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# ■ Auditory and Speech Processing and Reading Development in Chinese School Children: Behavioural and ERP Evidence

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By measuring behavioural performance and event-related potentials (ERPs) this study investigated the extent to which Chinese school children's reading development is influenced by their skills in auditory, speech, and temporal processing. In Experiment 1, 102 normal school children's performance in pure tone temporal order judgment, tone frequency discrimination, temporal interval discrimination and composite tone pattern discrimination was measured. Results showed that children's auditory processing skills correlated significantly with their reading fluency, phonological awareness, word naming latency, and the number of Chinese characters learned. Regression analyses found that tone temporal order judgment, temporal interval discrimination and composite tone pattern discrimination could account for 32% of variance in phonological awareness. Controlling for the effect of phonological awareness, auditory processing measures still contributed significantly to variance in reading fluency and character naming. In Experiment 2, mismatch negativities (MMN) in event-related brain potentials were recorded from dyslexic children and the matched normal children, while these children listened passively to Chinese syllables and auditory stimuli composed of pure tones. The two groups of children did not differ in MMN to stimuli deviated in pure tone frequency and Chinese lexical tones. But dyslexic children showed smaller MMN

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to stimuli deviated in initial consonants or vowels of Chinese syllables and to stimuli deviated in temporal information of composite tone patterns. These results suggested that Chinese dyslexic children have deficits in auditory temporal processing as well as in linguistic processing and that auditory and temporal processing is possibly as important to reading development of children in a logographic writing system as in an alphabetic system. Copyright © 2005 John Wiley & Sons, Ltd.

**Keywords:** developmental dyslexia; auditory processing; temporal processing; speech perception; mismatch negativity (MMN)

## INTRODUCTION

Phonological skills are proved to be important to reading acquisition and development by a large body of research (e.g. Wagner, Torgesen, & Rashotte, 1994). Longitudinal and training studies demonstrated that phonological ability could predict and might play a causal role in literacy development after children entering school (Bradley & Bryant, 1978, 1983; Bryant & Bradley, 1985; Lundberg, Frost, & Petersen, 1988). Phonological abilities are therefore suggested to be a primary source of variability in reading skills among children mastering alphabetic scripts. Deficits of phonological skills are also found to be a most prominent symptom of developmental dyslexia. For example, developmental dyslexics have impairments in tests of phonological awareness (Bradley & Bryant, 1978; Manis, Custodio, & Szeszulski, 1993; Share & Stanovich, 1995; Stanovich & Siegel, 1994), nonword repetition (Snowling, 1981), rapid naming (Katz, 1986), phonological recoding in working memory (Siegel & Ryan, 1988; Rack, 1985), phonological recoding in lexical access (Bowers & Wolf, 1993; Denckla & Rudel, 1976), and phonological representation in the lexicon (Swan & Goswami, 1997; Brown, 1997). It is believed that children's deficits in analysing and representing phonological structures lead to their difficulties in mastering the systematic relationship between spelling and sound (i.e. grapheme–phoneme correspondence) which is essential to reading development in alphabetic scripts.

Deficits in phonological skills in dyslexics may stem from more fundamental deficits in acoustic-auditory information processing and auditory temporal processing. Auditory sensory deficits are proposed to cause impaired speech perception, which, in turn, leads to deficits in the ability to process and manipulate speech sounds. Such phonological awareness problems subsequently result in difficulties in learning letter–sound correspondences during the process of reading development. Thus deficits for detecting rapidly presented or rapidly changing auditory stimuli play a direct role in dyslexic's problems with word decoding (Tallal, 1980; Tallal, Merzenich, Miller, & Jenkins, 1998; Witton *et al.*, 1998; but see Studdert-Kennedy & Mody, 1995; Studdert-Kennedy, 1997; Ramus, 2003; Bretherton & Holmes, 2003; Share, Jorm, Maclean, & Matthews, 2002; Agnew, Dorn, & Eden, 2004 for different views). Dyslexics are impaired in determining whether two pure tones presented in rapid succession are the same or different (Tallal, 1980). They need a longer inter-stimulus-interval (ISI) to

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 nonlinguistic materials could enhance dyslexics' reading ability (Kujala *et al.*, 2001; Temple *et al.*, 2003; Merzenich *et al.*, 1996; Tallal *et al.*, 1998), although Agnew *et al.* (2004) found that training with modified speech could improve auditory temporal discrimination, but this improvement did not generalize to reading skills.

Besides the behavioural evidence reviewed above, some ERP studies also demonstrated abnormality of auditory and phonological processing in dyslexics. In one study (Baldeweg, Richardson, Watkins, Foale, & Gruzelier, 1999), dyslexics showed significantly smaller mismatch negativity (MMN) in perceiving oddball (in terms of frequency) sounds. Schulte-Körne, Deimel, Bartling, and Remschmidt (1999) used complex tonal patterns as standard and deviant stimuli which were different in the temporal, but not in the frequency structure. Dyslexics had a significantly smaller MMN in the time window of 225–600 ms, suggesting that the temporal information embedded in speech sounds, rather than phonetic information *per se*, resulted in the attenuated MMN found in dyslexics in previous studies. However, other studies obtained ERP evidence showing deficits for dyslexia only in speech processing, not in auditory processing (Schulte-Körne *et al.*, 1999).

The Chinese language uses a logographic writing system in which the basic orthographic units, the characters, correspond directly to morphemic meanings and to syllables in the spoken language. With some exceptions, each character represents one morpheme and has one pronunciation in isolation, although different characters may have the same pronunciations. Because the number of syllables used in the language is limited to about 1300, whereas the number of commonly used morphemes is about 5000, Mandarin Chinese has a great many homophonic morphemes and homophonic characters. At the lexical or character level, there is no systematic correspondence between orthography and phonology. Although phonetic radicals in complex characters may have the function of pointing to the pronunciations of whole characters, due to the evolution of the writing system, this function is not complete, with exceptions and irregularities littered across the writing system.

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 administered 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

#### *Participants*

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.

#### *Design and procedure*

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.

### *Linguistic Tests*

The *vocabulary test* 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 use of in word-composition. Participants had to know the pronunciation, the orthographic form and meaning of the target character to complete the task.

The *Reading fluency test* 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 *phonological awareness test* 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 *orthographic similarity judgment task*, 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 and 龟) and complex characters contained the same radicals (e.g. 徒 and 陡). For each pair, the first character was presented for 400 ms, followed by a 100-ms blank interval. The second character was presented for 100 ms, and participants were asked to make 'yes' or 'no' judgment as quickly and as accurately as possible. There were 120 pairs of characters, with 60 requiring 'yes' responses and 60 requiring 'no' responses. In the regression analyses, only the latencies of 'yes' responses were used.

In the *character naming task*, 100 characters were presented one by one on the screen and participants were asked to name the characters as quickly and as accurately as possible into a microphone. Each character was presented for 400 ms. Naming latencies were recorded by the DMDX system and naming errors were monitored by an experimenter. These characters were all complex characters, each composed of a semantic radical and phonetic radical (Zhou & Marslen-Wilson, 1999). According to whether the whole character was

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).

#### *Auditory and temporal tests*

In the *tone frequency discrimination task*, 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 *tone temporal order judgment*, 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 *temporal interval discrimination*, 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 *composite tone pattern discrimination task* 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's 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.

#### *Correlations of observations*

Correlation coefficients between various tasks are presented in Table 1. Results show that linguistic measures correlated significantly with auditory processing

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 generally correlated to each other, so the auditory measures.

### Multiple regressions

To assess contributions of phonological awareness and auditory and temporal processing to vocabulary size, we entered first children's scores in Raven's standard progressive matrices test, which were taken as measures of children's IQ, into regression equations and other independent variables in different orders. Table 2 shows that after partialling out IQ's contribution, phonological awareness and auditory measures may have different contributions depending on which measures entered the equations first. If phonological awareness entered the equation first, it could explain 21% variance, but auditory measure showed no significant impact. If auditory scores entered the equation together, before phonological awareness, then scores in composite pattern discrimination had the largest (19%) contribution with no significant contributions from other auditory scores. The contribution of phonological awareness was reduced to 7%. If scores in auditory frequency discrimination was entered before other auditory measures, which were before phonological awareness scores, then auditory frequency discrimination had a significant 5% contribution, composite pattern discrimination had a 14% contribution and phonological awareness' contribution remained to be 7%. These results suggest that contributions to vocabulary size from auditory skills and phonological awareness are not wholly independent. While phonological awareness depends to some extent on auditory processing skills, the contribution of these skills to reading cannot represent wholly the contribution of phonological awareness. Among scores in auditory tasks, the tone composition pattern had the largest contribution to vocabulary development, but auditory frequency discrimination seems to have no unique contribution.

Similar regression procedures were used to assess contributions of various measures to reading fluency. No matter what the order of variables entering the equation is phonological awareness had no significant impact on reading fluency.

Table 2. Variance contributed to vocabulary size by auditory processing measures and phonological awareness after controlling for IQ and the order of entering equation of predictors

Dependent	Predictors	$R^2$	$R^2$ change	$t$
Vocabulary	1. Raven	0.05	0.05*	2.29*
	2. Composite tone pattern discrimination	0.24	0.19***	-3.55***
	3. Phonological awareness	0.31	0.07**	2.86**
	1. Raven	0.05	0.05*	2.29*
	2. Tone frequency discrimination	0.10	0.05*	-2.22*
	3. Composite tone pattern discrimination	0.24	0.14**	-3.55***
	4. Phonological awareness	0.31	0.07**	2.86**
	1. Raven	0.05	0.05*	2.29*
	2. Phonological awareness	0.26	0.21***	5.02***
3. Auditory processing measures	0.31	0.05		

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



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 predictors

Dependent	Predictors	$R^2$	$R^2$ change	$t$
Fluency	1. Raven	0.03	0.03	
	2. Tone temporal order judgment	0.17	0.14*	-2.01*
	3. Phonological awareness	0.172	0.002	
	1. Raven	0.03	0.03	
	2. Tone frequency discrimination	0.09	0.06*	-2.30*
	3. Tone temporal order judgment	0.17	0.08*	-2.01*
	4. Phonological awareness	0.172	0.002	
	1. Raven	0.03	0.03	
	2. Phonological awareness	0.06	0.03	
	3. Auditory processing measures	0.172	0.11*	

Note: \* $p < 0.05$ .

Table 4. Variance contributed to phonological awareness by auditory processing measures after controlling for IQ

	Predictors	$R^2$	$R^2$ change	$t$
Phonological awareness	1. Raven	0.12	0.12**	2.46**
	2. Tone temporal interval discrimination			-2.63**
	Composite tone pattern discrimination	0.44	0.32**	-4.9***
	1. Raven	0.12	0.12**	2.46**
	2. Tone frequency discrimination	0.16	0.04*	-2.14*
	3. Tone temporal interval discrimination			-2.63**
	Composite tone pattern discrimination	0.44	0.28**	-4.9***

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

Table 5. Variance contributed to character naming latency by auditory processing measures after controlling for IQ and the order of entering equation of predictors

Dependent	Predictors	$R^2$	$R^2$ change	$P$
Character naming	1. Raven( IQ )	0.00	0.00	0.84
	2. Auditory processing measures	0.16	0.16	0.00**
	3. Phonological awareness	0.17	0.007	0.66
	2. Phonological awareness	0.04	0.04	0.05*
	3. Auditory processing measures	0.17	0.13	0.01**

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

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. Regression 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 regression 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 *et al.*, 2000; Witton *et al.*, 1998). In addition to phonological skills, it is the temporal processing skill, not the auditory processing *per se* that affects Chinese reading directly.

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*

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 of Raven Standard Progressive Matrices (Zhang & Wang, 1985). The participants' ages ranged from 8 to 13 (mean age 11 years and 1 month, *S.D.*=1.34 months). Twenty participants took part in all of the five blocks of the experiment and other three took part in just some of the tests. All participants were right-handed and had normal hearing and normal or corrected-to-normal vision. None of the participants had a history of neurological or emotional disorders. All the participants gave their informed consent to participate in the experiment and were paid for their time and effort.

Three tests in the Hong Kong Test of Specific Learning-Difficulties in Reading and Writing (HKT-SpLD) (Ho, Chan, Tsang, & Lee, 2000) were adapted and administrated to a large group of school children before the participants were selected: Chinese word reading fluency, rapid digit naming and rhyme detection. Participants with standard scores lower than 7 in the reading tests were defined as dyslexics. The differences between scores for the two groups of participants were significant (see Table 6).

#### *Stimuli*

The passive oddball paradigm was used in the present study. Participants were asked to watch a funny movie 'Cat and Mouse' in silent while listening to

Table 6. Sample characteristics of dyslexics and controls

	Age mean (S.D.)	IQ mean (S.D.)	Chinese word reading <sup>a</sup>	Digit rapid naming <sup>a</sup>	Rhyme detection <sup>a</sup>
Controls	10.91 (0.34)	75.84 (4.24)	9.56	9.97	10.02
Dyslexics	11.18 (0.48)	81.81 (2.36)	5.7	7	5.875

<sup>a</sup>There is significant difference between two groups in the standard score in the Chinese word reading, Digit rapid naming and rhyme detection tests ( $p < 0.01$ ).

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 *simple tone* 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 *composite tone pattern* 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 numbers indicated the Chinese lexical tones. In the last three sets of stimuli, every syllable lasted for 40 ms, and there was an interval of 700 ms between the two successive presentations of stimuli.

### Procedure

Participants were seated in a comfortable sofa in a sound-proof booth, watching the movie 'Cat and Mouse' and listening passively to the five sets (five blocks) of stimuli. Participants had three breaks within each block, as well as breaks between the five blocks.

The electroencephalogram (EEG) was recorded from 30 scalp electrodes based on the advanced International 10–20 system. Electrodes Fz, Fcz, Cz, Pz, Cpz and Oz were distributed along the midline of the skull. Other electrodes were located approximately symmetrically at the two sides of the skull. The skin resistance of

each electrode was kept below 5 k $\Omega$ . The recording from an electrode on the right mastoid was used as reference. Eye blinks and vertical eye movements were monitored with electrodes located below and above the right eye. The horizontal electro-oculogram was recorded from electrodes placed 1.5 cm lateral to the left and right external canthi. The EEG was amplified (band pass 0.05–70 Hz) and digitized at a sampling rate of 250 Hz. The ERPs in each condition were averaged separately off-line with averaging epochs beginning 200 ms before stimulus onset and continuing for 750 ms for all the blocks of stimuli except for Block 2 with the *composite tone pattern* stimuli, in which the averaging epochs lasted for 2000 ms after stimulus onset. Trials contaminated by eye blinks, eye movements, or muscle potentials exceeding 150  $\mu\text{V}$  (peak to peak amplitude) at any electrode were excluded from data averaging.

## Results

Because some participants refused to continue after a few blocks of testing or skipped over the second, the longest block, data for the first set of stimuli (simple tone) came from 11 dyslexics and 7 controls, for second set of stimuli (composite tone pattern) came from 11 dyslexics and 6 controls. Data for the third (initial consonants) came from 11 dyslexics and 8 controls, for the fourth (vowel of a Chinese syllable) came from 11 dyslexics and 7 controls, for the last set (lexical tone) came from 10 dyslexics and 8 controls. The small number of participants may reduce the statistical power in finding difference between the groups. Mean amplitudes of ERPs were obtained at 20-ms intervals starting from 50 ms before the onset of stimulus. Because most of the previous studies (e.g. Schulte-Körne *et al.*, 1999; 2001) demonstrated that MMN at the Fz electrode is most sensitive to the differences between dyslexic and normal controls, we concentrated on the analyses of data here. But we did carry out analyses of mean amplitudes for all the electrodes and found no contradiction to the findings reported here. In the following paragraphs, we reported separately the analyses of MMNs for the five sets of stimuli.

For the first set of stimuli with deviant tone frequency, mean amplitude values of MMN in the control group and in the dyslexic group showed no significant differences ( $p > 0.05$ , see Figure 1). Marginally significant differences between the two groups of children, however, were found in their MMNs to composite tone

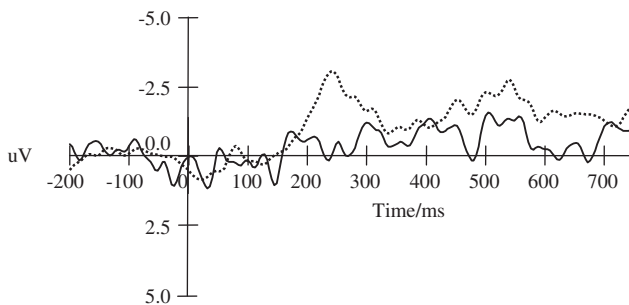


Figure 1. Grand average of the mismatch negativity MMN for tone frequency in dyslexic subjects (dotted line) and controls (solid line) at Fz (fronto-central lead).

patterns ( $0.05 < p < 0.1$ , see Figure 2). Compared with the control group, dyslexics showed smaller MMNs on average amplitudes from 150 to 500 ms. Thus brain activation of dyslexic children differed somehow from that of normal children in processing temporal information.

Differences between the two groups were also found in MMNs to syllables deviating on initial consonants. It is clear from Figure 3 that there was a significant difference on average amplitudes between 0 and 100 ms ( $p < 0.05$ ). Similarly, a deviant vowel of a Chinese syllable also produced significant differences in MMNs at the time window between 380 and 700 ms for the two groups of children ( $0.05 < p < 0.1$ , Figure 4). Finally, no significant differences between the two groups of participants were found in MMNs produced by deviant stimuli differing in lexical tone (Figure 5).

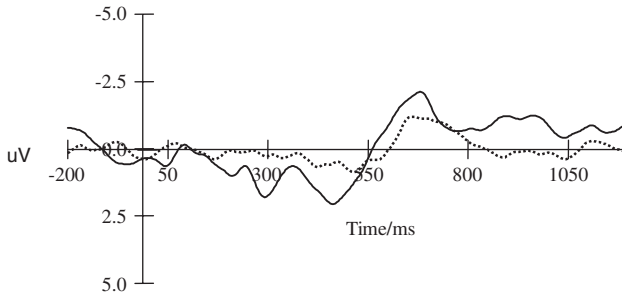


Figure 2. Grand average of the mismatch negativity MMN for composite tone pattern stimuli in dyslexic subjects (dotted line) and controls (solid line) at Fz (fronto-central lead).

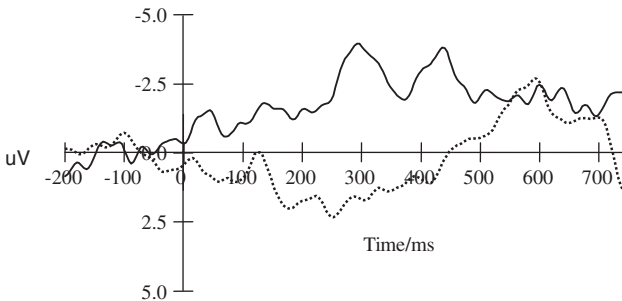


Figure 3. Grand average of the mismatch negativity MMN for initial consonant stimuli /da//ga/ in dyslexic subjects (dotted line) and controls (solid line) at Fz (fronto-central lead).

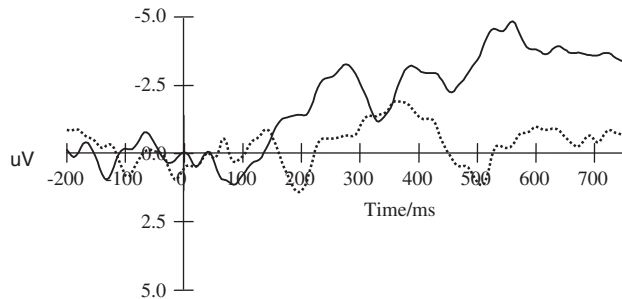


Figure 4. Grand average of the mismatch negativity MMN for vowel of Chinese syllable /dan//dai/ in dyslexic subjects (dotted line) and controls (solid line) at Fz.

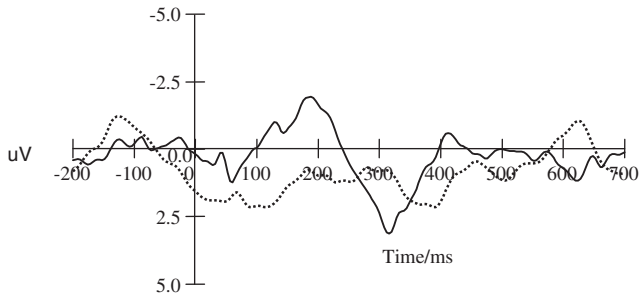


Figure 5. Grand average of the mismatch negativity MMN for Chinese lexical tone of stimuli in dyslexic subjects (dotted line) and controls (solid line) at Fz (fronto-central lead).

## 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-Körne *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. Regression 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 understanding structures in different domains and the mapping between structures. Such deficits will manifest themselves when children come across a new domain, say the orthographic structure. Thus Chinese children having difficulties in understanding the Chinese phonological structure may also have difficulties in understanding the Chinese orthographic structure, even though the Chinese orthographic structure has no systematic relations with the phonological structure (e.g. no letter-sound correspondences). Similarly, deficits in auditory temporal processing could reflect a general deficiency in temporal processing across various domains. This general deficiency can manifest in different domains at the same time, creating the apparent correlations between, say, temporal order judgment of pure tones and deleting of the initial consonant of a syllable.

The parallel finding of differences between dyslexic and control groups in MMN responses to deviating temporal and linguistic information is also important to our understanding of the neural basis of dyslexia in Chinese. Although the present data do not allow us to make strong conclusions due to the limit of participant number and statistical power, it is clear that MMN in particular and ERP in general are sensitive and informative methods to investigate the neural substrates of deficient cognitive processes involved in Chinese dyslexia. MMN might also provide earlier markers for children in risks of reading impairment by detecting their passive responses to deviating auditory or temporal information.



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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## REFERENCES

- Agnew, J. A., Dorn, C., & Eden, G. F. (2004). Effect of intensive training on auditory processing and reading skills. *Brain and Language*, *88*, 21–25.
- Ahissar, M., Protopapas, A., Reid, M., & Merzenich, M. M. (2000). Auditory processing parallels reading abilities in adults. *Proceedings of the National Academy of Sciences*, *97*, 6832–6837.
- Baldeweg, T., Richardson, A., Watkins, S., Foale, C., & Gruzelier, J. (1999). Impaired auditory frequency discrimination in dyslexia detected with mismatch evoked potentials. *Annals of Neurology*, *45*, 495–503.
- Bowers, P. G., & Wolf, M. (1993). Theoretical links among naming speed, precise timing mechanisms and orthographic skill in dyslexia. *Reading and Writing*, *5*, 69–85.
- Bradley, L. L., & Bryant, P. (1978). Difficulties in auditory organization as a possible cause of reading backwardness. *Nature*, *271*, 746–747.
- Bradley, L. L., & Bryant, P. (1983). Categorizing sounds and learning to read: A causal connexion. *Nature*, *301*, 419.
- Bretherton, L., & Holmes, V. M. (2003). The relationship between auditory temporal processing, phonemic awareness, and reading disability. *Journal of Experimental Child Psychology*, *84*, 218–243.
- Brown, G. D. A. (1997). Connectionism, phonology, reading, and regularity in developmental dyslexia. *Brain and Language*, *59*, 207–235.
- Bryant, P. E., & Bradley, L. (1985). *Children's reading difficulties*. Oxford: Basil Blackwell.
- Denckla, M. B., & Rudel, R. G. (1976). Rapid 'automatized' naming (RAN): Dyslexia differentiated from other learning disabilities. *Neuropsychologia*, *14*, 471–479.
- Forster, I. K., & Forster, C. J. (2003). DMDX: A windows display program with millisecond accuracy. *Behavior Research Methods, Instruments, & Computers*, *35*, 116–124.
- Ho, C., & Bryant, P. (1997). Phonological skills are important in learning to read Chinese. *Developmental Psychology*, *33*, 946–951.
- Ho, C. S.-H., Chan, D. W.-O., Tsang, S. M., & Lee, S. H. (2000). *The Hong Kong test of specific learning difficulties in reading and writing (HKT-SpLD)*. Hong Kong, China: Chinese University of Hong Kong & Education Department, HKSAR Government.
- Katz, R. (1986). Phonological deficiencies in children with reading disability: Evidence from a object naming task. *Cognition*, *22*, 225–257.

- Kujala, T., Karma, J., Ceponiené, R., Belitz, S., Turkkila, P., Tervaniemi, M., & Näätänen, R. (2001). Plastic neural changes and reading improvement caused by audiovisual training in reading-impaired children. *Proceedings of the National Academy of Sciences*, 98, 10509–10514.
- Lundberg, I., Frost, J., & Petersen, O. P. (1988). Effects of an extensive program for stimulating phonological awareness in preschool children. *Reading Research Quarterly*, 23, 263–284.
- Manis, F. R., Custodio, R., & Szeszulski, P. A. (1993). Development of phonological and orthographic skill: A two-year longitudinal study of dyslexic children. *Journal of Experimental Child Psychology*, 56, 64–86.
- McBride-Chang, C. (1995). Phonological processing, speech perception, and reading disability: An integrative review. *Educational Psychologist*, 30, 109–121.
- McBride-Chang, C., & Ho, C. S.-H. (2000). Developmental issues in Chinese children's character acquisition. *Journal of Educational Psychology*, 92, 50–55.
- McCroskey, R. L., & Kidder, H. C. (1980). Auditory fusion among learning disabled, reading disabled and normal children. *Journal of Learning Disabilities*, 13, 18–25.
- Menell, P., McAnally, K. I., & Stein, J. F. (1999). Psychophysical and physiological responses to amplitude modulations in dyslexia. *Journal of Speech and Hearing Research*, 42, 797–803.
- Merzenich, M. M., Jenkins, W. M., Johnston, P., Schreiner, C., Miller, S. L., & Tallal, P. (1996). Temporal processing deficits of language-learning impaired children ameliorated by training. *Science*, 271, 77–81.
- Rack, J. (1985). Orthographic and phonetic coding in normal and dyslexic readers. *British Journal of Psychology*, 76, 325–340.
- Ramus, F. (2003). Developmental dyslexia: Specific phonological deficit or general sensorimotor dysfunction. *Current Opinion in Neurobiology*, 13, 212–218.
- Schulte-Körne, G., Deimel, W., Bartling, J., & Remschmidt, H. (1998). Auditory processing and dyslexia: Evidence for a specific speech processing deficit. *NeuroReport*, 9, 337–340.
- Schulte-Körne, G., Deimel, W., Bartling, J., & Remschmidt, H. (1999). Pre-attentive processing of auditory patterns in dyslexic human subjects. *Neuroscience Letters*, 276, 41–44.
- Schulte-Körne, G., Deimel, W., Bartling, J., & Remschmidt, H. (2001). Speech perception deficit in dyslexic adults as measured by mismatch negativity (MMN). *International Journal of Psychophysiology*, 40, 77–87.
- Share, D. L., Jorm, A. F., Maclean, R., & Matthews, R. (2002). Temporal processing and reading disability. *Reading and Writing*, 15, 151–178.
- Share, D. L., & Stanovich, K. E. (1995). Cognitive processes in early reading development: Accommodating individual differences into a model of acquisition. *Issues in Education: Contributions from Educational Psychology*, 1, 1–57.
- Shu, H., Anderson, R. C., & Wu, N. (2000). Phonetic awareness: Knowledge of orthography–phonology relationships in the character acquisition of Chinese children. *Journal of Educational Psychology*, 92, 56–62.
- Shu, H., Chen, X., Anderson, R. C., Wu, N., & Xuan, Y. (2003). Properties of school Chinese: Implications for learning to read. *Child Development*, 74, 27–48.
- Siegel, L. S., & Ryan, E. B. (1988). Development of grammatical-sensitivity, phonological, and short-term memory skills in normally achieving and learning disabled children. *Developmental Psychology*, 24, 28–37.
- Siok, W. T., & Fletcher, P. (2001). The role of phonological awareness and visual-orthographic skills in Chinese reading acquisition. *Developmental Psychology*, 37, 886–899.
- Snowling, M. J. (1981). Phonemic deficits in developmental dyslexia. *Psychological Research*, 43, 219–234.
- Stanovich, K. E., & Siegel, L. S. (1994). The phenotypic performance profile of reading-disabled children: A regression-based test of the phonological-core variable-difference model. *Journal of Educational Psychology*, 86, 24–53.

- Studdert-Kennedy, M. (1997). Deficits in phoneme awareness do not arise from failures in rapid auditory processing. *Paper presented at the international symposium on basic neural mechanisms in cognition and language with special reference to phonological problems in dyslexia*, Stockholm, Sweden.
- Studdert-Kennedy, M., & Mody, M. (1995). Auditory temporal perception deficits in the reading impaired: A critical review of the evidence. *Psychonomic Bulletin and Review*, 2, 508–514.
- Swan, D., & Goswami, U. (1997). Phonological awareness deficits in developmental dyslexia and the phonological representations hypothesis. *Journal of Experimental Child Psychology*, 66, 18–41.
- Talcott, T. B., Witton, C., McLean, M. F., Hansen, P. C., Rees, A., Green, G. G. R., & Stein, J. F. (2000). Dynamic sensory sensitivity and children's word decoding skills. *Proceedings of the National Academy of Sciences*, 97, 2952–2957.
- Tallal, P. (1980). Auditory temporal perception, phonics, and reading disabilities in children. *Brain and Language*, 9, 182–198.
- Tallal, P., Merzenich, M. M., Miller, S., & Jenkins, W. (1998). Language learning impairments: Integrating basic science, technology, and remediation. *Experimental Brain Research*, 123, 210–219.
- Temple, E., Deutsch, G. K., Poldrack, R. A., Miller, S. L., Tallal, P., Merzenich, M. M., & Gabrieli, J. D. E. (2003). Neural deficits in children with dyslexia ameliorated by behavioral remediation: Evidence from fMRI. *Proceedings of the National Academy of Sciences*, 100, 2860–2865.
- Wagner, R. K., Torgesen, J. K., & Rashotte, C. A. (1994). Development of reading-related phonological processing abilities: New evidence of bidirectional causality from a latent variable longitudinal study. *Developmental Psychology*, 30, 73–87.
- Wang, X. L., & Tao, B. P. (1996). *Chinese character recognition test battery and assessment scale for primary school children*. Shanghai: Shanghai Education Press.
- Witton, C., Talcott, J. B., Hansen, P. C., Richardson, A. J., Griffiths, T. D., Rees, A., Stein, J. F., & Green, G. G. R. (1998). Sensitivity to dynamic auditory and visual stimuli predicts nonword reading ability in both dyslexic and normal readers. *Current Biology*, 8, 791–797.
- Zhang, H. C., & Wang, X. P. (1985). *Raven standard progressive matrices: Chinese city revision*. Beijing: The National Revision Collaborative Group.
- Zhou, X., & Marslen-Wilson, W. (1999). The nature of sublexical processing in reading Chinese characters. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 25, 819–837.