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Neural correlates of oral word reading, silent reading comprehension, and cognitive subcomponents

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1945

Abstract

The ability to read is essential for cognitive development. To deepen our understanding of reading acquisition, we explored the neuroanatomical correlates (cortical thickness; CT) of word-reading fluency and sentence comprehension efficiency in Chinese with a group of typically developing children ($N = 21$; 12 females and 9 males; age range 10.7–12.3 years). Then, we investigated the relationship between the CT of reading-defined regions and the cognitive subcomponents of reading to determine whether our study lends support to the multi-component model. The results demonstrated that children's performance on oral word reading was positively correlated with CT in the left superior temporal gyrus (LSTG), left inferior temporal gyrus (LITG), left supramarginal gyrus (LSMG) and right superior temporal gyrus (RSTG). Moreover, CT in the LSTG, LSMG and LITG uniquely predicted children's phonetic representation, phonological awareness, and orthography–phonology mapping skills, respectively. By contrast, children's performance on sentence-reading comprehension was positively correlated with CT in the left parahippocampus (LPHP) and right calcarine fissure (RV1). As for the subcomponents of reading, CT in the LPHP was exclusively correlated with morphological awareness, whereas CT in the RV1 was correlated with orthography–semantic mapping. Taken together, these findings indicate that the reading network of typically developing children consists of multiple sub-divisions, thus providing neuroanatomical evidence in support of the multi-componential view of reading.

There is an increasing interest in the neural impairments associated with reading difficulties (Altarelli et al., 2013; Clark et al., 2014; Frye et al., 2010; Hosseini et al., 2013; Liu et al., 2015; Ma et al., 2015; Qi et al., 2016; Richlan, Kronbichler, & Wimmer, 2013; Welcome, Chiarello, Thompson, & Sowell, 2011; Williams, Juranek, Cirino, & Fletcher, 2017). As a complement to group comparisons between impaired and typically developing individuals, exploring the neural mechanisms underlying typical reading development helps to reveal the critical period and the important neural circuits for developing reading skills (Goldman & Manis, 2013; Houston et al., 2014; Lu et al., 2007; Richardson & Price, 2009; Simon et al., 2013). To deepen our understanding of this issue, the present study explored the relationship between cortical thickness (CT) and reading competence as well as various cognitive subcomponents that underlie reading by using a brain–behavior correlation method (Golestani, 2014; Kanai & Rees, 2011).

Specifically, two characteristics of reading were taken into consideration. The first is that reading ability can be measured at different levels, and two major ones are word-reading fluency and sentence-reading comprehension (Lyon, Shaywitz, & Shaywitz, 2003). Compared to the limited research on sentence-reading comprehension (but see Benjamin & Gaab, 2012), numerous neuroimaging studies have together revealed a left-lateralized reading network for single-word reading. This network consists of the ventral occipito-temporal cortex (including the fusiform gyrus and the inferior temporal gyrus), posterior temporo-parietal regions (including the posterior superior temporal gyrus and the supramarginal gyrus) and inferior frontal gyrus, which are involved in orthographic processing, phonological decoding and articulatory planning, respectively (Price, 2012). Part of the reason why word-reading fluency has attracted more attention than sentence-reading comprehension is because poor performance on word reading is one of the defining criteria for the diagnosis of dyslexia, whereas poor reading comprehension is not. In fact, these two aspects of reading

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are relatively independent. On the one hand, children with dyslexia do not necessarily have difficulties in comprehension. These individuals are termed resilient readers (Welcome, Chiarello, Halderman, & Leonard, 2009; Welcome et al., 2011; Welcome, Leonard, & Chiarello, 2010). On the other hand, there are also individuals with a specific reading comprehension disorder who have intact word-reading performance but impaired reading comprehension (Nation, Cocksey, Taylor, & Bishop, 2010). Therefore, exploring the neural correlates of reading comprehension and identifying the shared and specific brain bases for different levels of reading is important for a better understanding of the different types of reading disorders and further establishing more efficient intervention programs.

The second characteristic of reading is that it is multi-componential in nature, that is, the entire process consists of many subcomponents (Norton & Wolf, 2012). Moreover, oral reading and reading comprehension are composed of different subcomponents (Tobia & Bonifacci, 2015). According to the Simple View of Reading (Gough & Tunmer, 1986), decoding skills contribute more to word reading, whereas oral comprehension contributes more to reading comprehension. More specifically, oral word reading mainly includes processes such as visual feature identification, sight-word recognition, morpho-phonological code retrieval, phonetic encoding and articulation (Indefrey, 2011; Indefrey & Levelt, 2004), whereas reading comprehension relies more on semantic processing and world knowledge (Welcome et al., 2009). In line with this dissociation, cognitive subcomponents, such as phonological processing, are strong predictors of word reading, whereas subcomponents, such as inference skills and knowledge of narrative text structure, predict reading comprehension in typically developing children (Oakhill & Cain, 2012). Given the multi-componential nature of reading, a successful reader (regardless of word reading or sentence comprehension) must integrate the activation of numerous brain areas that are responsible for specific subcomponents. Recently, the relationship between specific brain areas and various subcomponents of word reading has been identified in terms of brain activation (Graves, Desai, Humphries, Seidenberg, & Binder, 2010; McNorgan, Chabal, O'Young, Lukic, & Booth, 2015; Woodhead, Brownsett, Dhanjal, Beckmann, & Wise, 2011) and white mater tracts (Vandermosten et al., 2012). Because acquisition of fluent reading requires formal instruction and long-term training, and brain structural and functional properties could be simultaneously shaped by long-term experience (Anurova, Renier, De Volder, Carlson, & Rauschecker, 2015), it is reasonable to consider that such a hierarchical structure could also be found at the neuroanatomical level. Additionally, the multi-componential hypothesis is also worth exploring for the study of reading comprehension.

From a developmental perspective, reading ability changes rapidly, especially during childhood and adolescence (Cohen-Shikora & Balota, 2016). Given that different reading skills rely on different cognitive components at different developmental stages (Siu, Ho, Chan, & Chung, 2016; Vaessen et al., 2010), the brain–behavior relationship may also change across different stages of skill acquisition. Training studies have revealed that cortices thicken in the learning period but thin in consolidation (Lovden, Wenger, Martensson, Lindenberger, & Backman, 2013). As the acquisition of proficient reading skills requires years of learning and practice, the direction and strength of its correlation with specific brain measures might also change throughout development. If this is the case, we will find a positive correlation in the early stage and a negative correlation later. In line with this developmental perspective, studies

of at-risk/poor readers have demonstrated such abnormal trajectories in gray and white matter maturation (Clark et al., 2014; Yeatman, Dougherty, Ben-Shachar, & Wandell, 2012). When the brain–behavior relationships were investigated in typical readers, the primary method used was to calculate correlation coefficients between brain measures and behavioral indices while controlling for age. However, the relationships might be obscured, especially when the sample size is small but the age range is wide. In this case, examing the brain–behavior relationships within a specific age range would be helpful. Such results will help to further illuminate the development of the brain–reading relationship across childhood and adolescence.

Finally, the neural correlates of reading can be affected by the linguistic features of a given writing system (Frost, 2012; Perfetti & Harris, 2013; Ziegler & Goswami, 2005). For example, Zhang and colleagues (2013) identified a positive correlation between the CT of the left mid-fusiform gyrus and oral word-reading efficiency in Chinese college students. This result was different from the negative correlation found in English-speaking adults (Blackmon et al., 2010). The discrepancy might be partly related to the properties of Chinese characters, e.g. complex spatial shapes and artificial print-sound correspondences. In another word, successful reading of Chinese requires more orthographic analysis and orthographic–phonological mapping. The participants in Zhang's study were healthy adults with mature neural systems; however, the relationship between CT and reading performance in typically developing children remains largely unknown. In addition to the special writing system, Chinese is also a tonal language. One previous study revealed that Chinese dyslexic children have an abnormal neuronal response during the categorical perception of lexical tones. This abnormal response is similar to the impaired categorical perception of segmental features by children with dyslexia in alphabetic languages (Zhang et al., 2012). The brain regions associated with these specific speech processing skills in typically developing children are worth examining.

In this study, we aimed to explore the brain–reading relationship in a group of typically developing children. We focused on reading abilities at two different levels: word-reading efficiency and sentence comprehension. On this basis, we further used a series of tasks to measure different cognitive subcomponents involved in word reading and sentence comprehension to investigate the relationships between reading-defined regions and various cognitive subcomponents. Children aged 10–12 years were recruited because humans exhibit a high level of brain plasticity during this period (Brenhouse & Andersen, 2011) and are at the reading acquisition stage for Chinese (Shu, Chen, Anderson, Wu, & Xuan, 2003). Because participants in the current study were all native speakers of Chinese, the results could help us to understand the language-specificity of reading. The following predictions were made: (1) Given the stage of the children's reading development (Shu et al., 2003) and the prior knowledge that learning a new skill thickens specific regions (Lovden et al., 2013), we expected to observe positive relationships between regional CT and reading performance for both word-reading and sentence comprehension. (2) Previous studies of alphabetic languages have revealed that morphometric features in the left fusiform gyrus and inferior parietal cortex are associated with word-level reading efficiency (Houston et al., 2014; Jednorog et al., 2015; Simon et al., 2013), whereas the left angular gyrus and inferior frontal gyrus are associated with comprehension (Goldman & Manis, 2013). We expected that such a spatially distinctive pattern would also be observed in Chinese children. (3) Regarding the associations

between reading-related regions and subcomponents of reading, previous neuroanatomical studies have mainly focused on phonological awareness, which has been found to be correlated with morphometric development in the inferior frontal and inferior parietal regions (Houston et al., 2014; Lu et al., 2007). As functional and diffusion imaging studies have revealed differernt and specific cognitive subcomponents of reading (e.g., Graves et al., 2010; Vandermosten et al., 2012), we predicted that associations between specific brain regions and the subcomponents of reading could also be observed at the neuroanatomical level. Specifically, the temporo-parietal regions are more associated with phonological processing, and the ventral occipito-temporal regions are more associated with orthographic processing.

Materials and methods

Participants

A total of 21 typically developing children (12 females, mean age = 11.2 years, $SD = 0.3$ year, range = 10.7–12.3 years) from local primary schools (19 in Grade 5, and 2 in Grade 6) in Beijing were recruited. The current study focused on children in Grades 5–6 because this period is important for developing automatic oral reading efficiency and higher level reading comprehension skills (Shu et al., 2003). The following inclusion criteria were applied: 1) All participants were right-handed native speakers of Mandarin, and had normal or corrected-to-normal vision; 2) none of the participants had a history (via self-report) of any neurological or psychiatric disorders; 3) the typically developing children had normal reading abilities. Reading ability was measured by using a standardized character recognition test (z score mean = 0.333, $SD = 0.721$, range = −0.96–1.62) (Lei et al., 2011; Zhang et al., 2012). All of the children successfully completed MRI scans and neuropsychological tests. The image quality was assessed by an independent radiologist who was blinded to the research information, and no child was excluded because of poor image quality. Written informed assent and consent were obtained from the children and their parents. This study was approved by the Institutional Review Board at Beijing Normal University.

Neurocognitive measures

Neuropsychological tests were given to each child individually, covering reading abilities, reading-related cognitive subcomponents and general intelligence.

Reading abilities. We focused on fluency attainment at two levels. Word-reading efficiency and sentence-reading comprehension were measured by two time-limited tasks, respectively.

Word List Reading was used to measure word-reading efficiency. In this task, 180 two-character words with high frequency were arranged in a 9-column × 20-row matrix on one A4 paper. Children were instructed to read these words as accurately and rapidly as possible. The completion time and the number of error responses were recorded to calculate how many words the children read correctly per minute (Zhang et al., 2012).

Reading Fluency was used to measure sentence-reading comprehension. This test consisted of 100 single sentences or short paragraphs with an increasing number of characters from 7 to 159. Children were asked to silently read as many sentences as possible and indicate the correctness of the meaning of the sentences based on their world knowledge with a "√" or "×" within

3 minutes. The total score was calculated as the sum of characters in the sentences with correct responses (Lei et al., 2011).

Subcomponents of Word Recognition and Sentence Comprehension. A battery of tests was applied to measure the cognitive subcomponents that underlie word-reading efficiency and sentence-reading comprehension. According to prior knowledge, we treated phonological representation, phonological awareness, orthography–phonology mapping and orthographic identification as potential subcomponents of word-reading efficiency. Morphological awareness, orthography–semantic mapping and orthographic identification were regarded as potential subcomponents of sentence-reading comprehension. In the following section, we first describe the tasks orally presented and then the tasks with visual input.

Tone Identification was used to measure categorical perception of Chinese lexical tones and reflect phonological representation. The task consisted of 66 trials in total. During the task, participants were asked to decide whether the sound they heard was tone 2 (i.e., rising) or tone 4 (i.e., falling). A detailed description of the stimuli and task can be found in our previous study (Xi, Zhang, Shu, Zhang, & Li, 2010). Instead of using logistic regression, we conducted receiver operating characteristic (ROC) curve analysis and calculated the area under the curve (AUC) to quantify the category sensitivity. A larger ROC value (termed ROC area in this study) represents a better discrimination between the two categories.

Tone Detection was used to measure phonological awareness. There were 16 trials in total (8 in the speech condition and 8 in the non-speech condition). In any single trial, three syllables were presented sequentially. The participants had to note which syllable had a different tone by pressing the corresponding button. The accuracy and reaction time for each trial were collected. Inverse efficiency (the average reaction time of correct trials divided by the accuracy) was then calculated as the index of phonological awareness. This measure can address the speed-accuracy trade-off effect and has been used in previous studies examing brain–behavior relationships (e.g., Wei et al., 2012).

Morphological Production was used to measure morphological awareness. In each trial, a two-character word was orally given with one of the characters being the target. The children were asked to produce two new words containing this target character; in one word, the target character had the same morpheme as in the given word, whereas in the other, it had a different morpheme. For example, the two-character word /mian 4/ /fen 3/ ("flour") with /mian 4/ as the target was orally presented. The possible correct answers were /mian 4/ /bao 1/ ("bread") for the same morpheme response and /mian 4/ /kong 3/ for the different morpheme response. One correct answer was worth one point. A total of 15 characters were presented with a maximum score of 30.

Chain Tests were used to measure the subcomponents of character- and word-level reading. Chain tests are a set of cross-out tasks, the details of which can be found in our previous study (Zou, Desroches, Liu, Xia, & Shu, 2012). Briefly, the children were required to mark a specific target in each subtest. The number of correct responses and false alarms were counted and the final score was calculated as follows: ([number of correct responses] – [number of false alarms]) / (time limit in minute). It should be noted that we used Chain Tests (phonology-related subtests) instead of rapid naming because these tasks contain the same two essential elements (i.e., serial processing and orthography–phonology mapping) (Georgiou, Parrila, Cui, & Papadopoulos, 2013; Yan, Pan, Laubrock, Kliegl, & Shu, 2013) but are more appropriate to estimate

a relatively pure subcomponent of word reading as no stimuli are presented twice and no articulation is required. In total, six subtests were included: (a) *Orthography Judgment* consisted of 154 items, including 104 high-frequency characters and 50 non-characters. Children were asked to mark all non-characters with a slash "\" in 30 seconds. (b) *Onset Judgment* consisted of 308 high-frequency single-character words with an average word frequency of approximately 125 times per million. The pronunciation of 100 of the items began with /p/, whereas the remaining items did not. The items were ordered randomly. Children were asked to mark all words produced with an initial /p/ with a slash "\". The time limit for this task was 80 seconds. (c) *Rime Judgment* contained 120 characters with high frequency, of which 40 characters ended with the sound /u/. Participants were asked to mark them with a slash "\" as accurately and rapidly as possible in 80 seconds. (d) *Tone Judgment* consisted of 120 characters with high frequency, of which 34 characters had a sound with tone 3 (low-falling; e.g., /ma 3/). Participants had to mark the 34 characters with a slash "\" as accurately and rapidly as possible in 80 seconds. (e) *Animal Word Identification* consisted of 110 two- or three-character words with high frequency, 38 of which were animal words. Animal and non-animal words were presented in a random order. Children were asked to mark all the animal words with a slash "\" in 35 seconds. (f) *Homophone Discrimination* consisted of 110 two-character words with high frequency, of which 35 words had one character replaced by a homophone. These pseudo-homophone words do not exist in Chinese. Participants were required to mark all the pseudo-homophones with a slash "\" in 45 seconds. Three reading components were estimated based on *Chain Tests*. Specifically, orthographic processing was estimated with orthography judgment (min = -1.649, max = 1.688), orthography–phonology mapping was estimated with onset, rime and tone judgment (min = -1.539, max = 2.553), and orthography–semantic mapping was estimated with animal word identification and homophone discrimination (min = -1.300, max = 1.669). To create the composite scores for orthographic-phonological and orthographic–semantic mapping, raw scores were converted into z scores and averaged.

General intelligence. In this study, IQ was assessed by using the Chinese Wechsler Intelligence Scale for Children (WISC-CR) (Wechsler, 1974).

Image acquisition and processing

Before acquiring the real images, all of the children were familiarized with the scanner and the noise of the actual MRI environment in a mock scanner. All images were collected at Beijing Normal University's Brain Imaging Center using a TrioTim 3 Tesla Siemens scanner. A high-resolution, whole-brain, T1-weighted structural image was acquired (the magnetization-prepared rapid-acquisition gradient-echo (MPRAGE) sequence, repetition time (TR) = 2530 ms; echo time (TE) = 3.39 ms; inversion time (TI) = 1100 ms; flip angle = 7°; axial slices = 144; slice thickness = 1.33 mm; field of view (FOV) = 256 × 256 mm; matrix = 256 × 256 × 144; voxel size = 1.33 × 1 × 1.33 mm) for each participant.

CIVET pipeline (v1.1.9; http://www.bic.mni.mcgill.ca/Services Software/CIVET) was employed to acquire the surface-based morphometry, as previously described (Gong, He, Chen, & Evans, 2012). T1-weighted MR images were first registered into stereotaxic space using a 9-parameter linear transformation. Images were corrected for non-uniformity artifacts using the N3 algorithm (Sled, Zijdenbos, & Evans, 1998). The registered and corrected images were further segmented into gray matter, white matter, cerebrospinal fluid, and background by using a neural net classifier (Sled et al., 1998; Zijdenbos, Forghani, & Evans, 2002). The inner and outer gray matter surfaces were then automatically extracted from each hemisphere using the Constrained Laplacian ASP (CLASP) algorithm (Kim et al., 2005; MacDonald, Kabani, Avis, & Evans, 2000). Cortical thickness was measured in native space using the linked distance (i.e., t-link) (Lerch & Evans, 2005) between the two surfaces at 40,962 vertices per hemisphere. The cortical thickness algorithm has been validated using both manual measurements (Kabani, Le Goualher, MacDonald, & Evans, 2001) and simulation approaches (Lee et al., 2006). Prior to the statistical analyses, diffusion smoothing was performed using a 20-mm full-width half-maximum surface-based kernel for the thickness map of each participant (Chung et al., 2003).

Statistical analyses

The primary objective of this study was to investigate the neuroanatomical correlates of reading abilities at different levels, as well as the relationship between reading-related areas and various cognitive subcomponents. Before analyzing the brain, we first calculated the Pearson's correlations between word-reading efficiency, sentence-reading comprehension and the cognitive subcomponents while controlling for age, gender, and performance IQ to determine the relationships between reading and various subcomponents at the behavioral level.

Then, SurfStat (http://www.math.mcgill.ca/keith/surfstat/) was used to conduct vertex-based statistics to explore the neuroanatomical correlates of word-reading efficiency. Confounding factors (age, gender, and performance IQ) were controlled in the linear regression model. We used a whole-brain vertex-wise approach instead of using pre-defined regions-of-interest (ROIs) to avoid selection bias. A Random Field Theory (RFT) corrected p cluster < .05 (height p vertex < .005) was used to address the multiple comparison error. MNI coordinates were used to report significant clusters.

Following the whole-brain analysis, we created a mask for each significant cluster by using a circular ROI with a 4 mm-radius centered on the peak. The thickness value of each vertex in the mask was averaged and used in subsequent analyses. ROI analyses were performed with three aims. To test whether the regions were also correlated with reading comprehension (Aim 1), we calculated the Pearson's correlations (controlling for age, gender, and performance IQ) between the mean CT in each ROI and the sentence-reading comprehension. To examine whether the regions were specific to word-reading efficiency (Aim 2), we calculated the Pearson's correlations between the mean CT in each ROI and word-reading efficiency while further controlling for sentence-reading comprehension. To test the hypothesis that various brain areas were differentially correlated with specific subcomponents of reading (Aim 3), we carried out linear regression analyses. In each regression model, the cognitive measure was adjusted for confounding factors (age, gender, and performance IQ) and was entered as a dependent variable, whereas the CTs of all significant brain areas were entered as predictors using a stepwise selection method (criteria: probability of F to enter ≤.05, probability of F to remove ≥.100). A threshold of false discovery rate (FDR) corrected p < .05 was used in each test.

Table 1. Demographic information and behavioral performance on reading-related tasks.

Behavior task	Minimum	Maximum	Mean	Standard deviation
Full scale IQ (standard score)	95	122	107.50	7.90
Verbal IQ (standard score)	96	122	107.00	7.10
Performance IQ (standard score)	84	128	107.33	9.54
Word list reading (word/min)	64	122	93.89	14.57
Reading fluency (character/min)	172	562	315.52	79.28
Tone identification (area under the curve)	0.81	1.00	0.94	0.04
Tone detection (inverse efficiency)	3,447	17,186	8,477	4,094
Morphological production (correct response)	19	30	24.57	2.64
Chain tests (item/min)				
Orthography judgment	38.00	70.00	53.81	9.59
Onset judgment	11.25	31.50	18.86	5.04
Final judgment	7.50	28.50	15.64	4.50
Tone judgment	4.50	23.25	11.29	5.21
Animal word identification	27.43	41.14	32.49	4.07
Homophone discrimination	12.00	33.33	21.78	6.22

Note. $n = 21$.

Similar analyses were conducted for sentence-reading comprehension. First, a whole-brain vertex-wise analysis was conducted to determine whether the CT variations of a brain area could explain individual differences in reading comprehension. Next, ROI analyses were performed to answer the following questions: (1) whether these regions were also associated with word-reading efficiency or (2) were unique to sentence-reading comprehension, and (3) whether there were relationships between the reading-related areas and cognitive subcomponents underlying sentence-reading comprehension. For the third question, it is important to note that both the same stepwise selection method and significant threshold of corrected $p < .05$ were used in the linear regression models. All of the behavioral statistics and ROI analyses were performed using SPSS18.0 (IBM, Inc.).

Results

Descriptive statistics and correlations between behavioral measures

Table 1 shows the mean, standard deviation, minimal and maximal values of all behavioral measurements. The IQ of each child fell within the normal range (Full Scale IQ: 95–122, verbal IQ: 96–122, performance IQ: 84–128.). There was a wide range of reading performances in the word-reading and sentence comprehension tasks (word-reading efficiency: raw score 64–122; sentence-reading comprehension: raw score 172–562).

Word-reading efficiency and sentence-reading comprehension were significantly correlated ($r = 0.470$, $p = .049$; Table 2). Word-reading efficiency was also significantly correlated with several subcomponents including phonological representation ($r = 0.643$, $p = .004$), phonological awareness ($r = 0.516$, $p = .029$), orthography–phonology mapping ($r = 0.662$, $p = .003$) and orthography–semantic mapping ($r = 0.536$, $p = .022$). The correlations between word-reading efficiency with morphological awareness ($r = 0.165$, $p = .513$) and orthographical processing ($r = 0.149$, $p = .555$) were not significant. In contrast to word-reading efficiency, sentence-reading comprehension was significantly

correlated with morphological awareness ($r = 0.502$, $p = .034$) and orthographic processing ($r = 0.505$, $p = .032$). Sentence-reading comprehension was also significantly correlated with orthography–semantic mapping ($r = 0.772$, $p < .001$) and two out of the three phonological subcomponents (phonological representation: $r = 0.508$, $p = .032$; phonological awareness: $r = 0.203$, $p = .418$; orthography–phonology mapping: $r = 0.621$, $p = .006$).

Correlations between cortical thickness and word-reading efficiency/reading-related subcomponents

Whole-brain regression. Significant positive correlations between CT and word-reading efficiency were found in four brain areas after controlling for age, gender and performance IQ (Table 3, Figure 1A). These clusters were in the right superior temporal gyrus (RSTG: x, y, z = 43, −19, 3), left inferior temporal gyrus (LITG: x, y, z = −55, −31, −27), left superior temporal gyrus (LSTG: x, y, z = −39, −22, 6), and left supramarginal gyrus (LSMG: x, y, z = −60, −37, 37). In other words, children aged 10–12 years who performed better in word reading had a thicker cortex in these four regions. No regions showed a significant negative correlation.

ROI analyses. We extracted the mean thickness of the 4 ROIs identified by the whole-brain analysis. To examine the similarity, we determined whether these regions also correlated with the sentence comprehension scores. None of the correlations was significant after FDR correction (ps > .05, corrected). To test the specificity, we added the sentence comprehension score as a covariate of uninterest while calculating correlations between CT and word-reading efficiency. The results showed that the correlations in all four ROIs remained significant (RSTG: $r = 0.708$, $p = .001$; LITG: $r = 0.676$, $p = .003$; LSTG: $r = 0.712$, $p = .001$; LSMG: $r = 0.708$, $p = .001$). Finally, we examined the relationship between CT in these ROIs and the subcomponents of interest. Consequently, we found a significant contribution of the LITG in predicting orthography–phonology mapping ($t = 3.153$, $p = .005$), the LSMG in predicting phonological awareness ($t = 2.438$, $p = .025$), and the LSTG in predicting the categorical perception of lexical tones ($t = 3.17$, $p = .005$). All of the correlations remained significant (ps < .05) after the FDR correction for the number of analyses. There was no significant result for orthographic processing (Table 4 and Figure 2).

Correlations between cortical thickness and sentence-reading comprehension/reading-related subcomponents

Whole-brain regression. Two significant clusters correlated with sentence-reading comprehension independent of age, gender and performance IQ (Table 3, Figure 1B). These clusters were in the left parahippocampus (LPHP: x, y, z = −27, −1, −27) and right calcarine fissure (RV1: x, y, z = 9, −104, 5). In other words, children aged 10–12 years who performed better in reading comprehension had a thicker cortex in these two regions.

ROI analysis. In the ROI analysis, we first examined whether these regions also correlated with word-reading efficiency and found that all of the correlations were non-significant after FDR correction (ps > .05, corrected). Then, we added word-reading efficiency as

Table 2. Partial correlations between reading abilities and underlying cognitive skills, while controlling for age, gender, and performance IQ.

No	Measured Skills	1	2	3	4	5	6	7	8
1	Word reading efficiency	–							
2	Sentence-reading comprehension	0.470*	–						
3	Phonological representation	0.643**	0.508*	–					
4	Phonological awareness	0.516*	0.203	−0.634**	–				
5	Morphological awareness	0.165	0.502*	0.347	0.108	–			
6	Orthography–phonology mapping	0.662**	0.621**	0.674**	0.691**	0.181	–		
7	Orthography–semantic mapping	0.536*	0.772***	0.491*	0.288	0.406†	0.559*	–	
8	Orthographic processing	0.149	0.505*	−0.026	−0.116	0.260	0.158	0.431†	–

Note. $n = 21$; †$p < .1$, *$p < .05$, **$p < .01$, ***$p < .001$.

Table 3. Significant clusters identified by the whole-brain regression analyses for word-reading efficiency and sentence-reading comprehension.

Reading measures	Name	Regions	Number of vertex	p cluster (corrected)	95% confidence interval for β	Peak			
						t value	x	y	z
Word-reading efficiency	RSTG	Right superior temporal gyrus	501	0.011	22.331, 56.034	5.29	43	−19	3
	LITG	Left inferior temporal gyrus	451	0.029	22.750, 61.825	4.49	−55	−31	−27
	LSTG	Left superior temporal gyrus and Heschl gyrus	431	0.037	16.878, 44.305	5.78	−39	−22	6
	LSMG	Left supramarginal gyrus	290	0.041	31.968, 84.180	5.53	−60	−37	37
Sentence-reading comprehension	LPHP	Left parahippocampus	193	0.022	73.838, 219.046	4.27	−27	−1	−27
	RV1	Right calcarine fissure	334	0.023	167.590, 371.509	7.85	9	−104	5

Note. $n = 21$. Mean thickness of the cluster was used to calculate 95% confidence interval.

a covariate of uninterest when calculating the correlations between CT and sentence-reading comprehension to examine the specificity. We found that both correlations remained significant (RV1: $r = 0.897$, $p = .001$; LPHP: $r = 0.646$, $p = .005$). Finally, we examined the relationship between CT in the reading-defined regions with the cognitive subcomponent. The results showed a significant contribution of the RV1 in predicting orthography–semantic mapping ($t = 3.184$, $p = .005$) and the LPHP in predicting morphological awareness ($t = 3.08$, $p = .006$) (Table 4 and Figure 2). Both of these remained significant ($ps < .05$) after FDR correction for the number of analyses. No significant results were found for orthographic processing.

Discussion

Reading is an essential skill in modern society. Understanding the neural mechanisms underlying successful reading acquisition benefits educational practices, especially for those who have difficulties in reading. By combining structural images with a series of reading tasks, we identified spatially distinct neural correlates for reading competence at the level of word-reading efficiency and sentence comprehension in a group of typically developing children. Moreover, we demonstrated that the CT of specific reading-related regions predicts children's performance on different cognitive subcomponents, supporting the multi-componential view of reading.

Reading fluency and underlying cognitive subcomponents

Fluent word reading requires participants to name high-frequency words as accurately as possible. During this process, multiple cognitive subcomponents including orthographic identification, phonological representation and access, and speech articulation are recruited (Indefrey, 2011; Indefrey & Levelt, 2004). In line with such a multi-componential view, we found that the children's performance on this task positively correlated with three phonological processing skills, including phonological awareness, categorical perception of lexical tones and orthographic–phonological mapping. The importance of phonological awareness has been implicated when learning to read (Melby-Lervag, Lyster, & Hulme, 2012), and its impairment has been regarded as a major deficit in dyslexia (Gabrieli, 2009; Vellutino, Fletcher, Snowling, & Scanlon, 2004; Wagner & Torgensen, 1987). There is an ongoing debate on whether the deficit occurs in phonological representation or access to phonological processing as both hypotheses are supported by behavioral and neuroimaging research (Boets et al., 2013; Ramus, 2004; Ramus & Ahissar, 2012; Ramus & Szenkovits, 2008). On the one hand, the close link between poor phonological awareness and speech perception deficits (e.g., lack of categorical perception of phonological features) has demonstrated a preference for the representation explanation (Nittrouer & Pennington, 2010; Tong, Tong, & McBride-Chang, 2015; Wang, Huss, Hamalainen, & Goswami, 2012; Zhang et al., 2012). On the other hand, rapid naming explains unique variations in children's reading ability (Landerl et al., 2013; Norton & Wolf, 2012; Vaessen et al., 2010). The mechanisms underlying the close relationship between rapid naming and reading are thought to be the shared processes of serial processing and orthography–phonology mapping (Georgiou et al., 2013; Yan et al., 2013). Therefore, the access explanation of the phonological deficit hypothesis is supported. In the current study, we found significant correlations between reading ability and all three phonological processing-related subcomponents. This result suggests that representation, access and manipulation of phonological information

A. Correlation between Cortical Thickness and Word Reading Efficiency
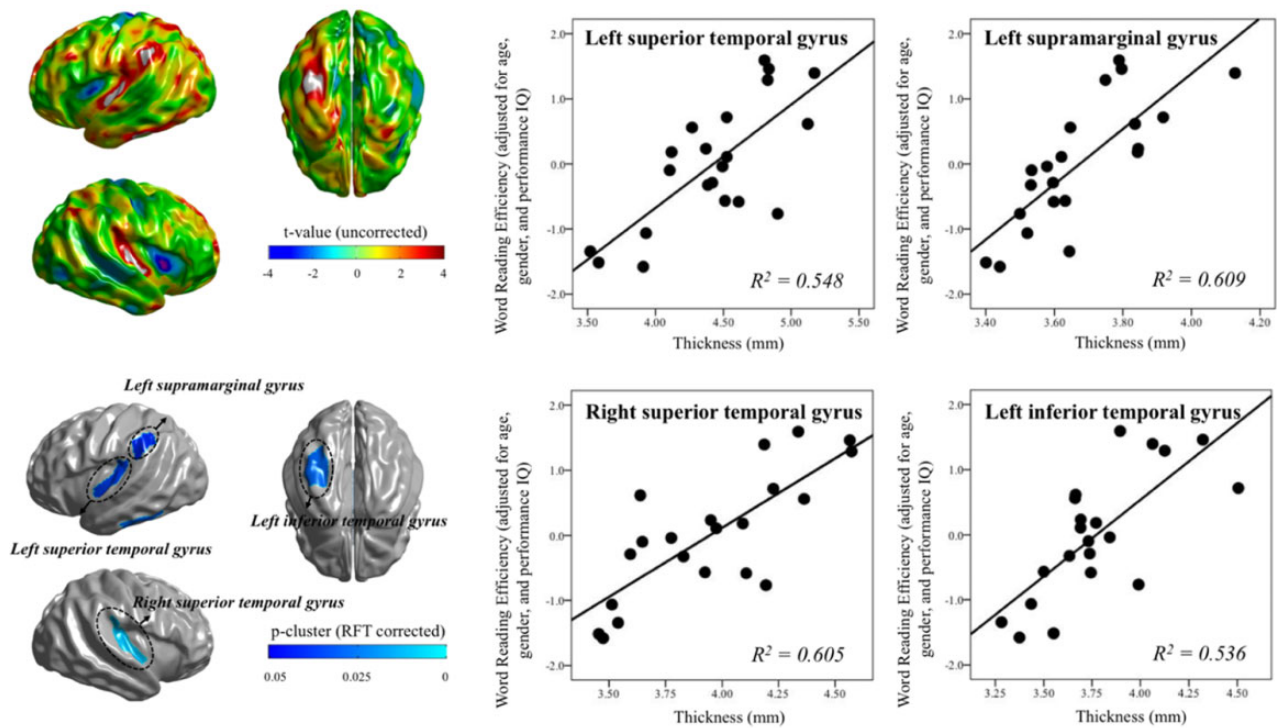
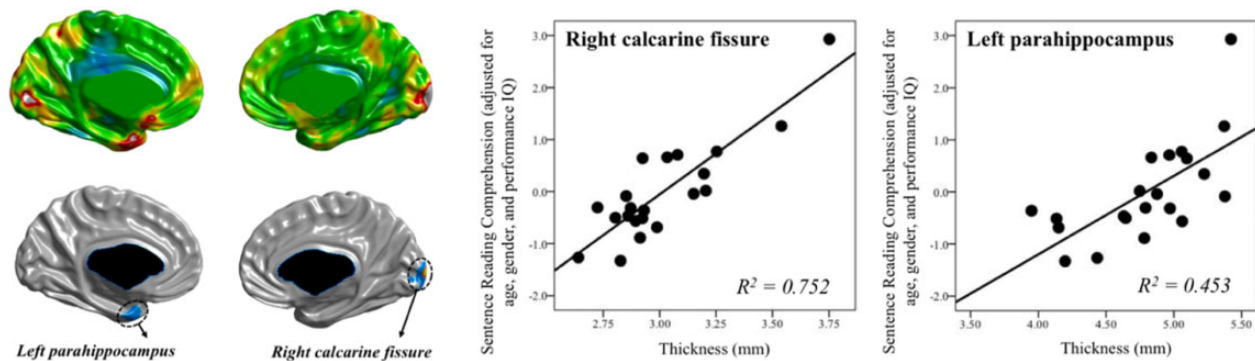## B. Correlation between Cortical Thickness and Word Reading Comprehension

Figure 1. A. Results of the whole-brain regression analysis between word reading efficiency and cortical thickness, controlling for age, gender and performance IQ ($n = 21$). Clusters that survived the random field theory (RFT) correction are presented on a standard inflated surface template. Left panel: clusters with an RFT-corrected $p < .05$ are projected on a standard surface template. Right panel: scatter plots present the brain–behavior correlation in each significant cluster (x axis: cortical thickness in mm, y axis: reading scores adjusted for age, gender and performance IQ). B. Results of sentence-reading comprehension are presented in the same way.

may all contribute to Chinese reading fluency, at least in typically developing children at the end of elementary school.

In contrast to oral word reading, better performance on silent sentence comprehension relies more on semantic processing and orthographic–semantic mapping. For example, Oakhill and Cain (2012) demonstrated that reading comprehension could be predicted by cognitive skills such as inference, comprehension monitoring, knowledge, use of story structure, vocabulary, and verbal IQ, most of which are related to basic and higher level semantic processes. Their finding is consistent with research on resilient readers (adults with intact reading comprehension skills despite poor phonological ability), whose reading comprehension performance is associated with high-level semantic skills, as well as general world knowledge (Welcome et al., 2009). The "lexical quality hypothesis" proposed by Perfetti and Hart (2002) posits that skilled reading comprehension depends on the quality of lexical representation and the retrieval of semantic information from orthographic forms. In accordance with this hypothesis and previous research, we found strong correlations between sentence comprehension and the sub-components including morphological awareness, orthographic skills, and orthographic–semantic mapping. Taken together, oral word reading and sentence comprehension recruit both common and distinct cognitive subcomponents in Chinese typically developing children in higher elementary school grades.

Table 4. Results of multiple regressions using thickness of regions-of-interest to predict subcomponents of reading.

Reading skills	Models	Subcomponents	Significant Regions	ΔR^2	t value	p value	95% confidence interval for β
Word-reading efficiency[a]	1	Orthographic processing	–	–	–	–	–
	2	Orthography–phonology mapping	Left inferior temporal gyrus	0.343	3.153	0.005	1.605, 7.944
	3	Phonological awareness	Left supramarginal gyrus	0.238	2.438	0.025	0.376, 4.940
	4	Phonological representation	Left superior temporal gyrus	0.346	3.170	0.005	0.425, 2.075
Sentence-reading comprehension[b]	5	Orthographic processing	–	–	–	–	–
	6	Orthography–semantic mapping	Right calcarine fissure	0.348	3.184	0.005	1.111, 5.375
	7	Morphological awareness	Left parahippocampus	0.333	3.080	0.006	0.300, 1.573

Note. $n = 21$.

[a]Mean cortical thickness in all four word-reading efficiency related regions-of-interest were entered into the model with a stepwise selection method (criteria: probability of F to enter $\leq .05$, probability of F to remove $\geq .100$).

[b]The two sentence-reading comprehension related regions-of-interest were entered into the model with the same stepwise selection method.

In all the analyses, subcomponents were first adjusted for age, gender and performance IQ. The residuals entered the model as dependent variables.
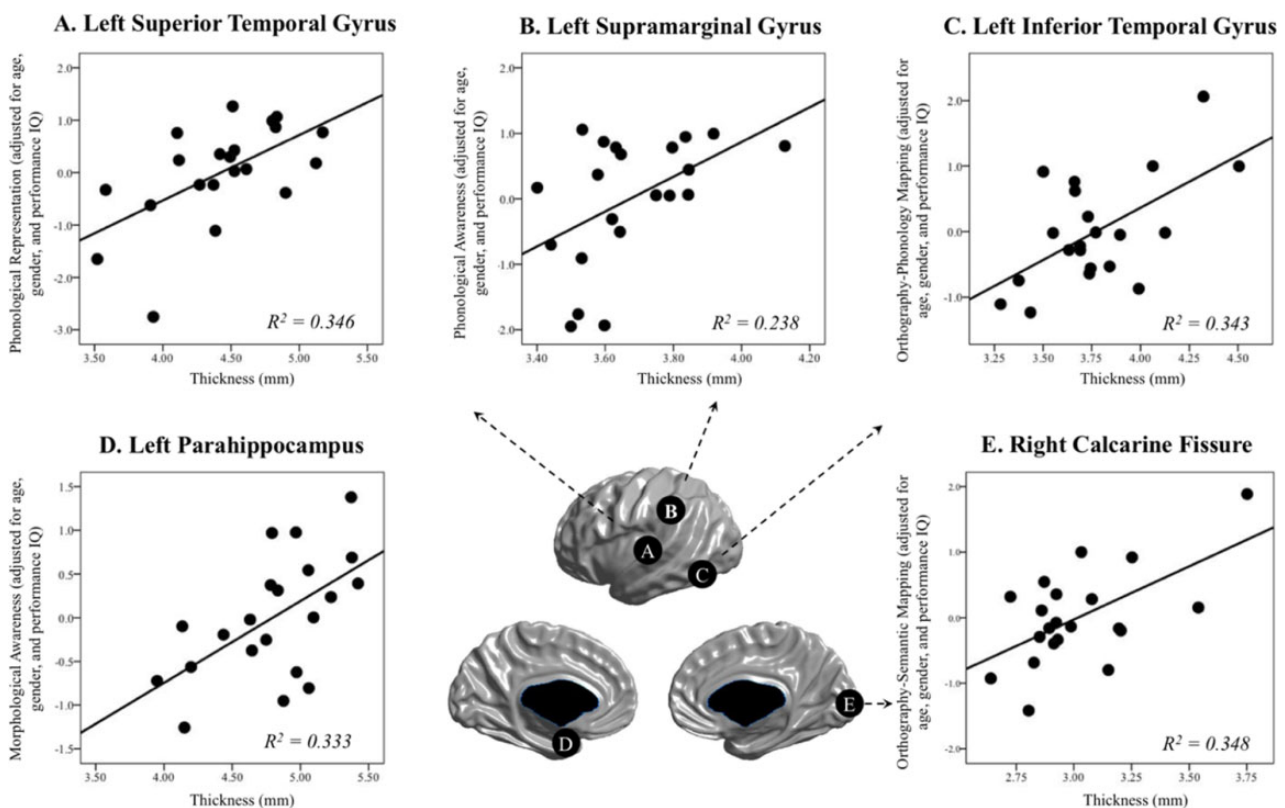

Figure 2. Scatter plots display the correlation between the significant predictor and the reading subcomponents ($n = 21$).
Note. The subcomponent scores were adjusted for age, gender and performance IQ. A. Phonological representation is predicted by cortical thickness in the left superior temporal gyrus. B. Phonological awareness is predicted by cortical thickness in the left supramarginal gyrus. C. Orthography–phonology mapping is predicted by cortical thickness in the left inferior temporal gyrus. D. Morphological awareness is predicted by cortical thickness in the left parahippocampus. E. Orthography–semantic mapping is predicted by cortical thickness in the right calcarine fissure.

Neuroanatomical properties of temporo-parietal and occipito-temporal cortices are associated with word-reading efficiency

In the present study, CT in the left temporo-parietal and occipito-temporal regions was positively correlated with children's word-reading efficiency, as well as cognitive subcomponents. The left temporo-parietal cortex was associated with phonological awareness, whereas the left occipito-temporal cortex was associated with orthography–phonology mapping. These results are consistent with previous fMRI studies whereby the left-hemispheric neural network, including the inferior frontal cortex, SMG and ITG, was found to be involved in reading (Dehaene & Cohen, 2011; Graves et al., 2010; Hartwigsen et al., 2010; Price, 2012; Price & Devlin, 2011; Sliwinska, Khadilkar, Campbell-Ratcliffe, Quevenco, & Devlin, 2012; Stoeckel, Gough, Watkins, & Devlin, 2009). Among these areas, the LSMG is mainly associated with phonological processing. For example, Jednorog et al. (2015) found

reading accuracy in time-limited tasks to be positively correlated with gray matter volume (GMV) in the LSMG, independent of varying in orthographic transparencies (French, German, and Polish). Applying repetitive transcranial magnetic stimulation to this region can cause a significant delay in participants' naming speed (Hartwigsen et al., 2010; Sliwinska et al., 2012; Stoeckel et al., 2009). Moreover, our finding that CT in the LSMG uniquely predicted phonological awareness is in line with the idea that impairment in this region might underlie the predominant phonological deficit in dyslexia (Gabrieli, 2009). The left occipito-temporal cortex is another region closely linked with reading. This region contains a small area termed visual word form area (Dehaene, Le Clec, Poline, Le Bihan, & Cohen, 2002), which displays consistent activation during processing words and word-like stimuli. Although in the past 10 years there has been debate regarding the precise function of this area, the left occipito-temporal cortex has been widely accepted to be an interface for orthographic, phonological, and semantic information (Dehaene & Cohen, 2011; Price & Devlin, 2011). In particular, the functional and structural properties of this area have been proven to be shaped by establishing a new correlation between orthography and phonology (Brem et al., 2010; Hashimoto & Sakai, 2004; Xue, Chen, Jin, & Dong, 2006). In line with this evidence, we found that CT variances in the reading-defined LITG could predict orthography–phonology mapping in typically developing Chinese children.

Dyslexia has been shown to be associated with altered brain morphometry in left hemispheric regions such as the left inferior frontal, bilateral temporo-parietal and occipito-temporal areas (Hoeft et al., 2007; Linkersdorfer, Lonnemann, Lindberg, Hasselhorn, & Fiebach, 2012; Richlan et al., 2013). However, the first CT study of dyslexia did not reveal any differences between adults with dyslexia and normal controls (Frye et al., 2010). Then, by using a novel functional localizer, Altarelli and colleagues identified a CT reduction in the fusiform gyrus in girls with dyslexia (Altarelli et al., 2013). Most recently, a reduced CT in bilateral occipito-temporal areas was demonstrated in patients with dyslexia using a relatively large sample size (Williams et al., 2017). This inconsistency might be because CT is affected more by environmental factors and experience, whereas cortical surface area (CSA), another measure of neuroanatomy, is affected more by genetic factors. For example, Clark et al. (2014) followed a group of preliterate children with or without risk of dyslexia and found that CT deficits in children with dyslexia emerged only when they were in the sixth grade, after a long time of reading instruction. By contrast, Black et al. (2012) found that familial risk was associated with CSA in the temporo-parietal region. These observations might explain why we found CT-reading competence correlations in typically developing children. As our participants were still at the stage of fluent reading development, they spent a great amount of time building phonological representations and mapping orthography and phonology information. Such intense training may drive anatomical changes in specific areas such as the left temporo-parietal and occipito-temporal regions. We will provide more discussion on this topic in the section below.

Relationships between the auditory cortex, speech–sound processing, and reading acquisition

In the present study, we found that CT in the bilateral auditory areas was significantly correlated with oral word reading which contains a production subcomponent. Based on the audio-centric view, the main goal of speech production is to generate a target sound (Hickok, Houde, & Rong, 2011), during which both phonological code representation and retrieval are important. Additionally, a Sylvian parietal temporal region has been regarded as the interface between auditory and motor system and plays an essential role in speech production. Therefore, the auditory system may act as a representation center, a feed-forward center or both during speech perception and production (Hickok et al., 2011). Importantly, we found that the CT in the reading-defined LSTG was also positively correlated with the categorical perception of lexical tones. Category perception affects print-sound mapping (Chang et al., 2010; Ramus, Marshall, Rosen, & van der Lely, 2013), and has been proven to be correlated with reading abilities across different languages (Nittrouer & Pennington, 2010). A previous study by our research group demonstrated that children with dyslexia displayed atypical neurophysiological activity, indicating a deficit in the categorical perception of lexical tones (Zhang et al., 2012). The neuroimaging finding of the present study suggests that the LSTG might be the potential neuroanatomical basis for this deficit. The behavioral result, on the other hand, extends the close relationship between lexical tone identification and character recognition in preliterate (Tong et al., 2015) to school-aged children.

From a more general perspective, basic aspects of auditory processing might underlie the association between the LSTG and reading as well as categorical perception. Children acquire the ability to process auditory signals only a few days after birth, and this ability is a good predictor of language and literacy development (Kuhl, 2004, 2010). Both behavioral and neuroimaging findings have indicated that dyslexic and at-risk children exhibit impaired speech–sound processing (Goswami et al., 2002; Guttorm, Leppänen, Hämäläinen, Eklund, & Lyytinen, 2010; Powers, Wang, Beach, Sideridis, & Gaab, 2016; Szenkovits & Ramus, 2005; Talcott et al., 2000; Tallal, 2004, 2012; Witton et al., 1998). A recent magnetoencephalography study found that people with dyslexia had altered low-gamma sampling in the left planum temporale. This area was associated with oral word-reading performance in adults, as well as three reading-correlated cognitive subcomponents: phonological awareness, rapid naming and verbal working memory (Lehongre, Ramus, Villiermet, Schwartz, & Giraud, 2011).

Neuroanatomical correlates of reading comprehension efficiency at the sentence level

Compared with the well-established neural network for reading at the word level, there is much less imaging research on reading comprehension efficiency (Benjamin & Gaab, 2012; Christodoulou et al., 2014; Langer, Benjamin, Minas, & Gaab, 2015). An fMRI study revealed that distributed regions in the bilateral frontal, temporal, and occipital lobes are activated during semantic judgment of sentences; among these areas, the activation level in the occipital/fusiform cortex increases with an increase in the stimuli (word) presentation rate (Benjamin & Gaab, 2012). Studies of dyslexia using a similar paradigm have revealed altered activation in the left inferior frontal region, left posterior temporal gyrus, and fusiform gyrus (Christodoulou et al., 2014; Langer et al., 2015). Regarding the brain structure, resilient readers show greater variability in the asymmetry of the mean length of the planum temporale than typical readers, whereas persistent poor readers display a trend in the same direction (Welcome et al., 2010). Across groups, planar asymmetry

is signficiantly correlated with decoding skill, but not with comprehension performance. These findings indicate that the anomaly in the auditory cortex might be driven by an impaired phonological ability shared by dyslexic and resilient readers and less associated with comprehension. This idea is further supported by a study that indicated that both poor and resilient readers have altered symmetry in temporo-parietal regions, but only poor readers show abnormality in frontal areas (Welcome et al., 2011).

In this study, we identified that the right visual and left para-hippocampal regions are associated with fluency in sentence comprehension. In other words, in children aged 10–12 years, the brain morphometry in these two regions is sensitive to reading comprehension performance. These areas have been found to be involved in fluent sentence processing and lexical processing at the word level (Binder et al., 2003). For example, the right primary visual cortex has been found to play an important role in word reading, in both feedforward and feedback communication (Woodhead et al., 2014). Cao et al. (2009) found that the right middle occipital gyrus, which is involved in the visuo-spatial analysis of Chinese characters, is more effectively engaged in skilled readers than children. Moreover, similar to the pattern found in oral word reading, a multi-componential pattern was also found for sentence comprehension; whereas CT in the RV1 was correlated with orthography–semantic mapping, CT in the LPHP was correlated with morphological awareness. Notably, we did not find any significant correlation between sentence comprehension and CT in either the frontal region or fusiform gyrus. This observation could be caused by several possibilities; for example, behavioral variations in this age range may be captured by functional brain measures other than morphometry. More discussion regarding this issue is provided in what follows.

Developmental perspective of reading brain maturation in a specific language

Results of previous studies of identifying reading-related brain areas are sometimes inconsistent. For example, even for studies conducted in the same language, the exact locations of significant brain areas are not the same. One possible reason for this inconsistency is that the direction and strength of the brain–reading correlation are age-specific. That is, the correlation patterns can change with development. The developmental dynamic has been confirmed in some previous studies. For example, Yeatman, Dougherty, Ben-Shachar, and Wandell (2012) examined the change in fractional anisotropy (FA) in specific white matter tracts of both poor and good readers. The authors found higher FA in poor readers than good readers at the first timepoint of testing. Then, in the following year, poor readers showed a decrease in FA, whereas good readers displayed an increase in FA. Finally, at the final MRI scan session, an opposite pattern appeared: poor readers showed lower FA than good readers. As for neuroanatomical measures, Clark et al. (2014) found that CT differences in putative reading areas (e.g., left occipito-parietal cortex) only exist in children with dyslexia in the sixth grade but not earlier. However, Xia, Hoeft, Zhang, and Shu (2016), using a Chinese sample, found that the left inferior frontal and occipito-temporal areas showed a decrease in GMV in a group of children with dyslexia at an average age of 11 years compared with that in age-matched controls but showed an increase in GMV in children with dyslexia at an average age of 14 years compared with that of non-dyslexic peers.

Imaging studies have shown that structural changes (e.g., GMV and CT) occur with skill learning, such as studies of motor and language learning (Lovden et al., 2013; Martensson et al., 2012; Zatorre, Fields, & Johansen-Berg, 2012). In general, acquisition of a new skill thickens specific cortical regions, whereas consolidation is associated with cortical thinning (Lovden et al., 2013). As for reading development, we hypothesize that at young ages, the correlations are positive, whereas at later stages the correlations are negative. Although weak and indirect, evidence to date seems to be in line with this hypothesis. In children, Lu et al. (2007) found that thickening of a region in the left inferior frontal gyrus was positively correlated with phonological skill development, which is one of the strongest predictors of reading acquisition in alphabetic languages. By contrast, Blackmon et al. (2010) found that CT in the LITG was negatively correlated with adults' performance on reading irregular English words. In this study, we focused on a narrow age range from 10 to 12 years, which is an important period for developing automatic oral reading fluency and gaining skilled reading comprehension (Shu et al., 2003). According to our hypothesis, positive correlations between thickness and reading skills should be observed. Such correlations found in the present study confirmed the importance of both factors, age and brain region, in the development of the reading neural network. That is, the age range of the subjects (age 10–12 years) might be one of the reasons that positive correlations were found between some specific brain areas and reading performance as well as various cognitive subcomponents. If we looked into another developmental stage, the correlation might change. Moreover, for some regions such as the fronto-parietal network, correlations might be found only during a specific period in which these regions are specifically recruited for reading (Church, Coalson, Lugar, Petersen, & Schlaggar, 2008). Therefore, describing the relationship between the brain and reading skills from birth to a mature stage is important to clarify at what time point which brain areas play an important role in reading.

Another important issue in reading research is whether the cognitive or neural mechanism of reading (Landerl et al., 2013) or the behavioral/neurobiological deficit in dyslexia is universal across languages (Jednorog et al., 2015; Paulesu et al., 2001). Unlike alphabetic languages, Chinese is a logographic language that has a higher visual complexity and a unique phonological system, thus providing a unique opportunity to answer this question (Xia, Hoeft, Zhang, & Shu, 2016; Zhou, Xia, Bi, & Shu, 2015). He et al. (2013) explored the relationships between the GMV of various brain regions and different reading subcomponents. However, the composite reading scores they used were extracted from tasks in both English and Chinese. As for the relationship between CT and reading skills, previous studies have shown relationships in different directions between English and Chinese, at least in a region located in the left occipito-temporal cortex (Blackmon et al., 2010; Zhang et al., 2013). In line with previous research (Lei et al., 2011; Shu, McBride-Chang, Wu, & Liu, 2006), the behavioral results of the present study demonstrated that phonological processing is a core component for word reading, whereas semantic processing is more important for sentence comprehension. In terms of neural correlates, we identified four regions associated with word reading in Chinese typically developing children with an average age of 11 years. These regions included the left SMG and ITG, which have been repeatedly reported to be involved in alphabetic languages. This result is understandable given that reading includes the process of mapping orthographic information to phonological information

regardless of language (Rueckl et al., 2015). As for reading comprehension, however, we cannot make a conclusion on the uniqueness or universality because of the limited number of studies on sentence comprehension in both English and Chinese.

Caveats and further directions

The findings of this study should be interpreted with caution. First, the findings need to be replicated by studies with larger samples. Second, this study covers a limited number of the central subcomponents of reading. For example, we did not have measures on articulation quality in word reading or semantic integration in sentence comprehension. Third, in this study we did not find a significant relationship between CT in the inferior frontal regions and reading performances either at the word or sentence level. This result is unexpected in Chinese because Chinese character processing recruits the left middle frontal region, which is considered a cross-modal center for orthographic–phonological and orthographic-to-semantic transformation (Siok, Niu, Jin, Perfetti, & Tan, 2008; Tan, Laird, Li, & Fox, 2005; Wu, Ho, & Chen, 2012). We propose several possible explanations for this result: 1) we focused on typical readers, whereas CT in this area might be altered in persons with dyslexia; 2) we focused on a narrow age range of 10–12 years, whereas CT in this area might be associated with reading performance at other developmental stages; 3) other brain measures of this area, e.g., functional connectivity, might be more sensitive to individual differences in reading and its subcomponents.

In addition to age and development, other factors need to be taken into consideration in future studies. First, reading experience plays a significant role in shaping the brain. For example, at the functional level, formal reading instruction profoundly refines cortical organization (Brem et al., 2010; Dehaene et al., 2010). There is also evidence to indicate that a reduced congruency effect in the planum temporale of those with dyslexia may be a consequence of abnormal reading acquisition (Blau et al., 2010). With regard to neuroanatomy, print exposure is associated with a thickened CT of distributed canonical reading-related areas, including the left ventral occipito-temporal and temporo-parietal regions (Goldman & Manis, 2013). In this sense, the relationship between the brain and reading is likely bidirectional and should be examined further. Gender is another important factor that needs to be taken into consideration. A previous study found that dyslexic girls had a thinner gray matter in the functionally defined visual word form area (Altarelli et al., 2013). Furthermore, environmental factors such as socioeconomic status modulate the brain–reading relationships (Gullick, Demir-Lira, & Booth, 2016). To further address these issues, longitudinal studies with large samples are needed.

Summary

This study identified distinct neuroanatomical correlates for word-reading fluency and sentence comprehension efficiency in non-impaired children and demonstrated that typical reading is associated with multiple cognitive subcomponents and CT in the corresponding brain areas. As the brain circuitry for reading is shaped by the interplay of genetic and environmental factors, future studies should explore how the brain–reading relationships change during development and the impact of these interactions.

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