to stimuli deviated in initial consonants or vowels of Chinese syllables and to stimuli deviated in temporal information of separate two sounds in gap detection (McCroskey & Kidder, 1980). And they are less sensitive to changes in amplitude (Menell, McAnally, & Stein, 1999) and frequency (Witton et al., 1998) of acoustic stimuli. Witton et al. (1998) found that sensitivity to dynamic auditory and visual stimuli predicted nonword reading performance in both dyslexic and normal readers. Talcott et al. (2000) used a battery of sensory psychophysical, psychometric and literacy skill tests on 32 unselected 10-year-old primary school children and found that, after controlling for intelligence and overall reading ability, children's sensitivity to visual motion explained independent variance in orthographic skill but not phonological ability while sensitivity to auditory stimuli covaried with phonological skill but not orthographic skill. Ahissar, Protopapas, Reid, and Merzenich (2000) found that auditory processing abilities accounted for more than 50% of the reading score variance in normal adults, but their correlation with reading scores was lower in people with childhood history of reading difficulties. This finding not only supports a link between impaired auditory resolution and poor reading, but also suggests that psychoacoustic difficulties are largely retained through adulthood and may be the source of prolonged reading difficulties. Some training studies also found that auditory training with

Such a complex orthographic structure may cause many cognitive difficulties for Chinese children struggling to master the writing system (e.g. associating a specific character with speech and meaning). Studies on reading development in Chinese have shown that children's reading achievements are strongly related to children's phonological skills in understanding speech structure and manipulating phonemes and lexical tones (Shu, Chen, Anderson, Wu, & Xuan, 2003; Siok & Fletcher, 2001; McBride-Chang & Ho, 2000; Ho & Bryant, 1997). But little is known whether reading development and its impairment in Chinese have anything to do with children's more fundamental acoustic or auditory processing abilities.

In the present study, we investigated the relations between auditory and speech processing and reading development in Chinese school children. Experiment 1 was conducted to examine specifically what aspects of cognitive processes in reading Chinese the auditory processing might have impact on. We tested 102 unselected normal children with both the auditory processing tasks and a number of reading-related tasks and conducted regression analyses to find out what variables that the auditory discrimination measures contributed to most. Experiment 2, using the ERP technique, was designed to examine whether Chinese dyslexic children have deficits and neurological markers in auditory and speech processing in similar ways as their western counterparts.

EXPERIMENT 1

We asked two questions in this experiment. First, whether auditory and temporal processing has a unique role in predicting children's reading performance? In order to answer this question, a battery of phonological and auditory tests was administrated and the data were entered into regression equations. The relative phonological and auditory contributions to reading development were then compared. Second, to what extent phonological awareness scores and reading performance are influenced by frequency or temporal structure of the auditory stimuli? Four auditory tasks were administered, one requiring frequency discrimination and other three requiring temporal pattern discrimination.

Method

One-hundred and two unselected Chinese fifth graders (52 boys and 50 girls, mean age = 129 months) in a middle-ranking primary school in Beijing were tested. All these children were native speakers of Mandarin Chinese with normal or corrected-to-normal vision, normal hearing and no history of ear infections or affective disorders.

The experiment consisted of two sessions. In the first session, the Chinese city version of Raven's standard Progressive Matrices test (Zhang & Wang, 1985) and a number of linguistic tasks, consisting of vocabulary, reading fluency, phonological awareness, orthographic similarity judgment and character naming tests were administered. In the second session, the four auditory perception tests, including tone frequency discrimination, tone temporal order judgment, temporal interval discrimination and composite tone pattern discrimination, were conducted. The test order of tasks in each session was randomized over participants, with the interval between two sessions being one and a half months.

The DMDX system (Forster & Forster, 2003) was used in the following four auditory tests to control the presentation of stimuli to participants and to record participants' responses. A phonological editing software Bliss and sound editing software Cooledit2000 were used to manipulate sound information. All sounds were presented through earphones at level of 60 dB.

[illegible]

The [illegible] was a standardized test (Wang & Tao, 1996) in which 210 characters were divided into 10 groups based on their reading difficulties. Participants were asked to write down a compound word based on a constituent morpheme provided orally. The performance was measured by the total number of correct characters (morphemes) the participants could make used of in word-composition. Participants had to know the pronunciation, the orthographic form and meaning of the target character to complete the task.

The [illegible] was a reading comprehension test which had 95 sentences, each sentence paired with 5 picture choices. Participants were asked to read each sentence and select from the five pictures the one that best reflected the meaning of the sentence. Children were encouraged to complete as many paragraphs as possible within a 10-minute time period.

The [illegible] used the oddball paradigm (Bradley & Bryant, 1978) in which participants were asked to pick out a phonologically odd item from four items. Three blocks of stimuli were tested, each having 20 quartets of items, with the oddity on either onset, rhyme or lexical tone. Items were presented orally and participants indicated on the answering sheet which spoken syllable was an odd one. The percentage of correct answers was taken as the measure of each participant's phonological awareness performance.

In the [illegible], children had to judge whether a pair of consecutively presented Chinese characters were orthographically similar. Orthographic similarity was defined in the way that simple characters had similar visual forms (e.g. 甲

pronounced in the same way as its phonetic radical, a character could be categorized as 'regular' or 'irregular'. There were 50 regular and 50 irregular characters, half of each were of relatively high frequency (109 / per million) and half of lower frequency (20 / per million).

[illegible]

In the [illegible], two pure tones, each with 300 ms duration, were presented consecutively with ISI of 500 ms between them. One was of standard tone (700 Hz), and the other was of variable tone. The range of frequency difference between the two tones was from 5 to 120 Hz, in 7 steps. Children were asked to judge which tone was of higher frequency. Seventy-five per cent accuracy threshold was calculated according to psychophysical functions.

In [illegible], children learned to label a 800 Hz tone as 'low' and a 2000 Hz tone as 'high' before the formal test. Each tone lasted 50 ms. Children were asked to label, using two response keys, a sequence of two tones presented successively. The ISI between the two sounds was varied from 5 to 50 ms, with a step of 5 ms. Each of the 10 steps had 10 trials. The 75% accuracy threshold was calculated.

In [illegible], two pairs of tones were presented successively, each tone (1000 Hz) having duration of 15 ms. The ISI between the two pairs was 500 ms. The interval between the two sounds of one pair was constant at 100 ms, while the interval between the two sounds of the second pair varied. The interval range of the variable pair was from 50 to 100 ms with a step of 10 ms (5 steps). Children were asked to judge which pair's interval was shorter. The 75% accuracy threshold was calculated.

The [illegible] used the oddball paradigm, in which two 2000 Hz and one 800 Hz pure tones were used. These tones formed two different composition patterns. The standard pattern was that the two intervals between the three tones was firstly 50 ms and secondly 150 ms; the deviant pattern was firstly 150 ms and secondly 50 ms. Children learned before formal test that one composite pattern was a standard stimulus; the other was the deviant one. In formal test, two composite patterns were presented randomly, with 75% standard stimuli and 25% deviant ones. Children's task was to count the number of deviant stimuli. The error rate of children's counting was recorded.

Results

In the statistical analyses, we first standardized the distribution of children' responses and then calculated correlations between different tests. Multilevel hierarchical regressions were finally conducted to assess the contributions of auditory and temporal processing to children's linguistic performance.

Table 1. Matrix of correlations between various tasks

	1	2	3	4	5	6	7	8	9	10
1. Raven										
2. Vocabulary	0.24*									
3. Reading fluency	0.16	0.33**								
4. Phonological awareness	0.35**	0.50**	0.22*							
5. Orthographic similarity judgment	0.10	−0.18	−0.27**	−0.20*						
6. Character naming RT	0.02	−0.34**	−0.37**	−0.18	0.38**					
7. Character naming ERROR	−0.20*	−0.35**	−0.14	−0.30**	0.01	0.06				
8. Tone frequency discrimination	−0.28**	−0.25**	−0.26**	−0.30**	0.18	0.10	0.06			
9. Tone temporal order judgment	−0.01	−0.22*	−0.31**	−0.26**	0.18	0.25**	0.02	0.34**		
10. Tone temporal interval discrimination	−0.27**	−0.23*	−0.28**	−0.46**	0.07	−0.01	0.14	0.21*	0.55**	
11. Composite tone pattern discrimination	−0.17	−0.43**	−0.22*	−0.56**	0.08	0.31**	0.22*	0.26**	0.26**	0.35**

Notes: *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

measures, except orthographic similarity judgment. Linguistic measures

Temporal order judgment had the most significant and stable contribution (see Table 3).

To assess the contribution of auditory and temporal processing to phonological awareness, scores in the four auditory tasks were either entered equation together after Raven test, or entered equation with frequency discrimination task first and the other three tasks later. Table 4 shows that auditory processing measures could account for 32% variance in phonological awareness after controlling the effect of IQ. Among the tasks, the temporal interval judgment and tone composition pattern had the most significant contribution while the contribution of tone frequency discrimination showed itself only when it was entered equation first.

Table 5 demonstrates that auditory processing measures, could significantly account for 16% or 13% variance in character naming latency when they entered equation in together before or after phonological awareness. Phonological awareness could account for 4% of variance if it was entered equation immediately after Raven test. Regression on orthographic similarity judgment

Table 3. Variance contributed to fluency by auditory processing measures and phonological awareness after controlling for IQ and the order of entering equation of predicators

Dependent	Predicators	R^2	R^2 change
Fluency	1. Raven	0.03	0.03
	2. Tone temporal order judgment	0.17	0.14*

found no significant impact from IQ, phonological awareness, or auditory processing tasks.

Discussion

The finding of significant correlations between phonological awareness and vocabulary size and reading fluency is consistent with many previous studies. Regressional analyses showed further that phonological awareness can explain at least 7% of variance in vocabulary size even after other effects were partialled out. These data suggest that knowing the phonological structure of the Chinese syllable helps children to learn Chinese characters, even though the orthographic structure of a Chinese character has no subcomponents corresponding directly with the initial consonant, rhyming part or lexical tone that were tested in phonological awareness.

The significant correlations between phonological awareness and children's performance in auditory and temporal tasks suggest that the development of phonological abilities may depend to some extent on children's auditory processing skills. The regressional analyses reported in Table 2 suggest that auditory processing may affect the development of vocabulary via phonological awareness because after partialling out the contribution of phonological awareness, auditory measures had no significant effect on vocabulary size but after partialling out the contribution of auditory tasks, phonological awareness still had a significant impact on the development of vocabulary.

However, auditory processing could uniquely affect reading fluency and the speed of character naming after the effect of phonological awareness was partialled out, suggesting that the skill of auditory processing may also affect Chinese reading directly. Compared with other auditory tasks, temporal order judgment was the most prominent task in predicting reading fluency and the speed of character naming. This may reflect the fact that both temporal order judgment and extracting phonological information during text reading and character naming depends on temporal organization of information available (Talcott ., 2000; Witton ., 1998). In addition to phonological skillsF(asur4Tf3.5850TD[et

Comparing the effect of tone frequency judgment on linguistic tasks with effects of other auditory tasks with the component of temporal processing, it is clear that the skills measured by both types of tasks impacted upon reading development. When the auditory temporal measures were entered equation before the scores of frequency discrimination, the latter had no significant effect on linguistic measures. But when the scores of frequency discrimination were put into equation first, it did have significant account for variance in vocabulary size and reading fluency. These results may suggest that both the frequency and temporal components of auditory processing affect Chinese reading development. However, it is temporal processing that has the stronger influence.

EXPERIMENT TWO

Results of Experiment 1 suggest that Chinese school children’s skills of auditory and temporal processing could affect their reading development either directly or via phonological awareness. Children who performed better on auditory and temporal processing tasks were also better on linguistic tasks. The purpose of Experiment 2 was to examine this conclusion in an opposite way. When children have deficits in reading development, do they also have significant deficits in auditory and temporal processing? Moreover, what are the neural markers of these deficits in auditory and temporal processing?

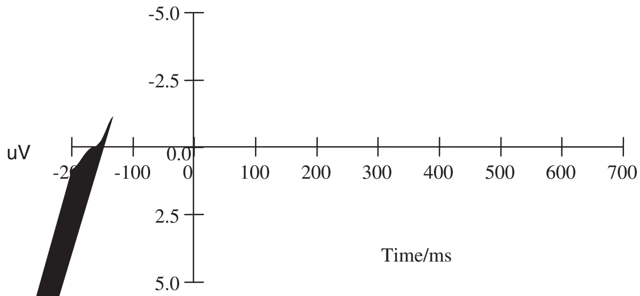
Method

Participants were 23 elementary school students: 11 dyslexic readers (2 females and 9 males) and 12 normal readers (2 females and 10 males). The two groups were matched on non-verbal IQ scores, as measured by the Chinese city revision different auditory and speech stimuli that were binaurally delivered through headphones. The movie was presented on a 21-inch colour monitor at a viewing distance of about 110 cm from the participants. The experiment was composed of five blocks, with each block having a different set of stimuli. In each set, the standard stimulus took 80% of the trials while the deviant stimulus took the remaining 20%.

All the participants were presented in the following order of the five sets of stimuli. In the first set (the [illegible] stimuli), the standard stimulus was a pure tone with 1250 Hz and the deviant stimulus was a 1400 Hz tone. Every tone lasted for 50 ms. There was an interval of 700 ms between the successive presentations of two tones. In the second set (the [illegible] stimuli), the standard stimulus was composed of three tones, two identical tones (2000 Hz), each lasting 50 ms at the beginning and the end of the sequence. The third tone (800 Hz), also lasting 50 ms, was inserted between the two identical tones, with an interval of 150 ms from the initial tone and 350 ms from the ending tone. The deviant stimulus was composed of the same tones, but with the middle tone 350 ms from the initial tone and 150 ms from the ending tone. There was an interval of 1000 ms between presentations of two successive tone sequences.

The last three sets of stimuli were linguistic tests, with the standard and deviant stimuli differed either in the initial consonant, the rhyming part, or the lexical tone. The third set had the Chinese syllable /da/ as the standard stimulus and /ga/ as the deviant stimulus. In the fourth set, the standard stimulus was the syllable /dan/ and the deviant stimulus was /dai/. The last set of stimuli had /ba1/ as the standard stimulus and /ba2/ as the deviant stimulus, where the

patterns (0.05< <0.



Discussion

Our results showed that dyslexics discriminated deviant stimuli in composite tone pattern, initial consonant and vowel of Chinese syllable less efficiently than controls, reflected by the smaller MMNs in dyslexic subjects. These results indicate that Chinese dyslexic children have deficits in auditory temporal processing and in linguistic processing. For the composite tone pattern stimuli, the difference between the standard pattern and deviant pattern is in temporal order. The difference here between dyslexic and control children supports the hypothesis that a basic perceptual processing deficit, especially the deficiency in discriminating temporal sound features is one of the core syndromes of dyslexia. This hypothesis applies to the Chinese dyslexics as well as their western counterparts (Merzenich *et al*., 1996; Schulte-Körne *et al*., 1999).

Moreover, the present results also demonstrated that Chinese dyslexic children have deficiency in linguistic processing. Several researchers have found that phonological awareness is an important predictor of Chinese school children's reading development (McBride-Chang, 1995; Shu, Anderson, & Wu, 2000). Findings here are in agreement with these behavioural studies on phonological processing in Chinese as well as with other behavioural and neurophysiological studies in Western languages (Ahissar *et al*., 2000; Kujala *et al*., 2001).

Chinese dyslexic children did not show a deficit in discriminating the frequency of pure tone, consistent with Schulte-Korne *et al*. (1998) but inconsistent with Baldeweg *et al*. (1999). Chinese dyslexics also showed insensitivity to the deviating lexical tone, which is somewhat surprising given that the lexical tone is used extensively to differentiate lexical items. Perhaps a large sample of participants is needed to detect the differences between the two groups.

GENERAL DISCUSSION

Findings from the present study can be summarized as follows. In behavioural tests, normal school children with different levels of reading development showed strong correlations between their performance in tests of auditory and temporal processing and their linguistic abilities tested by reading fluency, vocabulary size, phonological awareness and character naming. Regressional analyses found that tone temporal order judgment, temporal interval discrimination, and composite tone pattern discrimination could account for 32% variance in phonological awareness. Controlling for the effect of phonological awareness, contribution of auditory processing measures to variance in fluency and character naming latency was still significant. Experiment Two found that dyslexic children showed smaller MMNs to stimuli deviated in initial consonants or vowels of Chinese syllables and to stimuli deviated in temporal information of composite tone patterns. These findings suggested that auditory and temporal processing is possibly as important to reading development of children in a logographic, morpho-syllabic writing system as in an alphabetic system.

Apparently, our results are consistent with many studies on reading development and dyslexia in Western languages (e.g. Ahissar *et al.*, 2000; Witton *et al.*, 1998; Talcott *et al.*, 2000). As we reviewed earlier, one proposal on how the deficits in auditory, speech and temporal processing affect reading performance assumes that these deficits affect children developing phonological awareness, which in turn, affects their learning letter–sound correspondences. Although we did find correlations between measures of auditory and temporal processing and children's performance in phonological awareness tests, it is certainly not the letter–sound correspondences that are affected eventually by auditory and temporal processing since the Chinese writing system has only the character–syllable correspondences. We believe that deficits in auditory and temporal processing affect not just children's understanding of phonological structure and phonological content, but the whole speech and language system. Deficits in understanding the structure of sound could reflect a general inability in

In short, this study demonstrated that reading development in Chinese correlates strongly with children's ability in auditory and temporal processing. Deficits in processing auditory temporal information and in processing consonants and vowels of Chinese syllables can also manifest in dyslexic children's brain responses to deviant stimuli in the oddball paradigm.

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