Ann. of Dyslexia (2008) 58:15–35
DOI 10.1007/s11881-008-0015-4

The role of visual and auditory temporal processing for Chinese children with developmental dyslexia

Kevin K. H. Chung · Catherine McBride-Chang · Simpson W. L. Wong · Him Cheung · Trevor B. Penney · Connie S.-H. Ho

Received: 29 March 2007 / Accepted: 1 April 2008 /
Published online: 16 May 2008

Abstract This study examined temporal processing in relation to Chinese reading acquisition and impairment. The performances of 26 Chinese primary school children with developmental dyslexia on tasks of visual and auditory temporal order judgement, rapid naming, visual-orthographic knowledge, morphological, and phonological awareness were compared with those of 26 reading level ability controls (RL) and 26 chronological age controls (CA). Dyslexic children performed worse than the CA group but similar to the RL group on measures of accurate processing of auditory and visual-order stimuli, rapid naming, morphological awareness, and phonological awareness and a minority performed worse on the two temporal processing tasks. However, hierarchical regression analyses revealed that visual but not auditory temporal processing contributed unique variance to Chinese character recognition even with other cognitive measures controlled, suggesting it may be as important a correlate of reading ability in Chinese as in alphabetic scripts.

This research was supported by a Competitive Earmarked Research Grant to Kevin K.H. Chung from University Grants Committee (HKIED 8402/05H). The authors thank editors and the two anonymous reviewers for their suggestions to improve the manuscript. Also, we thank all of the students who participated in this study, Mrs Sue Lea, the teachers, and the school principals for their time, valuable assistance, and support.

K. K. H. Chung (✉)
Department of Educational Psychology, Counselling and Learning Needs,
The Hong Kong Institute of Education, 10 Lo Ping Road, Tai Po, N.T., Hong Kong, China
e-mail: kevin@ied.edu.hk

C. McBride-Chang · H. Cheung
The Chinese University of Hong Kong, Hong Kong, China

S. W. L. Wong
The Oxford University, Oxford, England

T. B. Penney
The National University of Singapore, Singapore

C. S.-H. Ho
The University of Hong Kong, Hong Kong, China

Keywords Chinese characters · Chinese children · Developmental dyslexia · Temporal order judgement · Temporal processing

Developmental dyslexia is a specific problem of learning to read, often accompanied by writing and spelling difficulties despite normal intelligence and adequate formal education and in the absence of any physical and psychological problems (Catts & Kamhi, 2005). Dyslexia is presumed to result from impaired phonological processing in all scripts tested thus far (e.g., Bradley & Bryant, 1983; Torgesen, Wagner, & Rashotte, 1994; Ziegler & Goswami, 2005). However, in Chinese, multiple cognitive deficits apart from phonological processing, including visual-orthographic skills (Ho, Chan, Tsang, & Lee, 2002), rapid or speeded naming (Ho & Lai, 1999), and morphological awareness (Shu, McBride-Chang, Wu, & Liu, 2006) have also been linked to developmental dyslexia. More basic perceptual processing underlying cognitive correlates of reading impairment have been suggested in both the visual (Eden, Stein, H. M. Wood, & F. B. Wood, 1995) and auditory (e.g., Tallal et al., 1996) modalities. However, few, if any, studies have examined both cognitive and temporal processing perceptual processes in relation to developmental dyslexia in Chinese. The purpose of the present study was to examine the relations of auditory and visual temporal processing to Chinese character recognition among children with dyslexia as well as normally achieving children.

Sensory temporal processing deficits in dyslexic readers of alphabetic languages

Among monolingual English readers, a basic domain-general deficit in processing brief components and rapid sequences of information, often suggested to reflect impaired rapid temporal processing, has been found among dyslexic readers (for a review, see Farmer & Klein, 1995; Habib, 2000). Such processing difficulties can emerge in either the visual or auditory modalities. According to Klein (2002), temporal processing deficits could involve a hierarchy of temporal information-processing functions ranging from the perception and identification of stimuli to individualizing and perceiving multiple stimuli presented in the correct sequences. Such deficits could be interpreted as reflecting a weakness in the rate of processing, a decrease of encoded information over time, or a decrease in processing temporal information where the times assigned to events or their properties are variable (Farmer & Klein, 1995). Furthermore, Farmer and Klein (1995) suggested that temporal processing deficits might occur in either or both visual and auditory modalities; thus, individuals with dyslexia could show significant problem in processing rapid or brief sequences of auditory and visual stimuli (Keen & Lovegrove, 2000; Kinsbourne, Rufo, Gamzu, Palmer, & Berliner, 1991; May, Williams, & Dunlap, 1988). Such processing deficits could give rise to poor reading through phonological and orthographic routes, respectively. Deficient auditory temporal processing is thought to cause interference with phonological processing which leads to difficulties in manipulating letter–sound correspondences (Booth, Perfetti, MacWhinney, & Hunt, 2000). Also, visual temporal processing deficit is thought to cause impaired letter position encoding and global word form perception, thus, leading to problems in ability to acquire the grapheme-to-phoneme correspondences (Hood & Conlon, 2004; Byrne & Fielding-Barnsley, 1989). Therefore, visual temporal processing deficits may reflect different degrees of impairment with coding underlying problems in orthographic processing and subsequent reading problems. Theoretically, these deficits have been argued to be linked with the neurological impairments of the magnocellular retinocortical visual system (Eden et al., 1996; Facoetti & Molteni, 2001; Livingstone, Rosen, Drislane, & Galaburda, 1991) and in the magnocellular layers of the medial geniculate nucleus in the auditory system (Galaburda, Menard, & Rosen, 1994) as these magnocellular impairments may develop in utero (Galaburda, Sherman, Rosen, Aboitiz, & Geschwind, 1985; Stein, 2001). The magnocellular system's response to briefly or rapidly presented auditory or visual stimuli would result in temporal processing deficits. Inefficiency in these temporal processes is likely to be associated with reading disability.

Empirical evidence for deficient auditory temporal processing among dyslexics whose native language is English has spanned more than three decades. Much of the evidence comes from studies that ask children to make temporal order judgments (TOJ) for either verbal or nonverbal stimuli presented at rapid rates. Using auditory TOJ tasks, Tallal (1980) initially found that children with dyslexia had difficulty in determining the order of two non-speech tones presented at shorter inter-stimulus intervals (ISIs; around 8–305 ms) but not at intervals longer than 305 ms and interpreted this result as evidence that dyslexics could have an abnormally low limit on the rate at which they could process auditory information. More direct evidence of a link between dyslexia and the presence of a low-level auditory impairment was also reported by Tallal (1980), who found high correlations of temporal processing of non-speech tones with phonological decoding (r=0.81), word knowledge (r=0.64), and spelling (r=0.67). Further evidence (Booth et al., 2000; Farmer & Klein, 1995) demonstrated that a subgroup of dyslexic children tended to perform worse on auditory TOJ tests as compared to normal children, in addition to exhibiting weaknesses on a variety of phonological awareness and reading tasks. Thus, it has been suggested that deficits in phonological skills may stem from more fundamental auditory temporal deficits (Booth et al., 2000; Farmer & Klein, 1995). Although all of the work cited above was done on children learning to read an alphabet, one study from China (Meng et al., 2005) demonstrated that a similar measure of auditory processing explained unique variance beyond phonological awareness in Chinese character naming latencies in a large unselected group of fifth graders from China, suggesting that auditory TOJ may be useful in understanding reading processes in Chinese as well. Apart from these studies on auditory temporal processing, phonological processing, and reading, differences between dyslexic readers and normal readers have been demonstrated using visual TOJ tasks (Slaghuis, Twell, & Kingstone, 1996) as well. For example, Hood and Conlon (2004) reported that not only auditory but also visual TOJ tasks accounted for significant independent variance in reading among normal readers. Differences were found between the dyslexic and normal reader groups on visual TOJ tasks, showing that those with dyslexia tend to perform less accurately than normally reading individuals when ISIs are short (Byrne & Fielding-Barnsley, 1989). Brannan and Williams (1988) also found significance between reader group differences on the visual TOJ tasks. Such deficient visual processing was also associated with problems in orthographic processing (Booth et al., 2000; Farmer & Klein, 1995). This finding is similar to those findings related to auditory TOJ deficits, which support the hypothesis of temporal processing deficit for interference with reading.

In spite of the empirical support for a temporal processing deficit in dyslexics, there have been a number of contradictory findings. There are studies that have failed to replicate auditory and visual processing deficits in dyslexia (e.g., Bretherton & Holmes, 2003; Nittrouer, 1999; Studdert-Kennedy, 2002). Some studies found no significant reader group differences on auditory TOJ tasks (Nittrouer, 1999) or on visual TOJ tasks (Farmer & Klein, 1993; Reed, 1989). Research found no relations among auditory TOJ, phonological processing, and reading measures (Bretherton & Holmes, 2003). Other research failed to identify systematic differences in auditory TOJ tasks between dyslexics and controls or in performance on the short and long ISIs between stimulus presentations (Heath, Hogben, & Clark, 1999; Marshall, Snowling, & Bailey, 2001; Nittrouer, 1999). Studdert-Kennedy and Mody (1995), see also Studdert-Kennedy (2002), focused particularly on the auditory TOJ task related problems in interpreting existing data for a rapid auditory processing deficit and suggested that the difficulties children with dyslexia had in performing on the task could be a result of reduced discriminative capacity rather than temporal order judgement difficulties. In addition, only a subgroup of dyslexics performed poorly on the auditory TOJ tasks (Rosen & Manganari, 2001; Tallal, 1980). Similarly, several studies demonstrated no group differences on the visual TOJ tasks (Farmer & Klein, 1993; Reed, 1989) and no associations between these tasks with orthographic processing and reading (Bretherton & Holmes, 2003; Gibson, Hogben, & Fletcher, 2006), while other studies found significant differences between reader groups on the visual TOJ performance at both short and long ISIs (Bretherton & Holmes, 2003; Cestnick, 2001; Cestnick & Jerger, 2000; Waber et al., 2001) or even only at long ISIs (Share, Jorm, Maclean, & Matthews, 2002). This contradicted the hypothesis of a specific impairment in processing rapidly presented stimuli. Because these results pose a challenge to the hypothesis that a temporal processing problem is a crucial underlying cause of reading difficulty, the hypothesis that dyslexics suffer from temporal processing deficits has been questioned (McArthur & Bishop, 2001; Mody, 2003; Rosen, 2003, for recent reviews). Therefore, the extent to which dyslexia is characterized by temporal processing deficits and how auditory and visual processing are related to reading skills in a sample of dyslexic children and controls remain unclear.

In the present study, we examined these effects in Chinese children with dyslexia as well as normal achieving peers of similar age (CA) and reading level ability (RL) controls. We sought to test the extent to which TOJ effects could be demonstrated in a nonalphabetic orthography. We reasoned that if similar evidence of sensory processing deficits were found in Chinese dyslexic readers as in English readers, this would support the assumption of an underlying neurobiological mechanism in perception supporting the reading process. One guide for the present research was the hypothesis proposed by Farmer & Klein (1995) and followed up by Booth et al. (2000), suggesting a stronger effect of visual TOJ on reading involving a strong visual-orthographic component. The way in which Booth et al. (2000) showed support for this hypothesis was by demonstrating stronger effects of visual, as compared to auditory, TOJ on exception word reading as compared to standard word reading in English-speaking children. Because Chinese features, in a sense, a much more "arbitrary" mapping of Chinese characters to oral language than does English, we conceptualized Chinese as being more visuo-orthographically than phonologically demanding. That is, learning to read Chinese, though it involves learning of many patterns, some of them phonological correspondences, may be more analogous to exception word, than to regular word reading in English. For this reason, one might expect that visual TOJ would be particularly important for reading Chinese, according to previous work (Booth et al., 2000; Farmer & Klein, 1995). To clarify a bit more about why we hypothesized this association, the main characteristics of the Chinese orthography are reviewed below.

Characteristics of Chinese orthography

Chinese is a morphosyllabic writing system where each basic graphic unit of Chinese is a character which is associated with a morpheme (meaning unit) and represents a syllable of spoken Chinese (DeFrancis, 1989; Mattingly, 1984). In Chinese, the unit of writing is the stroke, with each character consisting of a configuration of as many as 32 individual strokes

(Guo, 1995). Around 620 stroke patterns (sometimes called radicals) constitute the recurrent orthographic unit of Chinese characters, and these, then, make up different Chinese characters. Because the number of strokes that are confined to uniformly sized square-shaped forms defining the character is relatively high, the result is a high degree of visual complexity. Each character differs from others in terms of its number of strokes, its radicals, and its spatial configuration. About 95% of Chinese characters can be divided into subunits that form complex visual–spatial patterns such as top-down, left to right, and outside to inside orientation, all of which provide the basis for the orthographic processing of Chinese characters (Li, 1993). Because of the great number of visually complicated Chinese characters, visual-orthographic skills are important in learning Chinese characters (e.g., Huang & Hanley, 1994; Leck, Weekes, & Chen, 1995; Tzeng & Wang, 1983).

Thus, given the large numbers of visually distinct characters, visual processing at a basic level may be particularly important in learning to read Chinese. For example, difficulty in visual processing has been found to be strongly linked to dyslexia in Chinese readers, particularly for readers in Hong Kong where Chinese language teaching does not involve the use of a phonemic coding system such as pinyin or Fu-Yin-Zhu-Hao (Woo & Hoosain, 1984). In more recent work in Hong Kong, orthographic and visual processing deficits have been demonstrated in a fairly large subset of dyslexic Chinese readers (Ho, Chan, Lee, Tsang, & Luan, 2004; Ho et al., 2002). For example, Ho et al. (2004) reported that orthographic processing deficits were found in 42% of dyslexic readers, and cognitive visual deficits were demonstrated in 27% of them.

Despite this information on cognitive deficits among Chinese children with dyslexia, little is known about how Chinese dyslexic readers' sensory temporal processing could contribute to Chinese character recognition. In one study of lower level visual processes, Chow and Ho (2005) found that Chinese dyslexic children were less sensitive than average readers to coherent motion in a global motion coherence task. In addition, as mentioned previously, Meng et al. (2005) also found some links between auditory TOJ and Chinese reading measures. However, to the best of our knowledge, no study, thus, far has examined both auditory and visual TOJ in developing Chinese readers. Given the relative lack of sound-print consistency in Chinese (e.g., Shu & Anderson, 1997; Shu, Anderson, & Wu, 2000), it may be that visual TOJ is particularly important for Chinese character recognition, following arguments by Booth et al. (2000). Extrapolating from the arguments of Booth et al. (2000), who demonstrated a stronger link between visual as compared to auditory TOJ in irregular words, we anticipated that Chinese characters, which are somewhat arbitrary and irregular in sound-print consistency, at least relative to words in an alphabet, might be more strongly linked to visual as compared to auditory TOJ in developing Chinese readers.

Research aims

To summarize, given the salient differences in linguistic and print characteristic dyslexia in Chinese as compared with alphabetic languages, the present study aimed at investigating the performance of Chinese dyslexic children in visual and auditory temporal processing abilities and their associations, relative to several cognitive skills, to word recognition itself. Both sensory temporal processing TOJ tasks measured accuracy rate at both short and long ISIs. This study was designed with two major aims in mind. The first was to ascertain whether temporal processing deficits would be found among Chinese children with developmental dyslexia, as demonstrated previously in children learning to read alphabetic orthographies. If evidences for such deficits were obtained, the results would lend support to the hypothesis that temporal processing deficits underlie the basis of developmental dyslexia irrespective of the language in which reading difficulty occurs (Helenius, Uutela, & Hari, 1999; Talcott et al., 2003). The second aim addressed the question of whether, in Chinese dyslexic children, impaired visual temporal processing is more linked to the development of reading difficulty than is deficient auditory temporal processing, given the visual complexity of Chinese script and the relatively unreliable associations of sound and print in Chinese generally, following the ideas of Booth et al. (2000). We examined this question both by focusing on TOJ tasks alone and by examining these tasks in relation to cognitive measures previously demonstrated to explain variance across developing Chinese readers, including phonological awareness, morphological awareness, visual-orthographic knowledge, and rapid automatized naming (RAN; Ho et al., 2004; Shu et al., 2006).

Method

Participants

The participants who were 78 Cantonese-speaking Chinese primary school students in Hong Kong were divided into three groups. Details of the characteristics of the children are described in Table 1. Twenty-six dyslexic children were referred by the local education authority. They were diagnosed with developmental dyslexia by professional psychologists in accordance with the diagnostic criteria based on the Hong Kong Test of Specific Learning Difficulties in Reading and Writing (HKT-SpLD; Ho, Chan, Tsang, & Lee, 2000). This HKT-SpLD battery, which is a standardized test for diagnosis of developmental dyslexia with local norms in Hong Kong, consisted of 12 tests including three literacy tests, one rapid naming test, two phonological awareness tests, three phonological memory tests, and three orthographic knowledge tests. These 12 tests were combined to yield five composite scores in the domains of literacy, phonological awareness, phonological memory, rapid naming, and orthographic knowledge. Also, the Gardner's (1996) Test of Visual–Perceptual Skills (Non-motor) Revised (TVPS-R) was used to test the children's visual perceptual and visual memory skills. To classify as Chinese dyslexic children, their literacy composite score and at least one cognitive composite score had to be at least one standard deviation below the means of their respective age in the HKT-SpLD and TVPS-R. All of

Table 1 Characteristics of the three groups of participants

Characteristic or task	Reliability coefficient	Dyslexic (n=26) M (S.D.)	CA control (n=26) M (S.D.)	RL control (n=26) M (S.D.)	F-value F(2, 75)	Post-hoc Tukey HSD
Age (years)		8.90 (0.80)	8.91 (0.81)	8.30 (1.07)	3.90*	Dys = CA, Dys > RL
Raven's IQ		104.50 (11.18)	104.65 (12.72)	104.58 (12.05)	0.01	Dys = CA, Dys = RL
Chinese word reading (max=150)	.96	72.03 (23.88)	101.03 (21.73)	71.17 (24.58)	15.80***	Dys < CA, Dys = RL

Split-half reliability is reported for Chinese word reading from subtests of HKT-SpLD (Ho et al. 2000).
*p<.05, ***p<.001

them had an IQ greater than 85. These were the diagnostic criteria of developmental dyslexia used in Hong Kong. Furthermore, parents of the children in the dyslexia group were asked to complete a questionnaire on the child's educational history, general health, vision, hearing, therapy received (e.g., speech therapy or occupational therapy), and past diagnoses by specialists (attention-deficit–hyperactivity disorder (ADHD) or developmental coordination disorder). They were also asked to fill out the subtest of Attention Problems scale from the Child Behavior Checklist (Achenbach, 1991). This subtest was used to screen out the children with ADHD in Hong Kong as local norms were available. Therefore, the children in this study were carefully screened to ensure that they had had sufficient learning opportunities (for instance, new immigrants were excluded), and they did not have any suspected brain damage, uncorrected sensory impairment, serious emotional or behavioral problems, or learning disability (other than in reading).

Another 52 normally achieving children were recruited from three representative primary schools. None of these children had any history of developmental dyslexia or any other type of learning difficulty or psychopathology in childhood. They were equated to those in the Dyslexic group either on chronological age (the CA control group) or reading level ability (the RL control group). These 52 children had grade-appropriate reading achievement and normal intelligence. These two controls were carefully selected to match the Dyslexic group on age, IQ, and reading level (see Table 1).

Materials and procedures

The participants were administered ten tasks including a standardized test of nonverbal intelligence, two TOJ tasks, one morphological awareness task, one visual-orthographic task, one phonological awareness task, one RAN task and Chinese word reading task. Except for the nonverbal intelligence test and visual-orthographic test, all other tasks were administered individually. The parents' or guardians' consent for the child's participation were obtained before testing. All assessments were conducted by trained experimenters.

Nonverbal intelligence test

Raven's Standard Progressive Matrices This is a standardized test of nonverbal IQ that consists of 60 items with increasing difficulty. Each item consists of a target visual matrix with one missing part. The children were asked to select from six to eight alternatives to fill a missing patch in a visual matrix. Nonverbal IQ was estimated based on the local norm established by the former Hong Kong Education Department in 1986 (Raven, Raven & Court 1976).

Psychophysical tests

Visual temporal order judgement test This test was constructed based on the tests devised by Tallal and Piercy (1974, 1975) and Bretherton and Holmes (2003). The stimulus was a pair of white circles (O) and crosses (×) at the size of 25×25 mm. These stimuli appeared in the center of the computer screen against a black background screen via the IBM ThinkPad notebook computer with a 15-in. monitor. The stimuli were of 75 ms duration and appeared on the screen one after the other, separated by an ISI of 8, 15, 30, 60, 150, and 305 ms. The stimuli were presented with four possible pair sequences:×O, O×, ××, and OO. The order of presentation of the conditions was counterbalanced.

The children were seated at a distance of 50 cm from the computer screen. They were instructed to press the assigned keys on the keyboard and response orders were recorded by DMDX program stimulus presentation software developed at Monash University and the University of Arizona by K. I. Forster and J. C. Forster. There were eight practice trials with visual feedback of either ☺ (for correct response) or ☹ (for incorrect response) followed by 72 experimental trials consisting of 12 trials per ISI. No visual feedback was given for experimental trials. The dependent measure was the number of trials collapsed across ISI, on which the response was correct (accuracy). This measure has been used previous work (Farmer & Klein, 1993; Marshall et al. 2001).

Auditory temporal order judgement test The methodology of this test was analogous to the visual temporal order task. The stimulus was a pair of sine wave tones. The low tone had a frequency of 250 Hz while the high tone had a frequency of 500 Hz. Both tones were 75 ms in duration. There were four possible pair sequences: High–High, Low–Low, High–Low, and Low–High and were presented in random order. They were presented at each of ISIs of 8, 15, 30, 60, 150, and 305 ms separated presentation of the first and second tone. The tones were presented to participants via Logitech premium stereo headsets, and responses were recorded on the IBM ThinkPad notebook computer via DMDX program. The procedure was the same as for the visual temporal order judgement task. The children were given practice with feedback before the experimental trials. Seventy-two experimental trials were presented without feedback. The dependent measure was the number of trials, sum of the ISI, on which the response was correct (accuracy). This was consistent with the visual temporal order judgement that was used previously (Farmer & Klein, 1993).

Literacy test

Chinese word reading This literacy subtest was from the HKT-SpLD. In the Chinese Word Reading, the children were asked to read aloud 150 Chinese two-character words in the order of difficulty. The test was discontinued when the children failed to read 15 words consecutively.

Cognitive tests

Rapid automatized naming This was measured by using the Digit Naming subtest from the HKT-SpLD. Eight rows of five Arabic digits (2, 4, 6, 7, and 9) were printed on a piece of white A4 paper in a random order. The children were instructed to say the number names aloud in order on the sheet from beginning to end as accurately and quickly as possible. Each child named each list twice, and the score was the average naming latency across the two trials.

Visual-orthographic test The Lexical Decision subtest of the HKT-SpLD was adopted to assess the children's knowledge of Chinese character structure. There were 30 left–right-structured rare characters and 30 noncharacters. These items were two-radical characters and noncharacters of left–right structure. Each noncharacter was constructed by forming a semantic radical and a phonetic radical from different characters in their illegal positions (e.g.,[illegible]), two semantic radicals (e.g., [illegible]), or two phonetic radicals (e.g., [illegible]). The children were, then, asked to cross out all the noncharacters.

Phonological awareness test Phonological awareness was tested by combining items measuring syllable deletion, onset deletion, and rhyme production in graded difficulty level. All stimuli were presented orally by the experimenter. There were 15 three-syllable real and 14 pseudo-words in the Syllable Deletion test. On each trial, the children were required to take away one either the first, second, or third syllable and say aloud what was left. For example, the children were asked to say /din6/ /daan1/ /ce1/ without /din6/. The correct answer is /daan1/ /ce1/. In the Onset Deletion test, ten real and 12 pseudo one-syllable words were used. The children were asked to drop the first consonant of each item and say aloud what was left. For example, say /so1/ without the initial sound would be /o1/. There were 16 trials in Rhyme Production test which had three reference syllables sharing the same rhyme and tone on each trial. The children were to come up with and say aloud a Cantonese syllable having the same rhyme and tone as the references. For example, "say a Chinese syllable which had the same rhyme and tone as "侵" (侵 /cam1/ meaning "invade"). One acceptable answer would be "心" (心 /sam1/ meaning "heart"). Scores from the three tests were summed into a composite phonological awareness score.

Morphological awareness test Morphological awareness was measured by combining performances on tasks of morphological construction with homophone production in graded difficulty level. In the Morphological Construction test, 27 scenarios were presented in two- to four-sentence stories. The children were, then, asked to come up with words for the objects or concepts presented by each scenario. One example was: "朝頭早既時候日頭出嚟, 我哋叫佢做日出。咁夜晚既時候月亮出嚟, 我哋會點叫佢呀?" which means "Early in the morning, we can see the sun coming up. This is called a sunrise. At night, we might also see the moon coming up. What could we call this?" The correct response item was "moonrise". There were 14 items in the Homophone Production test. The children were given 20 s each to produce Chinese words that contained the target morpheme and the homophone of the target morpheme. For example, the possible correct responses for target morpheme "書" (/syu1/ means "book") would be "書包" (/syu1/ /baau1/ meaning "schoolbag") and "輸送" ("輸" /syu1/ had an identical pronunciation as "書" /syu1/; "輸送" /syu1/ /sung3/ means "transmit"). A composite score was computed by summing the scores from the two tests.

Results

Four types of analyses are presented. The first set of analyses shows the performance on literacy and cognitive skills across the three groups, while the second focuses on more in-depth analyses of performances in the visual and auditory temporal processing tasks. The third set of analyses compares the degree and severity of various visual and auditory temporal deficits. The fourth set of analyses examines the contributions of various cognitive measures to variance in Chinese word reading.

Group comparisons of literacy and cognitive measures

The means, standard deviations (SD) and F values for all tests are presented for the Dyslexic group, CA control, and RL control group in Table 2. Both dyslexic group and RL group were matched with Chinese word reading (see Table 1). A significant multivariate analysis of variance effects were obtained for various cognitive tasks, $F(2, 75)=4.10$,

Table 2 Reliability coefficients, mean scores, and standard deviations of various cognitive tasks of the dyslexic group, CA control group, and the RL control group and the F values for group differences on various measures

Task	Reliability coefficient	Dyslexic (n=26) M (SD)	CA control (n=26) M (SD)	RL control (n=26) M (SD)	F-value F(2, 75)	Post-hoc Tukey HSD
Phonological awareness (max=67)	.94	30.35 (9.08)	39.68 (10.23)	28.85 (8.37)	10.21***	Dys < CA, Dys = RL
Rapid naming	.91	25.04 (7.45)	17.81 (3.43)	22.84 (7.21)	9.00***	Dys > CA, Dys = RL
Morphological awareness (max=55)	.88	33.00 (6.64)	37.96 (7.27)	29.54 (8.39)	8.36**	Dys < CA, Dys = RL
Visual-orthographic knowledge (max=60)	.74	50.73 (4.39)	51.50 (4.20)	50.46 (5.92)	0.32	Dys = CA, Dys = RL

Cronbach's alpha reliability is reported for phonological awareness and morphological awareness, and split-half reliability is reported for rapid naming and visual-orthographic knowledge which are tapped by subtests of HKT-SpLD (Ho et al. 2000)

**p<.01, ***p<.001

p<.001, η^2=.19, and post hoc analysis was used to examine each task in Table 2. Using post hoc with Tukey test comparisons revealed that the dyslexic group was significantly worse than the CA group but similar to the RL group. The dyslexic group performed worse on most of the tasks than the CA group. The exception was on the visual-orthographic test, which appeared to be close to ceiling for the children. However, even for this task, while the differences did not reach the level of statistical significance, the dyslexic group appeared to perform less well than did the CA control group.

To further evaluate the magnitude of size effects on various cognitive tasks, the effect size analysis which was used by Nicolson & Fawcett (1995) is presented in Table 3. The effect size in the standard scores was computed by subtracting the mean of the dyslexic group from that of both RL- and CA control group and dividing scores by the pooled standard deviation (Cohen, 1988). The Cohen (1988) tentative interpretation was used to explain the

Table 3 Mean effect sizes (Cohen's d) for dyslexic children versus CA controls and RL controls

Variable	Dyslexic children vs.	
	CA controls[a]	RL controls[b]
Literacy skill		
Chinese word reading	−1.32	0.01
Cognitive skills		
Visual-orthographic knowledge	−0.18	0.05
Rapid naming	1.26	0.30
Phonological awareness	−0.96	0.17
Morphological awareness	−0.71	0.46

[a] ($Mean_{Dyslexic}$−$Mean_{CA}$ control)/pooled standard deviation

[b] ($Mean_{Dyslexic}$−$Mean_{RL}$ control)/pooled standard deviation

effect sizes (d=0.2 small, d=0.5 moderate, and d=0.8 large). A comparably large effect size for rapid naming, phonological, and morphological awareness was found in this analysis while a small effect size was obtained for the visual-orthographic knowledge test.

Group comparisons on visual and auditory temporal order judgement measures

The scores of accuracy on the visual TOJ measure for the dyslexic, CA control, and RL control group are presented in Fig. 1. A 3 (group) × 6 (ISI) analysis of variance with repeated measures showed that for scores of accuracy, there were significant main effects for groups, $F(2, 75)=4.71$, $p<.05$, $\eta^2=.11$, and ISIs, $F(5, 375)=36.30$, $p<.001$, $\eta^2=.33$. As expected, the dyslexic group was overall less accurate in processing the visual-order task than the CA control group but similar to the RL group. There was also no significant interaction between the groups and ISIs, $F(10, 375)=0.79$, $p=.64$, $\eta^2=.02$. Overall, these findings that indicated poor performance of visual stimuli comparison of the dyslexic group on the visual temporal task were in agreement with previous findings (Ben-Yehudah & Ahissar, 2004). However, in contrast to the predictions of Tallal (1980), all children made more errors and were slower as ISIs decreased.

The scores of accuracy on the auditory TOJ measure for the three groups are presented in Fig. 2. A 3 (group) × 6 (ISI) analysis of variance with repeated measures yielded significant main effects for the groups, $F(2, 75)=10.76$, $p<.001$, $\eta^2=.22$, and ISIs, $F(5, 375)=2.42$, $p<.05$, $\eta^2=.03$. No significant interaction was found between the groups and ISIs, $F(10, 375)=0.81$, $p=.62$, $\eta^2=.02$. These main effects indicated that the dyslexic group performed significantly worse than the CA but similar to the RL group. Note that this trend is contrary to the predictions of Tallal (1980) that shorter ISIs would better differentiate the dyslexics and controls.

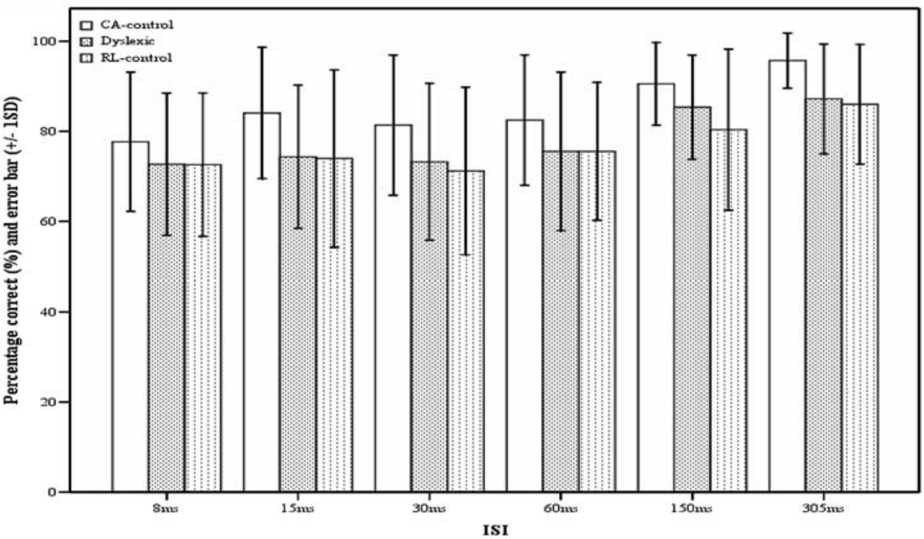

Fig. 1 Percentage *correct* and *error bars* (±1 SD) for the Dyslexic, CA control and RL control group over six ISI of the visual temporal order judgement task

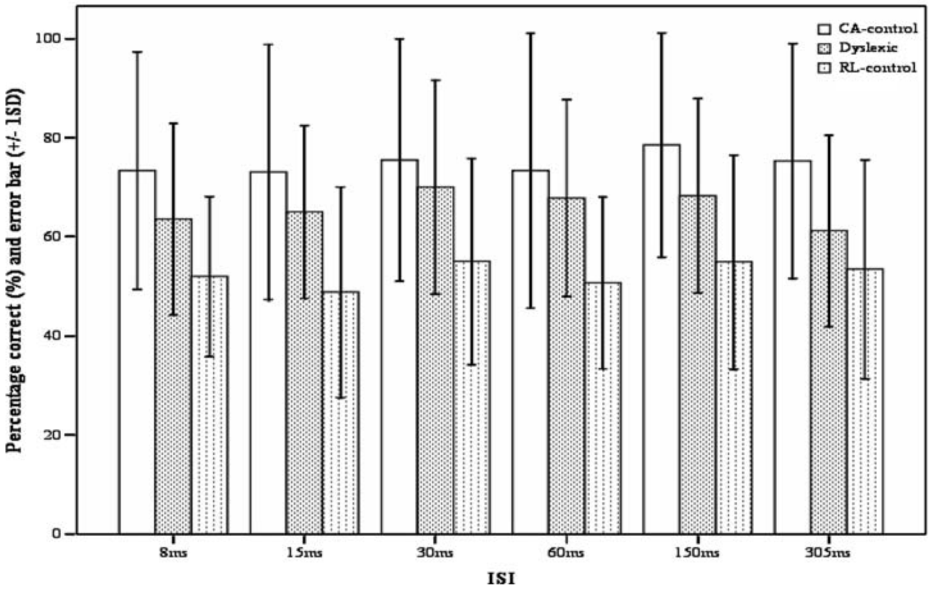

Fig. 2 Percentage *correct* and *error bars* (±1 SD) for the Dyslexic, CA control and RL control group over six ISI of the auditory temporal order judgement task

Variation of temporal processing among the individuals with dyslexia

To investigate the heterogeneity of visual and auditory temporal abilities on temporal order judgement tasks among the individual readers, the percentage of children with dyslexia whose scores fell more than 1 SD from the mean of the control group on each of the temporal measures was analyzed. The cutoff criterion was set to at least 1 SD below the control group as that is similar to the cutoff definition used for classifying individuals with dyslexia (Birch & Chase, 2004; Siegel, 1999; Siegel & Ryan, 1988). For the visual temporal tasks, on average, 38.5% (10/26) of the dyslexic children performed worse than 1

Table 4 Correlations among all variables controlling for IQ and age

		1	2	3	4	5	6	7
1	Chinese word reading	–	.39**	.50***	.23*	−.37**	.33**	.23
2	Phonological awareness		–	.62***	.21	−.25*	.33**	.30*
3	Morphological awareness			–	.33**	−.15	.18	.25*
4	Visual-orthographic knowledge				–	.00	.15	−.06
5	Rapid automatized naming					–	−.24*	−.16
6	Visual temporal processing						–	.11
7	Auditory temporal processing							–

$^{**}p<.01$, $^{***}p<.001$

standard deviation below the control mean on the visual TOJ (VTOJ), while auditory temporal deficits on the auditory TOJ (ATOJ) measure were present in 26.9% (7/26) of the children with dyslexia. Only 15.4% (4/26) of these children performed poorly on the two temporal tasks, suggesting that there was little overlap between the two temporal tasks.

Correlations between literacy, cognitive, and temporal processing measures

Partial correlations across all tasks, with nonverbal IQ, age, and grade statistically controlled, are presented in Table 4. Chinese word reading had a significant and moderate to strong association with most of the cognitive measures and with the visual TOJ and auditory TOJ tasks. Most of the reading-related measures were also significantly intercorrelated. However, there was no significant correlation between the visual TOJ and auditory TOJ measures.

Multiple regressions

Multiple regression analyses were used to examine the relations among temporal processing, rapid naming, visual-orthographic knowledge, and phonological and morphological awareness for the three groups of children. These analyses were performed to establish the importance of the TOJ tasks relative to other cognitive measures included in the battery. The order in which variables were regressed onto Chinese word recognition were nonverbal IQ, age, and grade at step 1 as control variables, and then the TOJ tasks at steps 2 and 3, alternately, to determine their independent contributions. Parenthetically, we included both age and grade in these analyses because reading, itself, depends not just on maturational development (for which age is a proxy) but also learning, as defined by grade in school. We also conducted four additional regressions in which each of the four cognitive measures were included one by one before the TOJ measures to demonstrate the independent associations of each measure to Chinese character recognition. These cognitive measures were entered with phonological awareness first because it is best established as a strong correlate of reading across orthographies (e.g., Bradley & Bryant, 1985; Ho, Law, & Ng 2000), morphological awareness was second because it has been shown to be strongly related to Chinese reading more recently (e.g., McBride-Chang, Shu, Zhou, Wat, & Wagner, 2003; Shu et al., 2006), visual-orthographic knowledge third because Chinese children with dyslexia often have deficits in this area (Ho et al., 2004), and, finally, RAN. We included RAN as the final cognitive correlate because it is a powerful correlate of reading in Chinese (Ho & Lai, 1999) and also because it involves a speed component, as do both TOJ tasks. There is still some theoretical debate about the nature of RAN, however, because it involves so many different abilities, including speed, visual sequencing, lexical access, and phonological processing, so we thought it should be included in the final step in order to examine precisely the importance of TOJ relative to the other more clearly defined theoretical constructs in the study.

In selecting predictors for hierarchical regression analyses from Chinese word reading, grade, age, and IQ were first entered as covariates in Step 1. They accounted for 35% of the variance in Chinese word reading as shown in Table 5. In Step 2 and 3, both of visual and auditory TOJ measures were selected. When visual TOJ was entered in Step 2 and 3, it accounted for 7% and 6% of the significant variance in word reading, respectively. However, only 4% of auditory TOJ made a significant contribution to word reading in Step 2 but not Step 3. Further regression analyses were conducted including phonological and morphological awareness, visual-orthographic knowledge, and RAN before TOJ measures.

Table 5 Hierarchical regression equations predicting Chinese word reading

Step		Cumulative R2	R2 change
1	Age, Grade, IQ	.35	.35***
2	VTP	.42	.07**
3	ATP	.45	.03
1	Age, Grade, IQ	.35	.35***
2	ATP	.39	.04*
3	VTP	.45	.06**
1	Age, Grade, IQ	.35	.35***
2	PA	.45	.10**
3	ATP	.46	.01
4	VTP	.49	.03*
1	Age, Grade, IQ	.35	.35***
2	PA	.45	.10**
3	MA	.52	.07**
4	ATP	.52	.00
5	VTP	.56	.03*
1	Age, Grade, IQ	.35	.35***
2	PA	.45	.10**
3	MA	.52	.07**
4	VO	.52	.00
5	ATP	.53	.01
6	VTP	.56	.03*
1	Age, Grade, IQ	.35	.35***
2	PA	.45	.10**
3	MA	.52	.07**
4	VO	.52	.00
5	RAN	.57	.03**
6	ATP	.58	.01
7	VTP	.60	.02****

VTP Visual temporal processing, *ATP* auditory temporal processing, *PA* phonological awareness, *MA* morphological awareness, *VO* visual-orthographic knowledge, *RAN* rapid automatized naming

*p<.05, **p<.01, ***p<.001, ****p<.08

When visual TOJ was entered after the phonological and morphological awareness as well as visual-orthographic knowledge, 3% of the variance in word reading was still accounted for. However, visual TOJ could only contribute 2% of the variance in and marginally related to word reading when entered after the rapid naming. This suggested that RAN was a much stronger predictor than visual TOJ, and this could reflect the importance of RAN for Chinese reading.

Multiple regression analyses were also performed in order to determine the relative contribution of RAN against visual TOJ factors to Chinese word reading. As shown in Table 6, two sets of regression analyses that differed in the presence and absence of RAN were conducted. In the first analysis without the RAN, visual TOJ made a unique contribution to the prediction of word reading. In contrast, for the second analysis with the RAN, it did not make an independent contribution to word reading. The results of the multiple regression analyses generally indicated that visual TOJ emerged as a significant predictor of Chinese word reading when RAN was excluded.

Table 6 Standardized betas for regression equations predicting Chinese word reading from predictor variables (with or without RAN)

Variables	Beta	t-value
Equation without RAN		
Age	−.10	−.64
Grade	.36	2.57*
IQ	−.13	−1.32
VTP	.20	2.22*
ATP	.09	.93
PA	.02	.18
MA	.42	3.02**
VO	.05	.60
Equation with RAN		
Age	−.04	−.28
Grade	.30	2.19*
IQ	−.11	−1.13
VTP	.16	1.81
ATP	.07	.75
PA	−.02	−.15
MA	.42	3.12**
VO	.07	.78
RAN	−.22	−2.52*

For equation predicting Chinese word reading, R^2 =.56 (without RAN), R^2 =.60 (with RAN)
VTP Visual temporal processing, *ATP* auditory temporal processing, *PA* phonological awareness, *MA* morphological awareness, *VO* visual-orthographic knowledge, *RAN* rapid automatized naming
*p<.05, **p<.01, ***p<.001

Discussion

It has been reported that results of psychophysical tasks in which visual and auditory stimuli are briefly or rapidly presented have shown that children with developmental dyslexia perform worse than the CA and RL groups. This suggests that temporal processing deficits may contribute to the existence of a general rate processing difficulty (Farmer & Klein, 1995; Talcott et al., 2003). This hypothesis was further tested in the present study using Chinese, which is a visually relatively complex script. A recent investigation found an association between auditory temporal processing and Chinese character recognition among normally achieving Chinese children (Meng et al., 2005). The present study extended the existing work on auditory temporal processing by including a visual temporal processing component in order to explore the possibility that a deficit in temporal processing of rapidly or briefly presented information might affect the dyslexic children. This study explored the importance of TOJ tasks in both the auditory and visual modalities in Chinese children with dyslexia and those with no reading disability. We did this by comparing TOJ task performances across groups and also by investigating their associations to Chinese word reading with four cognitive abilities, phonological awareness, morphological awareness, visual-orthographic knowledge, and rapid naming, statistically controlled. The results of this study confirmed that majority of Chinese dyslexic children found significant difficulty in reproducing the order of briefly presented visual and auditory stimuli on the TOJ tasks. Furthermore, our results showed that temporal processing, particularly in the visual modality, was likely to be linked to Chinese character recognition in regression analyses.

Our results found significance between reader group differences on the TOJ tasks, showing that the majority of children in the dyslexic group did perform more poorly on the accurate processing of auditory and visual-order tasks than the CA control group but were similar to the RL group. Difficulty in discriminating these tasks may affect reading performance which could increase children's difficulties in understanding the phonological and orthographic structures of Chinese, especially given that the visual complexity of Chinese characters are relatively unsystematically associated with their phonological structures. Although the children with dyslexia showed greater overall difficulty on the two temporal tasks than the control groups in the present study, all children became more error prone with decreasing ISIs. Also, our results did not find any significant interaction between ISIs and groups for the two temporal tasks. In other words, the dyslexic Chinese children were not selectively worse at processing tones and visual symbols at faster rates of presentation. This contradicted Tallal's (1980) hypothesis of a specific impairment in processing rapidly or briefly presented stimuli and to claims of visual and auditory deficits on the TOJ tasks as part of a more general temporal deficit in dyslexia. Recent research also reported findings congruent with our study. For example, Bretherton and Holmes (2003) and Waber et al. (2001) failed to find interaction effects of groups with inter-stimulus intervals among children with and without learning difficulties. In addition, Share et al. (2002) reported that the dyslexic children were impaired on the TOJ tasks at long ISIs relative to the controls but not at the short ISIs in an unselected sample of over 500 preschool children. Taken together, the current results do not lend to support Tallal's(1980) proposition that a deficit in temporal perception and production mechanisms underlies reading and language problems.

At the group level, the majority of Chinese children with dyslexia in the present study did perform poorly on visual and auditory-order tasks compared with controls. However, a closer examination at the individual level revealed that only 38.5% of the children scored at least 1 standard deviation below the mean of the control group on the visual TOJ, and 26.7% of them scored at least 1 standard deviation below the control mean on the auditory TOJ task. One possible explanation for the variability in visual TOJ and auditory TOJ performance might be that the subgroups of Chinese dyslexics could have more difficulties in visual rather than in auditory temporal processing. Decreases in the ability to discriminate visual stimuli on the visual TOJ are thought to be linked with the inability to extract orthographic information from text, whereas insensitivity to auditory stimuli on the TOJ could be associated with phonological processing problems (e.g., Booth et al., 2000; Farmer & Klein, 1995). It is also worth noting that there was only a small overlap (15.4%) between the deficits in the auditory and visual TOJ measures in our sample. Again, this suggests the possibility of a visual-order processing deficit that is independent of the tone-order processing difficulty, and this may relate to different deficient components of reading skills (e.g., Booth et al., 2000; Farmer & Klein, 1995). Our findings have a bearing on previous research studies conducted in Hong Kong (Ho et al., 2002, 2004) demonstrating that a proportion of Chinese dyslexic readers have more visual-orthographic problems than phonological processing problems. Overall, results from the current investigation revealed that only a subgroup of dyslexics had difficulties with visual or auditory processing, but not all individuals with dyslexia exhibited processing problems. Therefore, it might not reflect part of a general neural mechanism underlying visual and auditory deficiency in dyslexics.

Results of our study were also consistent with previous research (Ho et al., 2002, 2004) showing that there are likely multiple deficits in Chinese children with dyslexia. In the present study, there was a comparably large difference between the dyslexic and control group in rapid naming, phonological awareness, and morphological awareness, and all of these cognitive abilities were at least moderately associated with Chinese word reading itself. Unfortunately, the task of visual-orthographic knowledge did not yield group differences and was, correspondingly, nonsignficantly associated with Chinese word reading. This finding is likely attributable to the fact that most children were at ceiling on this particular task. Given the visual-orthographic complexity of the Chinese script, it is likely that our groups would have differed in their performances on other tasks of a higher difficulty level. It should also be noted that, in the final regression analyses, only rapid automatized naming and morphological awareness, but not visual-orthographic processing or phonological awareness, were uniquely associated with Chinese word reading. These results underscore the theoretical importance of understanding some unique features of Chinese, such that sound-print associations are relatively inconsistent, and morphological associations with the script are relatively important to consider in understanding Chinese reading development and impairment. For example, the somewhat weak association of phonological awareness to Chinese character recognition with other cognitive measures controlled may explain why the auditory TOJ had a weaker effect than the visual TOJ on Chinese character recognition in regression analyses. Visual skills may be particularly important for reading Chinese as compared to alphabetic scripts. However, in our initial hierarchical regression analyses, both auditory and visual TOJ tasks as temporal processing could account for Chinese word reading despite the fact that there were no significant correlations between the two temporal measures. This suggests that temporal processing skills in both visual and auditory domains likely affect Chinese reading.

The association of the visual TOJ task to Chinese word reading only became nonsignificant with the inclusion of the rapid naming task in the regression equation, reflecting the importance of rapid naming for Chinese reading. Rapid naming skills have been demonstrated consistently to be a means of discriminating good readers from poor readers (Ho & Lai, 1999; Ho et al., 2002) and of predicting ease of Chinese word reading. Moreover, as noted in a study by Manis, Seidenberg, and Doi (1999), Chinese character recognition is relatively "arbitrary," and a rapid naming measure may tap into the ability to learn arbitrary links between print and sound. Because both Chinese character recognition and a rapid naming task involve the automatic mapping of arbitrary language and print information, Chinese may be a writing system that is particularly strongly associated with a rapid naming task which becomes uniquely related to children's reading performance. Our results suggest that temporal processing has a significant impact on reading accuracy, in part, via rapid naming abilities. However, further investigation is required to determine the extent to which rapid naming abilities contribute to the underlying mechanisms of temporal processing and their role in reading skills among Chinese children with and without reading disability.

There were at least two limitations of the present study. First, across all measures administered, the dyslexic children did not differ in performance levels from their reading level controls. Similar findings have been demonstrated in previous studies (e.g., Ho et al., 2002; Ransby & Swanson, 2003). However, this finding is somewhat problematic for arguing about causality in reading. It is likely that dyslexia implies a general lag, rather than a permanent deficit, in a variety of cognitive and perceptual skills among Chinese children. Support for this conclusion can only be obtained through longitudinal studies, some of which follow dyslexics into adulthood. In addition, we had only single measures of temporal processing in each modality and measures of the mean group differences on the available data. Recent arguments have been made (See Kidd & Hogben, 2004 for review) against the group performance on psychophysical tasks in favor of establishing satisfactory threshold estimates for individuals. Because much research has viewed developmental dyslexia as a heterogeneous disability (e.g., Castles & Coltheart, 1993; Wolf & Bowers, 1999), it is suggested that individual rather than group threshold estimates on any psychophysical task be used in dyslexia so that evaluations of between-subject variability in performance can be accounted for. To test the generality of our findings, future research may be worth examining the relations of psychophysical tasks such as saltation tasks (Kidd & Hogben, 2004) in auditory and visual modalities with orthographic and phonological processing. Although the idea that visual TOJ may be associated with reading in Chinese given its links to visual-orthographic skills demonstrated in English previously (e.g. Booth et al., 2000; Farmer & Klein, 1995), it is also possible that our TOJ tasks differed in other unrelated dimensions such that the visual TOJ task was associated with word recognition for other reasons. Only future research with more varied tasks of TOJ in relation to reading in Chinese can determine the extent to which the visual, rather than the auditory modality of TOJ, is linked to performance in Chinese word reading.

Despite these limitations, the present study was among the first to show that temporal processing performance distinguished dyslexic from normally achieving Chinese children and explained some unique variance in Chinese word reading. That is, a subgroup of children with dyslexia had difficulties in performing low-level visual and auditory temporal tasks relative to those without dyslexia. This suggests that the majority of dyslexic children may have deficits in auditory and visual temporal processing. At the same time, however, when the data were examined at an individual level, only a subgroup of Chinese dyslexics showed more deficits in visual than auditory temporal processing, perhaps in part because the Chinese script is more visually and orthographically complexity than are alphabetic languages. However, as mentioned above, from our study alone, one cannot simplistically conclude that a deficient visual temporal processing will lead to poor reading ability in Chinese given that the results pertained to only a subgroup within our sample and only one visual temporal task was used to measure the visual problem. For a better understanding of the function of visual temporal processes in dyslexia, future research with a large Chinese sample should examine the relative role of visual temporal processing speed in a range of visual measures including global dot motion stimulus, flicker contrast sensitivity and Ternus tasks (Davis, Castles, McAnally, & Gray, 2001; Cornelissen, Hansen, Hutton, Evangelinou, & Stein, 1998; Edwards & Badcock, 1996). Having these measures would provide a more comprehensive view of impairments of visual temporal processing in relation to different component reading skills. Clearly, future work will need to include multiple temporal measures from multiple modalities. However, thus far, our results have confirmed that a subset of dyslexic children have auditory and visual deficits and in turn these findings do not lend support to major contention that a deficit in general temporal processing contributes to the acquisition of word recognition across all scripts.

References

Achenbach, T. (1991). *Manual for the Child Behavior Checklist/4–18 and 1991 Profile*. Burlington: University of Vermont Department of Psychiatry.

Ben-Yehudah, G., & Ahissar, M. (2004). Sequential spatial frequency discrimination is consistently impaired among adult dyslexics. *Vision Research*, *44*(10), 1047–1063.

Birch, S., & Chase, C. (2004). Visual and language processing deficits in compensated and uncompensated college students with dyslexia. *Journal of Learning Disabilities*, *37*, 389–410.

Booth, J. R., Perfetti, C. A., MacWhinney, B., & Hunt, S. B. (2000). The association of rapid temporal perception with orthographic and phonological processing in reading impaired children and adults. *Scientific Studies of Reading*, *4*, 101–132.

Bradley, L., & Bryant, P. (1983). Categorizing sounds and learning to read: A causal connection. *Nature*, *30*, 419–421.

Bradley, L., & Bryant, P. (1985). *Rhyme and reason in reading and spelling*. Ann Arbor, MI.: The University of Michigan Press.

Brannan, J. R., & Williams, M. C. (1988). Developmental versus sensory processing deficit effects on perceptual processing in the reading disabled. *Perception and Psychophysics*, *44*(5), 437–444.

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.

Byrne, B., & Fielding-Barnsley, R. (1989). Phonemic awareness and letter knowledge in the child`s acquisition of the alphabetic principle. *Journal of Educational Psychology*, *81*, 313–321.

Castles, A., & Coltheart, M. (1993). Varieties of developmental dyslexia. *Cognition*, *47*, 148–180.

Catts, H. W., & Kamhi, A. G. (2005). Defining reading disabilities. In H. W. Catts, & A. G. Kamki (Eds.), *Language and reading disabilities* (pp. 50–67). Boston: MA: Allyn & Bacon.

Cestnick, L. (2001). Cross-modality temporal processing deficits in developmentally phonological dyslexics. *Brain and Cognition*, *46*, 319–325.

Cestnick, L., & Jerger, J. (2000). Auditory temporal processing and lexical/nonlexical reading in developmental dyslexics. *Journal of the American Academy of Audiology*, *11*, 501–513.

Chow, E. M. -C., & Ho, C. S. -H. (2005). Visual motion perception in Chinese dyslexic children. *Journal of Psychology in Chinese Societies*, *6*(2), 161–178.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Hillsdale: Earlbaum.

Cornelissen, P. L., Hansen, P. C., Hutton, J. L., Evangelinou, V., & Stein, J. F. (1998). Magnocellular visual function and children's single word reading. *Vision Research*, *38*(3), 471–482.

Davis, C., Castles, A., McAnally, K., & Gray, J. (2001). Lapses of concentration and dyslexic performance on the Ternus task. *Cognition*, *81*(2), B21–B31.

DeFrancis, J. (1989). *Visible speech: The diverse oneness of writing systems*. Honolulu: University of Hawaii Press.

Eden, G. F., Stein, J. F., Wood, H. M., & Wood, F. B. (1995). Verbal and visual problems in reading disabled and normal children. *Journal of Learning Disabilities*, *28*(5), 272–290.

Eden, G., van Meter, J., Rumsey, J., Maisog, J., Woods, R., & Zeffiro, T. (1996). Abnormal processing of visual motion in dyslexia revealed by functional brain imaging. *Nature*, *382*, 66–69.

Edwards, M., & Badcock, D. R. (1996). Global motion perception: the interaction of colour and luminance signals. *Vision Research*, *36*, 2423–2432.

Facoetti, A., & Molteni, M. (2001). The gradient of visual attention in developmental dyslexia. *Neuropsychologia*, *39*(4), 352–357.

Farmer, M. E., & Klein, R. M. (1993). Auditory and visual temporal processing in dyslexic and normal readers. In P. Tallal, A. M. Galaburda, R. R. Linas, & C. V. Euler (Eds.), Temporal information processing in the nervous system: Special reference to dyslexia and dysphasia. *Annals of the New York Academy of Sciences*, *682*, 339–341.

Farmer, M. E., & Klein, R. M. (1995). The evidence for a temporal processing deficit linked to dyslexia: a review. *Psychonomic Bulletin and Review*, *2*, 460–493.

Galaburda, A. M., Menard, M. T., & Rosen, G. D. (1994). Evidence for aberrant auditory anatomy in developmental dyslexia. *Proceedings of the National Academy of Science*, *91*, 8010–8013.

Galaburda, A. M., Sherman, G. F., Rosen, G. D., Aboitiz, F., & Geschwind, N. (1985). Developmental dyslexia: Four consecutive patients with cortical anomalies. *Annals of Neurology*, *18*(2), 222–233.

Gardner, M. F. (1996). *Test of Visual–Perceptual Skills* (*non-motor*)*–Revised Manual*. Novato: Academic Therapy.

Gibson, L. Y., Hogben, J. H., & Fletcher, J. (2006). Visual and auditory processing and component reading skills in developmental dyslexia. *Cognitive Neuropsychology*, *23*(4), 621–642.

Guo, X. -C. (Ed.) (1995). Xian dai Han yu duo gong neng zi dian. [Modern Chinese Multi-purpose Dictionary]. Beijing: Zhi shi chu ban she.

Habib, M. (2000). The neurological basis of developmental dyslexia: an overview and working hypothesis. *Brain*, *123*, 2373–2399.

Heath, S. M., Hogben, J. H., & Clark, C. D. (1999). Auditory temporal processing in disabled readers with and without oral language delay. *Journal of Child Psychology and Psychiatry*, *40*, 637–647.

Helenius, P., Uutela, K., & Hari, R. (1999). Auditory stream segregation in dyslexic adults. *Brain*, *122*, 907–913.

Ho, C. S. -H., Chan, D. W. -O., Lee, S. -H., Tsang, S. -M., & Luan, V. H. (2004). Cognitive profiling and preliminary subtyping in Chinese developmental dyslexia. *Cognition*, *91*, 43–75.

Ho, C. S. -H., Chan, D. W., Tsang, S., & Lee, S. (2000). *The Hong Kong Test of Specific Learning Difficulties in Reading and Writing* (*HKT-SpLD*) *Manual*. Hong Kong: Hong Kong Specific Learning Difficulties Research Team.

Ho, C. S. -H., Chan, D. W., Tsang, S., & Lee, S. (2002). The cognitive profile and multiple-deficit hypothesis in Chinese developmental dyslexia. *Developmental Psychology*, *38*, 543–553.

Ho, C. S. -H., & Lai, D. N. -C. (1999). Naming-speed deficits and phonological memory deficits in Chinese developmental dyslexia. *Learning and Individual Differences*, *11*, 173–186.

Ho, C. S. H., Law, T. P. S., & Ng, P. M. (2000). The phonological deficit hypothesis in Chinese developmental dyslexia. *Reading and Writing*: *An Interdisciplinary Journal*, *13*, 57–79.

Hood, M., & Conlon, E. (2004). Visual and auditory temporal processing and early reading development. *Dyslexia*, *10*, 234–252.

Huang, H. S., & Hanley, J. R. (1994). Phonological awareness and visual skills in learning to read Chinese and English. *Cognition*, *54*, 73–98.

Keen, A., & Lovegrove, W. J. (2000). Transient deficit hypothesis and dyslexia: examination of whole-parts relationship, retinal sensitivity, and spatial and temporal frequencies. *Vision Research*, *40*, 705–715.

Kidd, J. C., & Hogben, J. H. (2004). Quantifying the auditory saltation illusion: an objective psychophysical approach. *The Journal of the Acoustical Society of America*, *116*, 1116–1125.

Kinsbourne, M., Rufo, D. T., Gamzu, E., Palmer, R. L., & Berliner, A. K. (1991). Neuropsychological deficits in adults with dyslexia. *Developmental Medicine and Child Neurology*, *33*, 763–775.

Klein, R. M. (2002). Observations on the temporal correlates of reading failure. *Reading and Writing: An Interdisciplinary Journal*, *15*, 207–232.

Leck, K. J., Weekes, B. S., & Chen, M. J. (1995). Visual and phonological pathways to the lexicon: evidence from Chinese readers. *Memory & Cognition*, *23*, 468–476.

Li, D. (1993). *A study of Chinese characters*. Beijing: Peking University Press.

Livingstone, M., Rosen, G., Drislane, F., & Galaburda, A. M. (1991). Physiological and anatomical evidence for a magnocellular deficit in developmental dyslexia. *Proceedings of the National Academy of Science*, *88*, 7943–7947.

Manis, F. R., Seidenberg, M. S., & Doi, L. M. (1999). See Dick RAN: rapid naming and the longitudinal prediction of reading subskills in first and second graders. *Scientific Studies of Reading*, *3*, 129–157.

Marshall, C. M., Snowling, M. J., & Bailey, P. J. (2001). Rapid auditory processing and phonological processing in normal readers and readers with dyslexia. *Journal of Speech, Hearing and Language Research*, *44*, 925–940.

Mattingly, I. G. (1984). Reading, linguistic awareness, and language acquisition. In J. D. R. Valtin (Ed.), *Language awareness and learning to read* (pp. 9–25). New York: Springer.

May, J. G., Williams, M. C., & Dunlap, W. P. (1988). Temporal order judgements in good and poor readers. *Neuropsychologia*, *26*, 917–924.

McArthur, G. M., & Bishop, D. V. M. (2001). Auditory perceptual processing in people with reading and oral language impairments: Current issues and recommendations. *Dyslexia*, *7*, 150–170.

McBride-Chang, C., Shu, H., Zhou, A., Wat, C. -P., & Wagner, R. K. (2003). Morphological awareness uniquely predicts young children's Chinese character recognition. *Journal of Educational Psychology*, *95*, 743–751.

Meng, X., Sai, X., Wang, C., Wang, J., Sha, S., & Zhou, X. (2005). Auditory and speech processing and reading development in Chinese school children: Behavioural and ERP evidence. *Dyslexia*, *11*, 292–310.

Mody, M. (2003). Phonological basis in reading disability: a review and analysis of the evidence. *Reading & Writing: An Interdisciplinary Journal*, *16*, 21–39.

Nicolson, R. I., & Fawcett, A. J. (1995). Dyslexia is more than a phonological disability. *Dyslexia*, *1*, 19–36.

Nittrouer, S. (1999). Do temporal processing deficits cause phonological processing problems. *Journal of Speech, Language, and Hearing Research*, *42*, 925–942.

Ransby, M. J., & Swanson, H. L. (2003). Reading comprehension skills of young adults with childhood diagnoses of dyslexia. *Journal of Learning Disabilities*, *36*, 538–555.

Raven, J., Raven, J. C., & Court, J. H. C. (1976). *Raven's Progressive Matrices Manual*. England: Oxford Psychologists.

Reed, M. A. (1989). Speech perception and the discrimination of brief auditory cues in reading disabled children. *Journal of Experimental Child Psychology*, *48*, 270–292.

Rosen, S. M. (2003). Auditory processing in dyslexia and specific language impairment: Is there a deficit? What is its nature? Does it explain anything. *Journal of Phonetics*, *31*(3), 509–527.

Rosen, S. M., & Manganari, E. (2001). Is there a relationship between speech and nonspeech auditory processing in children with dyslexia. *Journal of Speech, Language and Hearing Research*, *44*, 720–736.

Share, D. L., Jorm, A. F., MacLean, R., & Matthews, R. (2002). Temporal processing and reading disability. *Reading and Writing: An Interdisciplinary Journal*, *15*, 151–178.

Shu, H., & Anderson, R. C. (1997). Role of radical awareness in the character and word acquisition of Chinese children. *Reading Research Quarterly*, *32*, 78–89.

Shu, H., Anderson, R. C., & Wu, N. 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., McBride-Chang, C., Wu, S., & Liu, H. (2006). Understanding Chinese developmental dyslexia: Morphological awareness as a core cognitive construct. *Journal of Educational Psychology*, *98*, 122–133.

Siegel, L. S. (1999). Issues in the definition and diagnosis of learning disabilities: A Perspective on Guckenberger v. Boston University. *Journal of Learning Disabilities*, *32*, 304–319.

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.

Slaghuis, W., Twell, A., & Kingstone, K. (1996). Visual and language processing disorders are concurrent in dyslexia and continue into adulthood. *Cortex*, *32*, 413–438.

Stein, J. (2001). The magnocellular theory of developmental dyslexia. *Dyslexia*, *7*, 12–36.

Studdert-Kennedy, M. (2002). Deficits in phoneme awareness do not arise from failures in rapid auditory processing. *Reading and Writing: An Interdisciplinary Journal*, *15*, 5–14.

Studdert-Kennedy, M., & Mody, M. (1995). Auditory temporal perception deficits in the reading impaired: A critical review of the evidence. *Psychonomic Bulletin & Review*, *2*(4), 508–514.

Talcott, J. B., Aashild, G., Ingelghem, M. V., Witton, C., Stein, J. F., & Toennessen, F. E. (2003). Impaired sensitivity to dynamic stimuli in poor readers of a regular orthography. *Brain and Language*, *87*, 259–266.

Tallal, P. (1980). Auditory temporal perception, phonics, and reading disabilities in children. *Brain and Language*, *9*, 182–198.

Tallal, P., Miller, S. L., Bedi, G., Byma, G., Wang, X., Nagarajan, S. S., et al. (1996). Language comprehension in language-learning impaired children improved with acoustically modified speech. *Science*, *271*, 81–84.

Tallal, P., & Piercy, M. (1974). Developmental aphasia: Rate of auditory processing and selective impairment of consonant perception. *Neuropsychologia*, *12*, 83–93.

Tallal, P., & Piercy, M. (1975). Developmental aphasia: The perception of brief vowels and extended stop consonants. *Neuropsychologia*, *13*, 69–74.

Torgesen, J. K., Wagner, R. K., & Rashotte, C. A. (1994). Longitudinal studies of phonological processing and reading. *Journal of Learning Disabilities*, *27*, 276–286.

Tzeng, O. J. L., & Wang, W. S. Y. (1983). The first two R's. *Scientific American*, *71*, 238–243.

Waber, D. P., Weiler, M. D., Wolff, P. H., Bellinger, D., Marcus, D. J., Ariel, R., et al. (2001). Processing of rapid auditory stimuli in school-age children referred for evaluation of learning disorders. *Child Development*, *72*, 37–49.

Wolf, M., & Bowers, P. G. (1999). The double-deficit hypothesis for developmental dyslexia. *Journal of Educational Psychology*, *91*, 415–438.

Woo, E. Y. C., & Hoosain, R. (1984). Visual and auditory functions of Chinese dyslexics. *Psychologia*, *27*, 164–170.

Ziegler, J., & Goswami, U. (2005). Reading acquisition, developmental dyslexia, and skilled reading across languages: A psycholinguistic grain size theory. *Psychological Bulletin*, *131*(1), 3–29.