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The visual magnocellular pathway in Chinese-speaking children with developmental dyslexia

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ABSTRACT

Previous research into the cognitive processes involved in reading Chinese and developmental dyslexia in Chinese, revealed that the single most important factor appears to be orthographic processing skills rather than phonological skills. Also some studies have indicated that even in alphabetic languages some dyslexic individuals reveal deficits in orthographic processing skills, which are linked to a deficit in the visual magnocellular pathway. The current study therefore employed a visual psychophysical experiment together with visual and auditory event-related potential (ERP) experiments eliciting mismatch negativity (MMN) to investigate the link between visual magnocellular functional abnormalities and developmental dyslexia in Chinese. The performance levels of Chinese children with developmental dyslexia (DD) from the behavioural and electrophysiological experiments were compared to those of the chronological age-matched (CA) children and those of the reading level matched (RL) younger children. Both the behavioural and electrophysiological results suggest that the orthographic processing skills were compromised in the Chinese developmental dyslexics, which in turn is linked to a deficit in the visual magnocellular system.

1. Introduction

Developmental dyslexia is the most common learning disability and is characterized by a poor reading ability in children who otherwise have normal intelligence, sufficient sociocultural opportunities, and no known neurological damage or organic injury. These dyslexics represent a substantial minority group, and in English, up to 10–12% of the population falls into this group (Shaywitz, Shaywitz, Fletcher, & Escobar, 1990; Snowling, 2000). It is generally accepted that a phonological processing deficit is the core deficit associated with developmental dyslexia. This phonological deficit hypothesis has been developed based on the findings from both behavioral (Boada & Pennington, 2006; Desroches, Joanisse, & Robertson, 2006; Lieberman, Meskill, Chatillon, & Schupack 1985; Muter, Hulme, Snowling, & Taylor, 1998; Ramus, 2003; Wydell & Butterworth, 1999) and brain imaging (Bonte & Blomert, 2004; Hoeft et al., 2007; Shaywitz et al., 1998, 2002) research. However, some researchers argue that a phonological deficit may just be the external manifestation of developmental dyslexia, and not necessarily the core cause of dyslexia. It has thus been suggested that the source can be further traced to a more general perceptual dysfunction, involving a deficit in rapid auditory processing (Tallal, 1980). The deficit in rapid auditory processing compromised in developmental dyslexia is often revealed in tasks that involve processing short and fast sound transitions. A large body of research has found that individuals with developmental dyslexia show a low level deficit in rapid auditory processing that in turn leads to a phonological deficit (Stoodley, Hill, Stein, & Bishop, 2006; Tallal, 1980; Temple et al., 2000).

In contrast, other dyslexia researchers have been debating the existence of visual processing deficits in developmental dyslexia, more specifically a deficit in the magnocellular visual system (Cornelissen, Hansen, Hutton, Evangelinou, & Stein, 1998; Stein, 2001; Tallal, Miller, & Fitch, 1993). The visual magnocellular pathway is one of the most important features of the visual system, starting with magno-cells in the retina. Axons from the magnocells project onto the magnocellular layers of the dorsal lateral geniculate nucleus (LGN) of the thalamus. Magno-cells are particularly sensitive to low contrasts and moving stimuli with low spatial frequency (Shapley, 1990). Some studies found deficits in the visual magnocellular pathway in developmental dyslexics (Castro, Salgado, Andrade, Ciasca, & Carvalho, 2008; Livingstone, Rosen, Drislane, & Galaburda, 1991), and further many studies found that the function of the visual magnocellular pathway

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correlated with orthographic processing skills (Sperling, Lu, Manis, & Seidenberg, 2003; Stein, 2001, 2003).

Stein (2001) further argued that there are magno-cells which are specialized for temporal processing in all the sensory and motor systems. The magno-cells in the auditory system, which track the frequency and amplitude changes that distinguish phonemes, are in the magnocellular divisions of the nuclei which relay auditory signals to the auditory cortex (Trussell, 1998). Therefore, a deficit in the magnocellular system can influence a dyslexics' rapid auditory processing. Furthermore, the cerebellum is the head ganglion of the magnocellular systems, which contribute to binocular fixation and to inner speech for sounding out words, and it is clearly defective in dyslexics. Thus, according to Stein, there is evidence that most reading problems have a fundamental magnocellular deficit, be it auditory or visual modality.

However, several studies found that the deficit in the visual magnocellular pathway occurred only in some and not all developmental dyslexics (Ramus, 2003; Stein, Talcott, & Walsh, 2000). Hence the hypothesis of a visual magnocellular deficit in developmental dyslexia in alphabetic languages remains controversial.

The conflicting results may be due to the heterogeneous nature of dyslexia (Seymour, 1986) as well as differences in the research methodologies including the selection criteria for dyslexic participants and the stimuli employed in psychophysical experiments typically used to isolate magnocellular function (Hayduk, Bruck, & Cavanagh, 1996; Hulme, 1998; Skottun, 2000). Rogers-Ramachandran and Ramachandran (1998) conducted a visual psychophysical experiment, and their results revealed two distinct systems in human vision: "a fast, sign-invariant system concerned with extracting contours" which is the magnocellular visual system, and "a slower, sign-sensitive system concerned with assigning surface colour" which is the parvocellular visual system (Rogers-Ramachandran & Ramachandran, 1998, p. 71). Based on the paradigm employed by Rogers-Ramachandran and Ramachandran (1998); Sperling et al. (2003) conducted a psychophysical experiment with normal and dyslexic children (aged 12). Sperling et al. found that the performance of all the participating children significantly correlated with measures of orthographic skills in the Magnocellular Condition. They therefore argued that the finding is in agreement with other studies which link orthographic ability with a magnocellular type of processing (Talcott et al., 2000). The study also revealed that not all dyslexic children showed a magnocellular deficit which is in accordance with other studies (Talcott et al., 2000; Witton et al., 1998).

2. Chinese orthography and reading processes

Before discussing the current study, a brief review of the cognitive processes and neural correlates involved in reading Chinese is given.

Unlike alphabetic orthographies where graphemes (visual form) map onto phonemes (the smallest sound units of spoken language), 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. The pronunciations of Chinese characters are represented at the monosyllabic level, and no phonemes are represented in a character. That is, reading a Chinese character does not allow the segmental analysis (i.e., grapheme-to-phoneme conversion), which is fundamental in alphabetic orthographies. There is only limited systematic correspondence between orthography and phonology (Meng et al., 2005). Further, Mandarin Chinese has a large number of homophonic morphemes and homophonic characters. Therefore the use of phonological information may not be as critical in reading Chinese as it is in reading alphabetic languages (Ho, Chan, Lee, Tsang, & Luan, 2004; Ho, Chan, Tsang, & Lee, 2002; Shu, McBride-Chang, Wu, & Liu, 2006). This challenges the view that a phonological deficit is the main cause of developmental dyslexia for Chinese. Although some studies have found that Chinese dyslexic children have phonological deficits including rapid naming (Ho, Law, & Ng, 2000) as well as auditory processing deficits (Meng et al., 2005), other studies found deficits in orthographic processing skills (Ho et al., 2002), and/or in morphological processing skills (Shu et al., 2006). Therefore some studies concluded that the major cause of developmental dyslexia in Chinese is a deficit in orthographic processing skills, rather than in phonological processing skills (Chan, Ho, Tsang, Lee, & Chung, 2006; Ho et al., 2004).

3. Neural correlates of reading in Chinese and developmental dyslexia

In a fMRI study, Siok, Niu, Jin, Perfetti, and Tan (2008) found that there were functional and structural abnormalities in the left middle frontal gyrus of Chinese dyslexic children, but not in the left temporoparietal and occipitotemporal regions that are typically compromised in dyslexic children in alphabetic languages (Siok et al., 2008; Siok, Perfetti, Jin, & Tan, 2004). In their experiment, the participating children (aged 11) were asked to judge if a pair of simultaneously presented Chinese characters had an identical pronunciation to each other (homophone judgements), while in the Control Condition, the children were asked to judge if a pair of characters had the same physical size (font-size judgements). The results revealed reduced activation in the left middle frontal gyrus (LMFG) in the dyslexic children, instead of reduced activation in the left temporoparietal regions, which is often seen as "a biological signature of English reading disability" (Siok et al., 2004, p. 74L) in alphabetic languages (Horwitz, Rumsey, & Dohohue, 1998). Other studies also found that the LFMG is identified as a crucial cortical area for skilled Chinese reading (Siok, Jin, Fletcher, & Tan, 2003). Siok et al. (2004) stated that the LMFG "carries out the representation and working memory of visuo-spatial and verbal information, and coordinates cognitive resources as a central executive system" (p. 74L). That is, reading Chinese characters first requires a greater cognitive demand for visuo-spatial processing than reading in English, and also requires a greater inter-activity between orthography and phonology (e.g., retrieving phonology as a whole rather than addressing phonology in a piece-meal fashion). Siok et al., therefore, suggested that the biological abnormality in impaired reading was dependent on culture.

As was mentioned earlier, in the studies in English, orthographic processing skills were positively correlated with visual magnocellular processing (Sperling et al., 2003; Stein, 2001, 2003). However, to our knowledge the relationship between a visual magnocellular processing deficit and developmental dyslexia in Chinese has not been systematically examined. Therefore, the purpose of the present study was to investigate the relationship between magnocellular deficit and reading disability using a visual psychophysical behavioural study as well as an ERP study. In the visual psychophysical experiment, reaction times and accuracy were used as indices for measuring possible deficits in the visual magnocellular pathway of developmental dyslexics. In the ERP study, a visual mismatch negativity (vMMN) paradigm was adopted to provide the corresponding neurological evidence for a visual magnocellular deficit in developmental dyslexics in Chinese. MMN reflects the difference between the ERPs elicited by standard and deviant stimuli. Similarly, some researchers employed an auditory mismatch negativity paradigm, and reported that developmental dyslexics had a MMN abnormality with frequency modulation (FM) tones (Meng et al., 2005; Stoodley et al., 2006), and thus an auditory MMN is also regarded as an important clue to distinguish indi-

Table 1
The characteristics of the developmental dyslexics and control children participating in the behavioural experiment.

Characteristic	Mean (SD)		
	DD ($n = 16$)	CA ($n = 16$)	RL ($n = 16$)
Age	11.55 (0.59)	11.19 (0.57)	10.27 (0.67)
Gender	9 male, 7 female	9 male, 7 female	11 male, 5 female
Handedness	All right-handed	All right-handed	All right-handed
Raven	103.00 (11.35)	101.69 (14.60)	110.28 (9.96)
Written vocabulary	2290.17 (141.52)	2833.17 (131.72)	2217.11 (167.64)

viduals with developmental dyslexia from normal readers. In the visual modality, the stimuli typically consisting of deviant contrast, spatial frequency and motion direction have all elicited visual MMNs (Kremlacek, Kuba, Kubova, & Langrova, 2006; Pazo-Alvarez, Cadaveira, & Admenando, 2003). In addition, in a Magnocellular Condition with low contrast and low spatial frequency stimuli, a visual MMN can be clearly elicited by motion direction (Kremlacek et al., 2006). Based on previous findings that (i) a deficit in orthographic processing skills was one of the most important indicators for the Chinese developmental dyslexics, and that (ii) a deficit in the visual magnocellular system was linked to a deficit in orthographic processing skills (Sperling et al., 2003; Stein, 2001, 2003), it was hypothesized that the developmental dyslexia found in Chinese might be due to a deficit in the visual magnocellular system.

4. Behavioural study with Chinese children as participants

4.1. Method

4.1.1. Participants

16 developmental dyslexic children (DD-group), 16 average readers of the same Chronological Age (CA-control-group) and 16 average readers of the same Reading Level (RL-control-group), in total 48 children participated in the study. The children were grade 3–5 pupils aged 8–11 years old. All of the participants were right-handed, and had normal hearing and normal or corrected-to-normal vision without ophthalmological or neurological abnormalities. Informed consent was obtained from each participant once the test procedure was explained to them.

In order to divide the children into the three groups described above, Raven's Standard Progressive Matrices (RSPM) and the Character Recognition Measure and Assessment Scale for Primary School Children (Wang & Tao, 1993), which are widely used for screening Mandarin-speaking Chinese children for dyslexia (Wu & Shu, 2004; Shu et al., 2006), were employed. The criteria for the DD-group were that while their IQs were normal (IQ > 85) their vocabulary test scores were at least one and a half standard deviations below the average score of the same grade children. The CA-Group who had normal vocabulary scores (within one standard deviation) were from the same grade as those in the DD-group. The RL controls were from the lower grade that had the same vocabulary scores as those in the DD-group. This is illustrated in Table 1.

4.1.2. Stimuli and procedure

The motion-onset paradigm, a common paradigm to detect the magnocellular pathway (Kremlacek et al., 2006; Schulte-Korne, Bartling, Deimel, & Remschmidt, 2004) was used. The visual stimuli, with a visual angle of $3.9^\circ \times 3.9^\circ$ at a 50 cm viewing distance, consisted of horizontal sinusoidal gratings which moved rapidly (54°/s) in the central visual field and involved two conditions: one was a low contrast (10%), low spatial frequency (1 c/$^\circ$) grating as the visual Magnocellular Condition (MC) and the other was a high contrast (50%), high spatial frequency (4 c/$^\circ$) grating as the Control Condition (CC). In each condition, the moving gratings were randomly presented 40 times (20 times moving upwards and 20 times moving downwards). Participants were asked to press a response button according to which direction the stimuli moved. Half of the children in each group were asked to press the left button for the upward direction, and right button for downward, and vice versa. The stimuli were presented on a 17″ computer monitor.

4.2. Results

Table 2 shows the mean reaction times (RTs), and accuracy of motion direction discrimination in the Magnocellular Condition (MC) and Control Condition (CC) of the DD-, CA-control, and RL-control groups.

In the Magnocellular Condition, independent-sample t-tests for RTs showed that the difference between the DD-group and the CA-control-group was significant, $t(30) = 2.355$, $p < .05$, while the difference between the DD-group and RL-control-group was not significant ($t(30) = -0.043$, $p > .05$). That is, the dyslexic children responded significantly slower than the age-matched controls but responded similarly to the reading level matched younger children. Further, the difference between the CA-control-group and the RL-control-group was significant, $t(30) = -2.861$, $p < .05$. That is, the older normal children responded significantly faster than the younger normal children.

The results for accuracy for the same condition showed that the difference between the DD-group and the RL-control-group was approaching significance, $t(30) = -1.779$, $p = .085$. However, neither the difference between the DD-group and the CA-control-group ($t(30) = -0.65$, $p > .05$) nor the difference between the CA-control-group and the RL-control-group ($t(30) = -1.208$, $p > .05$) was significant.

In the Control Condition, t-tests for RTs showed that neither the difference between the DD-group and the CA-control-group ($t(30) = 1.477$, $p > .05$) nor the difference between the DD-group and the RL-control-group ($t(30) = -0.52$, $p > .05$) were significant. However, the difference between the CA-control-group and the RL-control-group was significant, $t(30) = -2.162$, $p < .05$, which meant

Table 2
Mean RTs and accuracy of motion direction discrimination in Magnocellular Condition (MC) and the Control Condition (CC) for the developmental dyslexics and the controls.

	DD ($n = 16$)	CA ($n = 16$)	RL ($n = 16$)
RTs in MC (ms)	396.22 (145.92)	299.32 (76.19)	398.24 (115.43)
Accuracy in MC (%)	59.72 (0.35)	67.03 (0.28)	76.56 (0.14)
RTs in CC (ms)	363.47 (141.59)	302.44 (85.31)	388.92 (135.39)
Accuracy in CC (%)	61.09 (0.33)	68.44 (0.30)	76.25 (0.13)

Table 3
The characteristics of the developmental dyslexics and control children participating in the ERP experiment.

Characteristic	Mean (SD)		
	DD (n = 11)	CA (n = 12)	RL (n = 13)
Age	10.84 (0.76)	10.53 (0.51)	9.18 (0.34)
Gender	7 male, 4 female	6 male, 6 female	4 male, 9 female
Handedness	11 right-handed	12 right-handed	13 right-handed
Raven	100.45 (12.65)	105.3 (14.19)	116.38 (8.62)
Written vocabulary	2224.88 (273.82)	2796.91 (132.6)	2224.98 (149.03)

that the older normal children responded significantly faster than the younger normal children.

The results for accuracy for the same condition showed that differences between the DD-group and the CA-control-group ($t(30) = -0.666$, $p > .05$), between the CA-control-group and the RL-control-group ($t(30) = -0.966$, $p > .05$), and between the DD-group and the RL-control-group ($t(30) = -1.733$, $p > .05$) were not significant.

4.3. Discussion

In order to differentiate the reading attainment/performance level from developmental dyslexia itself, reading level matched (RL-control) children as well as chronologically matched (CA-control) children were included in the study. The current visual psychophysical experiment showed that for the critical Magnocellular Condition, the dyslexic (DD) children responded significantly slower than the chronologically matched (CA-control) normal children, but similarly to the younger reading level matched (RL-control) children. Further, the dyslexic (DD) children were less accurate (though statistically it was approaching significance) than the reading level matched (RL-control) younger children. It is worth noting however that there was a speed and accuracy trade-off for the reading level matched younger (RL-control) children. Their RTs were longer than the older (CA-control) children but their accuracy was higher than that of the older (CA-control) children, although this was not statistically significant. In contrast, this speed and accuracy trade-off was not evident in the dyslexic (DD) children. The dyslexic children were consistently less accurate than both the reading matched (RL-control) and age-matched (CA-control) children. Given that in reading Chinese, the use of phonological information may not be as critical as the orthographic processing skills (Ho et al., 2002, 2004; Shu et al., 2006), the results seem to lend support to the link between Magnocellular processing and orthographic skills, and in turn the link between a Magnocellular deficit and dyslexia due to poor orthographic processing skills, as suggested by other researchers (Sperling et al., 2003; Stein, 2001, 2003; Talcott et al., 2000). The current visual psychophysical experiment also indicate that the Chinese dyslexic children from the current cohort might have a deficit in the visual magnocellular system.

5. ERP study

5.1. Method

5.1.1. Participants

11 children from the DD-group, 12 children from the CA-Control Group, and 13 children from the RL-Control Group, in total 36 children participated in the current ERP study.

Table 3 shows the characteristics of the participating children.

5.1.2. Stimuli and procedure

In addition to the ERP study of visual mismatch negativity (vMMN), an auditory MMN condition was also included in the study (see Wei, Chan, and Luo (2002) for similar paradigm), in order to make the former task (vMMN) as an incidental task (i.e., trying to keep participants' attention away from the task). The procedure is shown in Fig. 1.

Therefore, each participant was asked to "attend" the auditory task. The visual stimuli (moving gratings) were interposed between auditory stimuli (tones) and a signal (red cross). The participants were required only to discriminate between the standard and deviant 'auditory' stimuli by pressing the response button.

For the auditory MMN condition, the stimuli (20 ms, 60 dB SPL) consisted of an 800 Hz tone for standard stimuli (85%) and 1000 Hz tone for the deviant stimuli (15%), both of which were presented on each trial before a click (2 ms, 18 dB SPL). When hearing the click, participants were asked to press one of the two mouse buttons as quickly and accurately as possible. Half of the children in each group pressed the left button for 800 Hz and right button for 1000 Hz, the other half pressed the right button for 800 Hz and the left button for 1000 Hz. Between the tone and the click, between 0 and 2 motive gratings were presented randomly. The SOAs between the tone and the grating were between 250 ms and 700 ms, as were the SOAs between the grating and the click.

For the vMMN condition, the visual stimuli were the same as those in the behavioural study. Each participant underwent four recording sessions (two sessions for the Magnocellular Condition and two sessions for the Control Condition), and each session consisted of 200 stimuli (each stimuli lasting 200 ms): 176 standard stimuli (88%) and 24 deviant stimuli (12%). The standard stimuli consisted of a 100 ms of upward motion followed by a 100 ms of downward motion, and the deviant stimuli consisted of a 100 ms of downward motion followed by 100 ms of upward motion. The stimuli were presented on a 17″ computer monitor.

5.1.3. Recordings and analysis

The ERP acquisition was performed in a darkened, sound attenuated, electromagnetically shielded room with a background luminance of 2 cd/m^2. Each participant sat in a comfortable chair and was instructed to fixate on the center of the monitor.

ERPs were recorded (band pass 0.05–100 Hz, sampling rate 500 Hz) with a **Neuroscan Synamp2 Amplifier**, using an electrode cap with 32 Ag/AgCl electrodes placed according to the 10/20 system, with the tip of the nose as the reference lead. Vertical eye movements (VEOG) were recorded by a pair of electrodes placing on the supraorbit and infraorbit of the left eye, and horizontal eye

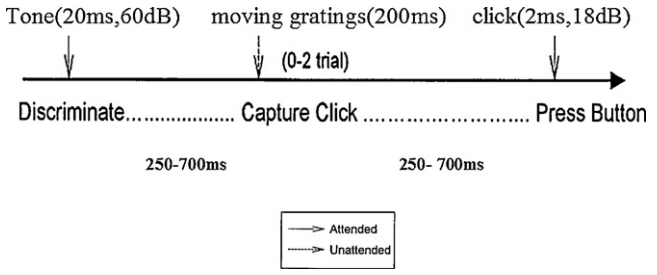

Fig. 1. The "cross-modal delayed response" paradigm. The gratings and tones were either standard or deviant stimuli.

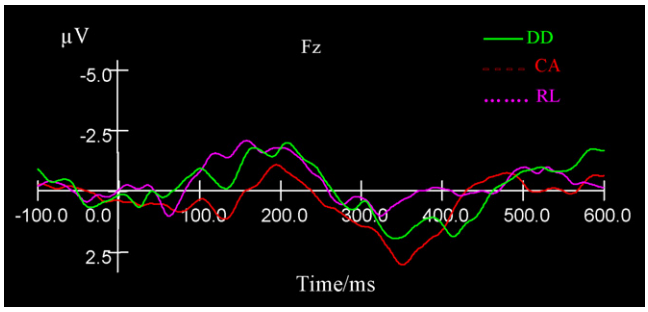

Fig. 2. Grand average of mismatch negativity for tone frequency in developmental dyslexics (solid line), the CA controls (dashed line), the RL controls (dotted line) at Fz (frontal-central lead).

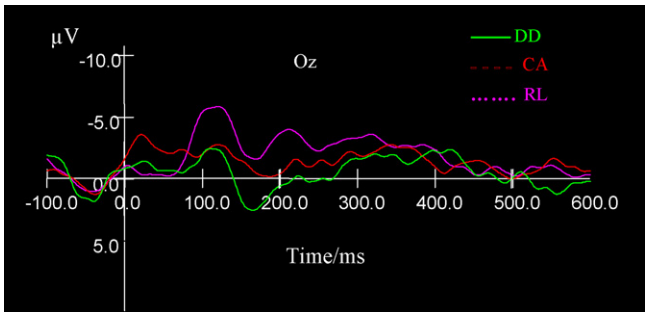

Fig. 3. Grand average of mismatch negativity for the magnocellular condition (low contrast, low spatial frequency) motion direction in developmental dyslexics (solid line), the CA controls (dashed line), the RL controls (dotted line) at Oz (occipito-central lead).

movements (HEOG) were recorded by a pair of electrodes placed beside the outer canthus of both eyes. Electrode impedances were kept below 5 kΩ. The EEG signal was digitized at a sample rate of 500 Hz, amplifying at a band-pass filter of 0.05–100 Hz.

ERPs were segmented offline into 700 ms long trials with a pre-stimulus interval of 100 ms. Trials containing blinks, movements or EEG baseline drift were rejected on the basis of the visual inspection of each recording by semi-automatic artifact detection. After filtering using a low pass filter with a cut-off frequency of 30 Hz, trials with peak to peak detection intervals exceeding 100 μV were excluded from averaging. ERPs were averaged for each participant, condition and channel, respectively.

5.2. Results

5.2.1. Behavioural data

In the attended condition the auditory accuracy was recorded. t-Tests revealed no statistically significant differences between the DD-group and the CA-control-group ($t(21) = -1.164$, $p > .05$), between the DD-group and the RL-control-group ($t(22) = -0.453$, $p > .05$), and between the CA-control-group and the RL-control-group ($t(23) = 0.800$, $p > .05$).

5.2.1.1. aMMN. In the auditory modality, the early deviance-related negativity (DRN) which includes auditory mismatch negativity (aMMN) and N2b was calculated by subtracting the ERPs elicited by the standard stimuli from those of the deviant stimuli. The component of the DRN in the time interval of 150–250 ms is often considered as aMMN, and Fz (sensor in the auditory cortex area) is the most sensitive electrode. In this condition, there was no difference in the aMMN between the developmental dyslexic (DD) children and the two control (CA-control and RL-control) groups (both at $p > 0.05$). This is illustrated in Fig. 2.

5.2.1.2. vMMN. The vMMN was elicited by the most sensitive electrode Oz (sensor in the occipital cortices) in the time interval of 150–300 ms. The latency of the vMMNs was 150–250 ms in the Magnocellular Condition and 200–300 ms in the Control Condition.

Fig. 3 shows the differences in the amplitudes of vMMNs for the Magnocellular Condition across different groups of (DD, CA-control and RL-control) children. The vMMNs of the developmental dyslexics (DD) was significantly reduced compared to that of the age-matched (CA-control) children, $p < 0.05$, as well as the reading level matched (RL-control) children, $p < 0.01$. There was however no difference in vMMNs between the older (CA-control) and the younger (RL-control) children (both at $p > 0.05$). The results thus indicated that the dyslexic children's vMMN was significantly attenuated compared to the other (CA-control and RL-control) children in the Magnocellular Condition.

Fig. 4 illustrates the amplitude differences in vMMNs for the Control Condition. For this condition, there was no difference in the vMMNs between any two of the three groups of (DD, CA-control and RL-control) children (all at $p > 0.05$).

Fig. 5A shows significant differences in the amplitudes of the vMMNs of the developmental dyslexic (DD) children between in the critical Magnocellular Condition (150–250 ms) and in the Control Condition (200–300 ms), $p < 0.05$. The results thus revealed that for the earlier latency the amplitude of the vMMNs for the Magnocellular Condition was significantly greater than that for the Control Condition, and for the later latency, the pattern of the data was reversed.

However, Fig. 5B and C shows no such difference between the two conditions for the age-matched (CA-control) children and the reading level (RL-control) children (both at $p > .05$), respectively.

5.3. Discussion

The "cross-modal delayed response" paradigm was utilised in the study, which is a common paradigm to detect vMMN in ERP studies (Livingstone et al., 1991; Wei, Chan, & Luo, 2002; Zhao & Li, 2006). In order to avoid the influence of accommodation on ERPs during the course of visual movements, two opposite directions of motion were adopted in the study, in which the standard stimuli moved from an upward to a downward direction, and the deviant stimuli moved from a downward to upward direction. vMMNs were elicited for all the participants in the occipital cortex in the interval of 150–300 ms, which corroborated with the previous studies on vMMNs (Kremlacek et al., 2006; Pazo-Alvarez et al., 2003).

In the Magnocellular Condition, the mean amplitude of vMMNs in the developmental dyslexics was smaller than that in both the CA-control and the RL-control children, and there was no significant difference between the latter two control groups. In the Control

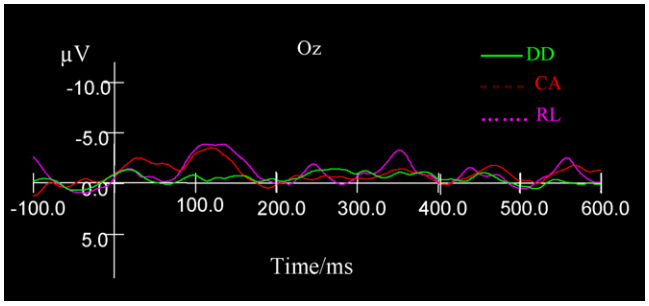

Fig. 4. Grand average of mismatch negativity for the control condition (high contrast, high spatial frequency) motion direction in developmental dyslexics (solid line), the CA controls (dashed line), the RL controls (dotted line) at Oz (occipito-central lead).

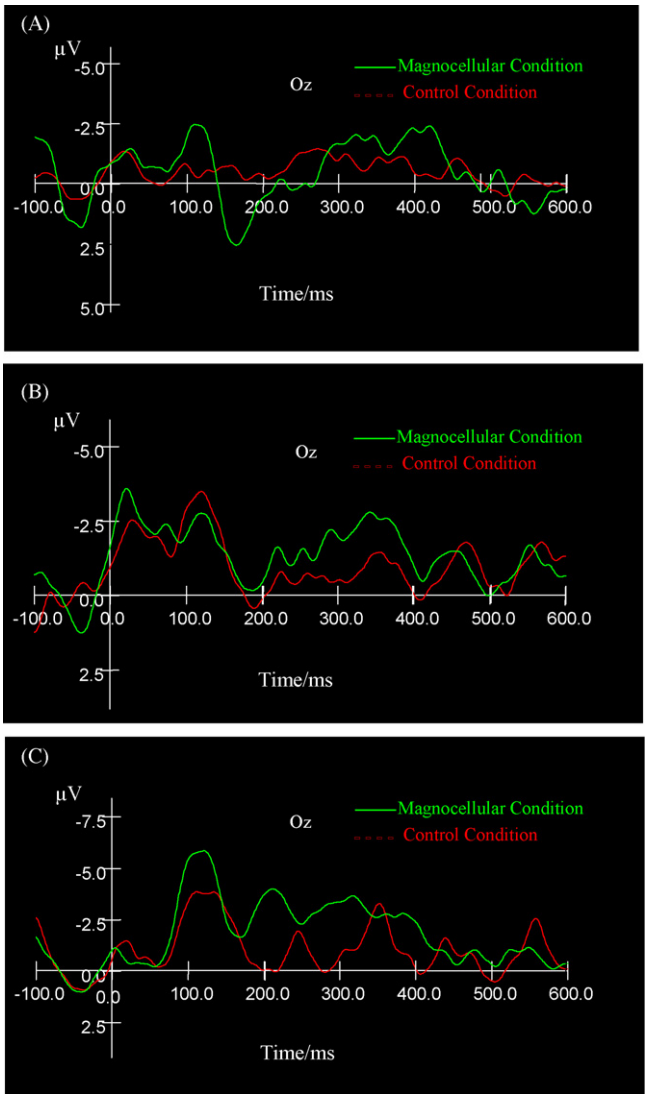

Fig. 5. (A) Grand average of mismatch negativity for magnocellular condition (solid line) and control condition (dashed line) in developmental dyslexics at Oz (occipito-central lead). (B) Grand average of mismatch negativity for magnocellular condition (solid line) and control condition (dashed line) in the CA controls at Oz (occipito-central lead). (C) Grand average of mismatch negativity for magnocellular condition (solid line) and control condition (dashed line) in the RL controls at Oz (occipito-central lead).

Condition, there was no significant difference between any two of the three groups. Thus, the present ERP data indicated that the magnocellular system was compromised for the current Chinese dyslexic group compared to both of the control groups. In addition, the mean amplitude of vMMNs in the Chinese dyslexics was reduced in the visual Magnocellular Condition, compared to that in the Control Condition, but the two controls did not show this trend, thus suggesting that the current Chinese dyslexics had reduced sensitivity in the visual magnocellular pathway. Similarly, Castro et al. (2008) suggested that "developmental dyslexia might involve impairments in a network of cortical areas, a weakness of the magnocellular pathway that provides input to the posterior cortical attentional network and, at the same time, are involved in eye movement control" (Castro et al., 2008, p. 840). Castro et al. used ophthalmologic and visual tests (including visual acuity, ocular dominance, ocular alignment and eye movement) instead of a visual psychophysical experiment, and found less eye movement control in voluntary convergence, and unstable binocular fixation in their dyslexic children aged between 8 and 13. If the Chinese dyslexic individuals in the current study were subjected to the same tests, they might also reveal similar results to Castro et al.'s dyslexic children. This would further strengthen the argument for the relationship between a deficit in the visual magnocellular pathway and developmental dyslexia. Further research needs to be conducted in this area.

In summary, the current results, indicating that the developmental dyslexics had a deficit in the visual magnocellular pathway, are consistent with many studies conducted in alphabetic languages (Livingstone et al., 1991; Scheuerpflug et al., 2004; Schulte-Korne et al., 2004). These studies in general advocate the hypothesis of a visual magnocellular deficit in developmental dyslexia (Stein, 2001, 2003). However, in alphabetic languages, not all of the developmental dyslexics exhibit the deficit in the visual magnocellular pathway (Ramus et al., 2003), and therefore researchers argue that developmental dyslexia could also be due to a common phonological deficit based on a rapid auditory processing disability (Stoodley et al., 2006; Tallal, 1980; Temple et al., 2000).

In Chinese, orthographic processing skills appear to be more critical to reading than phonological skills (Ho, Ng, & Ng, 2003; Ho, Wong, & Chan, 1999). Some even argue that orthographic processing skills are the single most important factor in reading Chinese especially for the early years when children are learning to read (Wei, Bi, Chen, & Weng, under review). The deficit in orthographic processing skills (Chan et al., 2006; Ho et al., 2002, 2004) may be ascribed to a deficit in the visual magnocellular pathway.

Moreover, no significant differences between developmental dyslexics and any of the two controls in the amplitude of aMMN were found, suggesting that developmental dyslexics did not have a deficit in auditory tone processing. This finding was consistent with the results of previous studies on Chinese developmental dyslexics (Meng et al., 2005), but was different from the results from studies on developmental dyslexia in alphabetic languages (Stoodley et al., 2006). These contradictory findings therefore might reflect different manifestations of developmental dyslexia in different languages or cultures. In alphabetic languages, the core deficit is considered to be a phonological deficit, and the general auditory processing deficit caused by a phonological deficit would lead to reading problems. However, as was discussed above, a phonological deficit might not necessarily be a core deficit for the Chinese developmental dyslexics (Siok et al., 2008).

In conclusion, the current study showed that the Chinese developmental dyslexics had a deficit in the visual magnocellular pathway, which was supported by both the behavioural data and the ERP evidence.

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