese orthography is processed bilaterally in the occipito-temporal cortex, whereas alphabetic orthographies primarily engage the left occipito-temporal cortex (Bolger, Perfetti, & Schneider, 2005; Tan, Laird, Li, & Fox, 2005). This suggests that Chinese dyslexia, in contrast to alphabetic systems, may be marked by a disconnection between bilateral occipito-temporal cortex and prefrontal regions.

2. Methods

2.1. Participants

Sixteen typically developing (TD) children (M age=11.6, SD =0.51, range from 11 to 13; 11 males) and 16 reading disabled (RD) children (M age=12.02, SD =0.4, range from 11 to 13; 11 males) participated in the rhyming and semantic judgment task. The participants were all in sixth-grade and were recruited from two primary schools in Beijing. Informed consent was obtained from all participants and informed consent procedures were approved by the Institutional Review Board at Beijing Normal University and Northwestern University.

Inclusionary criteria, based on an informal interview, for both TD and RD groups were the following: (1) native Chinese speakers; (2) right-handed; (3) normal hearing and normal/or corrected to normal vision; (4) no neurological disease or psychiatric disorders; (5) not taking medication affecting the central nervous system, and (6) no Attention Deficit Hyperactivity Disorder (ADHD).

Standardized and informal tests were given to examine mental ability and reading achievement in both TD and RD groups. Mental ability was measured with the Chinese version of the Wechsler Intelligence Scale for Children–Revised (WISC-R) (Wechsler, 1974). Scoring procedures were based on local norms (Lin & Zhang, 1986). Reading achievement was measured by the Character Recognition Measure and Assessment Scale for Primary School Children (CRM) (Wang & Tao, 1993) and by a Character Reading Fluency (CRF) test (Siok & Fletcher, 2001; Siok et al., 2004). CRM is a widely used standardized test for screening Mandarin-speaking Chinese children with dyslexia. In this test, children were asked to make words using given written Chinese characters. The task of making words rather than naming characters was used because there are many homophones in Chinese, and therefore, correct pronunciation itself cannot ensure the children understand the meaning of the characters. This test provided an index of reading accuracy but not reading fluency. Because there is no standardized test of reading fluency in Mainland China, we administered an informal character reading fluency test as in several previous studies (Siok & Fletcher, 2001; Siok et al., 2004). This test consisted of 135 high-frequency Chinese characters. These characters are all from primary school textbooks for Chinese language and were arranged into five columns from easy to hard. Children were asked to read aloud characters as fast and as accurate as possible. Reading fluency was computed by the number of correct characters divided by total reading time. This reading fluency test was not used for screening children with dyslexia, but only as an index of reading fluency.

RD children met the following inclusionary criteria: (1) Performance IQ above 90 (2) 1.5 years below their corresponding age on the CRM test. The age-matched TD children met the following inclusionary criteria: (1) Performance IQ above 90 (2) less than 1.5 years below their corresponding age on the CRM test.

Due to low task accuracy (less than 50%) or large head movement (>4 mm), 5 subjects were discarded in the rhyming task, of whom 2 subjects were discarded for low task accuracy in the RD group, 3 for large head movement (1 in the TD group and 2 in the RD group). To match the statistical power between the TD and RD group, 4 ‘good’ subjects in the TD

group and 1 ‘good’ subject in the RD group were also discarded so that two groups have an equal number of participants. In addition, to match the statistical power between the rhyme and semantic tasks, the same subjects were also discarded from the semantic task. After these exclusions, 11 RD children (M age=12.05, SD =0.43, range from 11 to 12; 6 males) and 11 TD children (M age=11.75, SD =0.24, range from 11 to 12; 7 males) were included, and the two groups were matched on age, but there was a trend for an age difference ($t(20)=-2.079$, $p=0.051$). To rule out the influence of an age difference, age was co-varied out in the following group difference analysis for both behavioral and neuroimaging data.

Table 1 presents the means and standard deviations for the mental ability and reading achievement tests in the TD and RD groups. The TD and RD groups were matched on Performance IQ ($t(20)=0.717$, $p=0.482$), but there were significant differences between groups on both reading achievement measures: CRM ($t(20)=9.387$, $p<0.001$) and CRF ($t(20)=7.661$, $p<0.001$).

2.2. Experimental procedure

In the rhyming judgment task (or semantic judgment task), two Chinese characters were visually presented sequentially with each character presented for 800 ms followed by a 200 ms blank interval. A red fixation cross (+) appeared on the screen after the second stimulus was removed, indicating the need to make a response during the subsequent interval jittered equally between 2200, 2600 and 3000 ms. The participants were asked to judge whether the two characters rhyme in the rhyming task or were semantically related in the association judgment task. Half of the word pairs rhymed (or were semantically related) and half did not. If a pair of characters rhymed (or was semantically related), participants were asked to press a yes button with the right index finger; if the pair of characters did not rhyme (or were semantically unrelated), the participants were asked to press a no button with the right middle finger. Semantic association strength between the first and the second character was assessed using a 7-point scale. In a pilot study, 30 adults in Beijing were asked to judge to what extent pairs of characters were related. An average score across subjects below 3 was considered unrelated ($M=2.18$), whereas an average score over 4.5 was considered related ($M=5.95$).

For the rhyming task, four conditions independently manipulating orthographic and phonological information were included. For two of the conditions, two characters in a pair shared an identical phonetic radical, but half of the pairs rhymed (for example, 波 and 婆, sharing the phonetic radical ‘波’, pronounced as /bo1/ and /po1/) and half did not (for example, 井 and 晴, sharing the phonetic radical ‘井’, pronounced as /ban4/ and /pang4/). For the other two conditions, two characters in a pair did not share a phonetic radical, and half of the pairs rhymed (for example, 井/chen4/ and 震/zhen4/) and half did not (for example, 仍/reng2/ and 杨/yang2/). This manipulation ensured that a correct response could not be based solely on the phonetic radical.

For the semantic task, four conditions independently manipulating the orthographic and semantic information were included. For two of the conditions, two characters in a pair shared an identical semantic radical, but half of the pairs were related (for example, 冷 and 凉, sharing the semantic radical ‘冫’, meaning ‘cold’ and ‘cool’) and half were not (for

example, 桃 and 板, sharing the semantic radical ‘木’, meaning ‘peach’ and ‘board’). For the other two conditions, two characters in a pair did not share a semantic radical, and half of the pairs were related (for example, 蛇 (snake) and 咬 (bite)) and half were not (for example, 植 (plants) and 峡谷 (canyon)). This manipulation ensured that a correct response could not be based solely on the semantic radical.

There were two kinds of control trials for each lexical task. The two kinds of control trials were designed to account for activation due to visual analysis, decision making, and executive motor processing in the character trials. In the perceptual trials, two symbols were visually presented sequentially and the participants were asked to judge whether the pair of symbols was identical or not. If a pair of symbols was identical (for example, 𐄣 and 𐄣), the participants were asked to press yes button with the right index finger and if not (for example, 𐄣 and 𐄤), the participants were asked to press no button with the right middle finger. Half of the symbol pairs were identical and half were not. The symbols were Tibetan characters of which none of the children were familiar. The timing for perceptual trials was the same as for character trials. For the null trials, two black fixation-crosses were visually presented sequentially with each black fixation-cross presented for 800 ms followed by a 200 ms blank interval. A blue fixation cross appeared on the screen after the second black fixation-cross was removed. Participants were asked to press a yes button with the right index finger when the second black fixation-cross turned blue during the subsequent interval jittered equally between 2200, 2600 and 3000 ms.

We used an event-related design with four 6 min 44 s runs including two runs of each task. In each run, there were 48 pairs of character stimuli, 12 pairs of perceptual stimuli, and 24 pairs of null stimuli. The order of character and control trials was optimized for event-related design using OptSeq (<http://www.surfer.nmr.mgh.harvard.edu/optseq>). Before each run, a short instruction (‘rhyming task’ or ‘semantic task’) was presented to indicate the experimental task. The administration of the two tasks was counter balanced across participants. In each run, there was a 12 s equilibration period at the beginning, and a 22 s period at the end in order to be able to deconvolve the whole hemodynamic response function (HRF) for the last trial. Before the fMRI scanning, a short practice was given to the subjects to get them familiar with the experimental procedure and task requirements.

2.3. Stimulus characteristics

Several lexical variables were controlled for the rhyme and semantic tasks. First, all characters were from Chinese language textbooks from Grade 1 to Grade 6. Second, the characters were matched for frequency, acquisition term and strokes across the rhyme and semantic tasks (see Table 2). A 2 character (first, second) by 2 task (rhyme, semantic) ANOVA showed no main effects or interactions with the frequency, acquisition term or strokes. Third, for the rhyme task, the two characters in a pair shared an identical lexical tone, so that tone information would not potentially interfere with the rhyming judgment.

2.4. Data collection

All images were acquired using a 3 T Siemens scanner at Beijing Normal University. Gradient-echo localizer images were acquired to determine the placement of the functional

slices. For the functional imaging, a susceptibility weighted single-shot EPI (echo planar imaging) method with BOLD (blood oxygenation level-dependent) was adopted. The following scan parameters were used: TR=2000 ms; TE=20 ms; flip angle=80°; slice thickness=3 mm, gap=0.48 mm; number of slices=32; FOV=220*206.25 mm; matrix=128*120*32; pixel size=1.71875*1.71875*3.48 mm. In addition, a high resolution, T1 weighted 3D image was acquired (MPRAGE, axial slices=160; slice thickness=1 mm; FOV=256*256 mm; matrix=256*256*160; voxel size=1*1*1 mm; TR=2300 ms; TE=3.36 ms).

2.5. Data analysis

Data analysis was performed using SPM5 (Statistical Parametric Mapping) (<http://www.fil.ion.ucl.ac.uk/spm>). Image pre-processing included: slice timing, realignment, co-registration, tissue segmentation, normalization, and smoothing. Specifically, the functional images were corrected for differences in slice-acquisition time to the middle slice and were realigned to the first volume in the scanning session. No included participants had more than 4.0 mm of movement within run in any plane. Subjects' functional images were then co-registered with their corresponding high-resolution structural MRI images. The co-registered high-resolution structural MRI images were segmented and normalized to standardized tissue probability templates (based on Montreal Neurologic Institute (MNI) stereotactic space; <http://www.bic.mni.mcgill.ca>). Using the parameters from the structural MRI images segmentation and normalization, the functional images were normalized with a resample voxel size of 2*2*2 mm and then smoothed with Gaussian filter of FWHM (full width half max)=4×4×8 mm.

The general linear model was used to estimate condition effects for each subject using an event-related analysis procedure. To ensure the brain differences between groups were not caused by performance differences (See behavioral results), we only included correct items in all analyses. Because this resulted in unequal numbers of items across groups, items were randomly eliminated from TD group so that the numbers of items in each condition were equated across groups. Three conditions “character”, “perceptual”, and “null” per task were modeled using a canonical HRF (hemodynamic response function). For each subject, one contrast of interest was computed: (character–perceptual). Parameter estimates from this contrast of the canonical HRF in single subject models were entered into random-effects analysis. One-sample t tests were used to test if this contrast was significant, separately for each group and for each task. A 2 group by 2 task ANCOVA analysis on this contrast with task as a within-subject factor and age as a covariate was used to investigate whether group differences were larger in one task than another. Results reported are corrected for multiple comparisons with the Monte-Carlo simulations (see the AlphaSim command at <http://afni.nih.gov/afni/docpdf/AlphaSim.pdf>). The individual voxel threshold was set at $p < 0.0002$ and a cluster with its volume larger than 145 mm³ (18 adjacent voxels) yields a corrected significance threshold of $p < 0.05$ within the GM mask.

3. Results

3.1. Behavioral results

Table 3 presents behavioral data for the rhyme and semantic tasks. We calculated 2 group (TD, RD) by 2 task (rhyme, semantic) repeated measure ANOVAs on accuracy and reaction time with task as a within-subject factor and age as a covariate separately for the character, perceptual and null condition.

For the character condition, analyses on accuracy revealed a significant main effect of group ($F(1,19)=10.577, p=0.004$). No significant main effect of task or group by task interaction effect was revealed. Follow-up t tests showed that TD had significant higher accuracy than RD both in the rhyming task ($t(20)=3.452, p=0.003$) and in the semantic task ($t(20)=2.363, p=0.028$). Analyses on reaction time revealed a significant group by task interaction effect ($F(1,19)=6.469, p=0.020$). Follow-up t tests showed that RD had significant faster reaction time than TD in the rhyming task ($t(20)=2.841, p=0.010$) but not in the semantic task ($t(20)=1.156, p=0.261$).

For the perceptual and null condition, analyses revealed no significant main effect of group or task or group by task interaction either for accuracy or reaction time.

fMRI activation results—Below we report the group differences (main effect of group), task differences (main effect of task), as well as group differences in the rhyme vs semantic task (group by task interaction). We then report correlations between the brain regions showing the group differences.

Table 4 and Fig. 1 present the main effect of group (AlphaSim corrected, $p<0.05$). The calculation of the main effect of group was confined through using a mask of the positive activation in the /character–perceptual/ contrast across the two groups and the two tasks ($p<0.05$ uncorrected). The main effect of group was revealed in left dorsal inferior frontal gyrus (IFG, BA44) and right cuneus (BA18). Beta values were extracted separately for the two groups and the two tasks from these clusters showing the main effect of group. As illustrated in Fig. 1, TD showed greater activation than RD in both regions for both tasks. To investigate whether the abnormality in RD for left dorsal IFG and for right visual cortex (cuneus) reflects independent or correlated deficits, we conducted a correlation analysis between activation in the two regions. The analysis within the TD group failed to show significant correlation for IFG-cuneus for either the rhyming task ($r=-0.170, p=0.617$) or semantic task ($r=-0.017, p=0.961$). The analysis within the RD group revealed significant correlations for IFG-cuneus ($r=0.800, p=0.003$), only in the semantic task.

Because left occipito-temporal (OT) cortex and the middle frontal gyrus (MFG) have been frequently found to show abnormalities in Chinese dyslexics (Hu et al., 2010; Siok et al., 2004, 2008), we conducted regions of interest (ROI) analysis to investigate whether these two regions would show a main effect of group or group by task interaction. Although left temporo-parietal cortex has been frequently reported to show abnormalities in dyslexia in alphabetic writing systems (Hoeft et al., 2006, 2007; Paulesu et al., 2001; Shaywitz et al., 2002), it has rarely been reported in Chinese dyslexics, so we did not include this region for

a ROI analysis. Based on previous literature, we expected that Chinese dyslexics would show reduced activation in left OT region and MFG compared to typically developing children in both tasks. However, previous literature has not investigated whether these differences would be larger for phonological or semantic processing. Anatomical masks based on the aal template (fusiform gyrus+inferior temporal gyrus) for left OT and middle frontal gyrus for left MFG were used for the 2 group by 2 task ANCOVA analysis with age as a covariate. No significant group by task interaction effect was revealed in left OT. However, a main effect of group was revealed in a 4 voxel cluster peaking at $-44 -60 -16$ (fusiform gyrus). Beta values were extracted from this cluster separately for the two groups and the two tasks. As illustrated in Fig. 2, the TD showed greater activation than RD in this region for both rhyming and semantic task. A correlation analysis between the activation of left dorsal IFG and left OT was also conducted. A significant correlation was revealed in both the TD ($r=0.721$, $p=0.012$) and RD ($r=0.609$, $p=0.047$) group, only in the semantic task. To investigate whether the significant correlation of the left OT–left IFG in the semantic task was specific, we also conducted correlation analysis between left OT and right cuneus. No significant correlations were revealed in TD ($r=-0.421$, $p=0.197$) or RD ($r=0.436$, $p=0.180$) in the semantic task. ROI analysis on left MFG failed to show a main effect of group or a significant group by task interaction effect.

Table 4 and Fig. 3 present the main effect of task (AlphaSim corrected, $p<0.05$). The main effect of task was revealed in bilateral ventral inferior frontal (BA11) and left middle temporal gyrus (BA21, BA39). Beta values were extracted from these clusters showing the main effect of task. As illustrated in Fig. 3, the semantic task showed greater activation than the rhyming task in all regions for both groups. No significant group by task interaction was revealed.

4. Discussion

Using functional magnetic resonance imaging (fMRI), the present study investigated whether Chinese children with dyslexia have a larger deficit in the mapping between orthography and semantic due to the logographic nature of Chinese characters or whether they are marked by a larger deficit in orthography to phonology mapping as in alphabetic languages. Both control and dyslexic children were asked to make rhyming judgments and association judgments to visually presented character pairs. A 2 group by 2 task ANOVA on the neuroimaging data failed to find any group by task interaction, suggesting that group differences were similar across tasks. But the ANOVA analysis revealed significant main effect of group in right cuneus and left inferior frontal gyrus with TD showing greater activation than RD, and an ROI analysis showed greater activation for the TD than RD in left occipito-temporal cortex. Inter-regional correlation analyses were further conducted among brain regions showing reduced activation in RD and revealed significant correlations between bilateral visual cortex and left inferior frontal gyrus in RD, only in the semantic task. Finally, the ANOVA analysis also showed significant main effect of task in bilateral ventral inferior frontal gyri and left middle temporal gyrus with greater activation in the semantic than rhyming task.

Our findings of similar group differences for the rhyming and semantic tasks are consistent with the behavioral results that showed no group by task interaction for task accuracy. Our findings of similar effects for the rhyming and semantic tasks are also consistent with one previous study in Chinese dyslexia (Siok et al., 2004) which reported parallel deficits in orthography to phonology mapping and in orthography to semantic mapping. Of note, a significant group by task interaction was found for reaction time in the current study, with dyslexic children showing significantly faster reaction time than controls in the rhyming task, but not in the semantic task. The faster reaction time in the dyslexic group compared to controls in the rhyming task is unusual, and may be due to dyslexic children emphasizing speed over accuracy for the more difficult rhyming task. Due to this speed-accuracy tradeoff, one must be cautious in using this group by task interaction in the reaction time as an evidence to support a task difference in the group effect. All together, our results do not support the notion that Chinese children with dyslexia are marked by a larger deficit in the semantic system due to the logographic nature of Chinese characters.

Though we did not find task differences in the group effect, we found significant group differences in both rhyming and semantic task in right occipital cortex. Our finding is consistent with one recent developmental study of Chinese demonstrating that adults, who are more skilled, showed greater activation than children in right occipital cortex for both rhyming and semantic tasks (Cao et al., 2009). The reduced activation of right occipital cortex in Chinese dyslexia has also been reported in a previous study on Chinese dyslexia in a perceptual judgment task (Siok et al., 2009). Ours is the first study showing reduced activation for Chinese dyslexics in right occipital cortex in two different reading tasks (rhyming and semantic judgments). Moreover, this dysfunction of right occipital cortex was more robust than the dysfunction of left occipito-temporal region because the latter difference was only revealed in a region of interest analysis. A language-specific role of right visual cortex in Chinese reading has been suggested by many previous studies. Two previous meta-analyses suggest that right occipital cortex is involved to a greater degree in Chinese reading than in English reading (Bolger et al., 2005; Tan et al., 2005). A recent study also reported that right cuneus is more sensitive to Chinese character degradation than English word degradation (Sun, Yang, Desroches, Liu, & Peng, 2011). Chinese characters are comprised of strokes packed into a square shape, usually including two or more spatially arranged radicals. Unlike the linear left-right spatial layout of alphabetic writing systems, the spatial relationship between radicals in a Chinese character can be left-right (for example, 村, meaning village), up-down (for example, 爸, meaning father) and inside-outside (for example, 國, meaning country). Due to the complicated spatial layout, visual recognition of Chinese characters requires substantial holistic visual-spatial processing (Xue et al., 2005). Several studies have suggested that right visual cortex is specialized for holistic spatial processing (Kosslyn et al., 1993; Smith et al., 1995). Reduced activity in right visual cortex in Chinese children with dyslexia across both of our tasks suggests a deficit in holistic visuo-orthographic analysis in Chinese dyslexia.

We also found group differences in both the rhyming and semantic task in the left occipito-temporal region in a less conservative analysis using an anatomical mask. The peak coordinate (−44 −60 −16) is very close to those reported in two previous studies (Hu et al., 2010; Siok et al., 2004) on Chinese dyslexia (−46, −65, −12 in Siok et al., 2004; −46 −58

–14 in Hu et al., 2010). The reduced activation in left occipito-temporal has also been consistently reported in alphabetic dyslexia studies (Maisog, Einbinder, Flowers, Turkeltaub, & Eden, 2008; Richlan, Kronbichler, & Wimmer, 2009, 2011). The reason that the group difference in the left occipito-temporal region in the current study is relatively weak may be due to the complicated ‘perceptual’ baseline. Though the Tibetan symbols were unfamiliar to the subjects, they were perceptually similar to the characters. The left occipital-temporal region has been suggested to be involved in both whole word recognition and serial sub-lexical processes (Kronbichler et al., 2004; Richlan et al., 2010; Schurz et al., 2010). The weak group difference in this region in the Chinese children with dyslexia in our study may indicate a deficit in visuo-orthographic analysis at both whole-character level and sub-character level (e.g., radicals, strokes). This is consistent with several behavioral studies suggesting visuo-orthographic deficits in Chinese children with dyslexia (Ho et al., 2002, 2004).

We also found reduced activation in left posterior dorsal inferior frontal gyrus. Reduced activation in left dorsal inferior frontal gyrus has been found in dyslexics for both alphabetic and non-alphabetic languages (Georgiewa et al., 1999; Shaywitz et al., 2002; Siok et al., 2008). This region has been suggested to be involved in controlled phonological retrieval and manipulation (Devlin, Matthews, & Rushworth, 2003; Fiez, 1997; Fiez, Balota, Raichle, & Petersen, 1999; Poldrack et al., 1999). Because this region did not show greater activation in the rhyming task than in the semantic task, the reduced activation in this region in Chinese dyslexics is unlikely to reflect a deficit in phonological processing. In contrast, it may reflect a deficit in controlled retrieval of general lexical representations (Badre, Poldrack, Pare-Blagoev, Insler, & Wagner, 2005; Badre & Wagner, 2007; Cao et al., 2010).

In addition, we found significant correlations between left inferior frontal gyrus and posterior orthographic regions (bilateral occipito-temporal regions), suggesting that the abnormality in left inferior frontal gyrus and that in bilateral visual cortex may reflect deficits in connectivity. There are two possible explanations for this correlation. One explanation is that the reduced activation in left inferior frontal gyrus could result from decreased input from posterior visuo-orthographic regions. One recent study (Richlan et al., 2010) reported that abnormality in left occipito-temporal cortex was accompanied by absent responsiveness to increased sublexical reading demands in left inferior frontal gyrus. This explanation is also supported by recent effective connectivity studies showing abnormal connectivity from left occipito-temporal regions to left inferior frontal gyrus in dyslexic readers (Cao et al., 2008; van der Mark et al., 2011). Alternatively, the correlation may suggest that the reduced activation of the posterior regions is due to decreased top-down influence from frontal regions. However, previous studies have suggested that altered activation in posterior regions reflects a qualitative weakness in dyslexia (Hoeft et al., 2007; Pugh et al., 2001; Richlan et al., 2010). The altered activation in frontal regions may be due to altered input from posterior regions or compensatory processes to overcome dysfunctional posterior processing. One of our previous studies (Liu et al., 2010) has reported a deficit of bottom-up connections from left fusiform gyrus but not a deficit of top-down connections from inferior frontal gyrus in dyslexic children. Nevertheless, our study is the first to establish a relationship between abnormal activation in posterior occipito-temporal regions and in anterior frontal regions in Chinese dyslexia.

Interestingly, the significant correlation between the activation of left dorsal inferior frontal gyrus and bilateral visuo-orthographic regions was only found for the semantic task. A recent DTI study (Vandermosten et al., 2012) suggests that the left inferior fronto-occipital fasciculus, which connects the left ventral occipito-temporal region with the left inferior frontal gyrus, may be involved in the ventral route underlying reading by whole word orthographic access. For Chinese reading, mapping orthography to meaning is more direct and systematic than mapping orthography to phonology due to its logographic nature, which may be the reason that the correlation between left dorsal inferior frontal gyrus and bilateral visuo-orthographic regions was only found for the semantic task.

We also found significant task effects with greater activation in the semantic task compared to rhyming task in bilateral ventral inferior frontal gyrus and left middle temporal gyrus. The involvement of anterior ventral inferior frontal gyrus and middle temporal gyrus in semantic processing has been confirmed by a recent review (Lau, Phillips, & Poeppel, 2008). This review suggests that left middle temporal gyrus is involved in representing semantic information and that the anterior part of left inferior frontal gyrus is involved in controlled retrieval of semantic representations. Our finding of greater involvement of ventral inferior frontal gyrus and middle temporal gyrus for the semantic task is also consistent with our previous studies on semantic processing in Chinese (Booth et al., 2006; Liu et al., 2009).

In summary, Chinese children with dyslexia showed hypoactivation in bilateral visuo-orthographic and left inferior frontal regions for both the rhyme and semantic judgment tasks. The results of the correlation analysis suggest that the abnormalities in frontal cortex and in posterior visuo-orthographic regions may reflect a deficit in the connection between brain regions. Moreover, there was no evidence for greater group differences in the semantic task, suggesting that the central deficit of dyslexia in Chinese may not be in semantic processing. However, the absence of the task difference in the group effect in the current study may also be due to relatively small sample size or the nature of the experimental tasks. It is possible that a semantic task that was more difficult or that tapped into a different morphological process would show differences between dyslexic and typical readers. Indeed, previous research shows that certain morphological tasks, especially those requiring morpheme parsing from words with two or more morphemes, tend to be more difficult for Chinese children with dyslexia (Chung, Ho, Chan, Tsang, & Lee, 2011; Shu et al., 2006).

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Fig. 1.

Differences between TD and RD in left frontal and right visuo-orthographic regions. Left: Brain regions showing the main effect of group. Middle: Bar plots of the brain activation for the TD and RD in the two tasks for the regions showing the main effect of group. Right: Significant correlations in the semantic task between left frontal and right cuneus in the RD group, but not in the TD group. IFG=Inferior Frontal Gyrus. TD=Typically Developing; RD=Reading Disability.

Fig. 2.

Differences between the TD and RD in left occipito-temporal cortex. Upper Left: Left occipito-temporal region ($-44 -60 -16$) showed a main effect of group when using an anatomical mask (fusiform gyrus+inferior temporal gyrus). Upper Right: Bar plots of the brain activation for the TD and RD in the two tasks for the left occipito-temporal region. Lower: Significant correlations between left frontal and left occipito-temporal in the TD and RD groups in the semantic task. TD=Typically Developing; RD=Reading Disability. IFG=Inferior Frontal Gyrus; OT=Occipito-Temporal Region.

Fig. 3.

Brain regions showing differences between the semantic and rhyming task. IFG=Inferior Frontal Gyrus; MTG=Middle Temporal Gyrus. TD=Typically Developing; RD=Reading Disability.

Table 1

Demographic information and test scores for typically developing (TD) and reading disability (RD) groups.

	TD	RD	Significance
Gender	7M 4F	6M 5F	$p=0.664$
Age(months)	141.0(2.8)	144.6(5.1)	$p=0.051$
PIQ	109.4(15.9)	105.3(10.5)	$p=0.482$
CRM	3010(130)	2550(98)	$p<0.001$
CRF	1.12(0.18)	0.60(0.14)	$p<0.001$

Note: M=Male, F=Female; PIQ=Performance Intelligence Quotient; CRM=Character Recognition Measure and Assessment Scale for Primary School Children; CRF=Character Reading Fluency. PIQ is in standard scores with a mean of 100 and a standard deviation of 15. CRM is the number of characters that can be recognized out of the 3500 common Chinese characters. CRF is in characters per second.

Table 2

Stimuli characteristics for the rhyming and semantic tasks.

	Frequency		Acquisition term		Strokes	
	First	Second	First	Second	First	Second
Rhyme	31.27 (27.90)	31.47 (39.94)	5.03 (2.19)	5.31 (2.46)	10.07 (2.66)	10.03 (2.58)
Semantic	31.57 (31.07)	31.31 (30.08)	5.29 (2.40)	4.90 (2.43)	10.52 (3.04)	10.33 (2.63)

Note: Frequency is the number of times of a character shown in the Chinese language textbooks from Grade 1 to Grade 6 in the primary school. Acquisition term is the term when a character is first shown in the Chinese language textbooks.

Table 3

Mean accuracy and reaction time (and standard deviations) for experimental tasks for typically developing (TD) and reading disability (RD) groups.

Groups	Rhyme			Semantic		
	Character	Perceptual	Null	Character	Perceptual	Null
<i>ACC</i>						
TD	0.74(0.11)	0.99(0.03)	0.99(0.02)	0.85(0.08)	0.98(0.02)	0.98(0.02)
RD	0.61(0.07)	0.92(0.10)	0.97(0.04)	0.75(0.12)	0.89(0.13)	0.97(0.06)
TD-RD	0.13**	0.07	0.02	0.10*	0.09	0.01
<i>RT</i>						
TD	1751(328)	1044(302)	1464(269)	1480(318)	1057(276)	1526(273)
RD	1310(397)	947(345)	1445(218)	1329(293)	944(323)	1471(205)
TD-RD	441*	97	19	151	113	55

Note: ACC=Accuracy; RT=Reaction Time, TD-RD=difference score between groups.

*
 $p < 0.05$.

**
 $p < 0.005$.

Table 4

Brain regions showing the main effect of group, task, and group by task interaction.

Regions	<i>H</i>	BA	<i>x</i>	<i>y</i>	<i>z</i>	<i>F</i>	Voxels
<i>Main effect of group</i>							
Inferior frontal gyrus	<i>L</i>	44	-58	14	20	23.29	20
Cuneus	<i>R</i>	18	16	-92	18	17.54	18
<i>Main effect of task</i>							
Inferior frontal gyrus	<i>L</i>	11/47	-40	34	-12	30.32	97
Middle temporal gyrus	<i>L</i>	21	-64	-50	0	23.47	19
Middle temporal/angular gyrus	<i>L</i>	39	-44	-64	20	20.86	142
Inferior frontal gyrus	<i>R</i>	11	34	36	-14	24.72	19
<i>Group by task interaction</i>							
-	-	-	-	-	-	-	-

Note: *H*=hemisphere; *L*=left; *R*=right; BA=Brodmann's Areas; *x*, *y*, *z*: Montreal Neurological Institute (MNI) coordinates; *F*=*F* score; Clusters presented are those surviving a threshold of AlphaSim corrected $p < 0.05$.