Ann. of Dyslexia (2011) 61:161–176
DOI 10.1007/s11881-010-0049-2

Dynamic visual perception and reading development in Chinese school children

Xiangzhi Meng · Alice Cheng-Lai · Biao Zeng · John F. Stein · Xiaolin Zhou

Received: 19 September 2007 / Accepted: 19 November 2010 / Published online: 15 January 2011

Abstract The development of reading skills may depend to a certain extent on the development of basic visual perception. The magnocellular theory of developmental dyslexia assumes that deficits in the magnocellular pathway, indicated by less sensitivity in perceiving dynamic sensory stimuli, are responsible for a proportion of reading difficulties experienced by dyslexics. Using a task that measures coherent motion detection threshold, this study examined the relationship between dynamic visual perception and reading development in Chinese children. Experiment 1 compared the performance of 27 dyslexics and their age- and IQ-matched controls in the coherent motion detection task and in a static pattern perception task. Results showed that only in the former task did the dyslexics have a significantly higher threshold than the controls, suggesting that Chinese dyslexics, like some of their Western counterparts, may have deficits in magnocellular pathway. Experiment 2 examined whether dynamic visual processing affects specific cognitive processes in reading. One hundred fifth-grade children were tested on visual perception and reading-related tasks. Regression analyses found that the motion detection threshold accounted for 11% and 12%, respectively, variance in the speed of orthographic similarity judgment and in the accuracy of picture naming after IQ and vocabulary size were controlled. The static pattern detection threshold could not account for any variance. It is concluded that reading development in Chinese depends to a certain extent on the development of dynamic visual perception and its underlying neural pathway and that the impact of visual development can be specifically related to orthographic processing in reading Chinese.

X. Meng · B. Zeng · X. Zhou (✉)
Department of Psychology, Peking University, Beijing 100871, China
e-mail: xz104@pku.edA21e1325.3(xz.cn23TD(2.3189:)-325ng)TJ/F61Tf11.(e-mail:)-325TheTJ6X.Jon-32256.4.1()ity7(ki)2
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spatial attention (Casco & Prunetti, 1996; Facoetti, Paganoni, Turatto, Marzola, & Mascetti, 2000; Facoetti, Trussardi, Ruffino, et al., 2010; Hari, Valta, & Uutela, 1999;

also shown that phonological skill is an important factor in Chinese reading development and dyslexia (Shu, Chen, Anderson, Wu, & Xuan, 2003; Siok & Fletcher, 2001; McBride-Chang & Ho, 2000; Ho & Bryant, 1997). Findings concerning general visual skills in the development of Chinese reading, however, are less consistent, with some studies observing positive associations between visual skills and Chinese character recognition (Huang & Hanley, 1995; McBride-Chang & Chang, 1995; Siok & Fletcher, 2001; Meng, Zhou, Zeng, Kong, & Zhuang, 2002; Ho et al., 2004; Chung, McBride-Chang, Wong, Cheung, Penney, & Ho, 2008) and other studies finding no such association (Ho, 1997; Hu & Catts, 1998; Huang & Hanley, 1997; McBride-Chang & Ho, 2000). A possible reason for this discrepancy is that tasks used to measure visual skills in the aforementioned studies involve mostly higher level cognitive processing and are not sensitive enough to lower level visual processes that rely on the magnocellular pathway.

In this study, we employed coherent motion detection, a task that has been proven to be sensitive to the functions of magnocellular pathway (Hansen, 2001; Conlon et al., 2009). Two patches of randomly moving white dots are presented on the left and right sides of screen, with one patch having a certain percentage of dots moving coherently. Participants have to judge which patch has such coherently moving dots. The percentage of these dots is varied adaptively to determine the participants' detection threshold. Using this task, Talcott et al. (2000) found that English children's sensitivity to dynamic visual stimuli is related to their literacy skills. Visual motion sensitivity can explain independent variance in orthographic skill, but not in phonological ability. Witton et al. (1998) found that dyslexic individuals are less sensitive to dynamic stimuli, with higher threshold in detecting the coherent motion. We also obtained evidence in a preliminary study showing that dynamic visual perception may be related to orthographic processing in Chinese (Meng et al., 2002). In this study, we more systematically investigated the relations between dynamic visual perception and reading development in Chinese. Experiment 1 was conducted to examine whether Chinese dyslexics have the same deficits in detecting coherent motion as their English counterparts. If Chinese dyslexics have deficits in the functions of magnocellular pathway, they will show reduced sensitivity to dynamic coherent motion compared with controls. Experiment 2 was designed to examine more specifically what aspects of cognitive processes in reading Chinese might be related to dynamic visual processing. To achieve this, we tested 100 randomly selected normal school children with both the visual perception tasks and a number of reading-related tasks and conducted regression analyses to determine possible predictive contributions of the coherent motion detection task to the reading-related measures.

Experiment 1

Method

Participants

Twenty-seven dyslexic children and 27 controls participated in the study. These two groups of children were matched on chronological age and nonverbal IQ (see Table 1). The 27 dyslexics were screened from a pool of 420 school children, with the percentage of incidence at 6.43%. The psychometric screening tests, which were administered in groups, are described below. This study was approved by the Academic Committee of the Department of Psychology, Peking University.

Table 1 Meas res for the d sle ic and control gro ps in E periment 1, ith standard de iation in parenthesis

Meas rement	D sle ics	Controls	*F*	*p*
Age	124.7 (12)	123 (15)	0.13	>0.1
Ra en	78.1 (13)	81.6 (10)	1.20	>0.1
1-min reading	66.9 (15)	94.6 (11)	61.10	<0.001
Word reading	94.04 (23)	130.9 (19)	173.04	<0.001
Word dictation	45.3 (12)	81 (9)	141.91	<0.001
Vocab lar	1,935 (370)	2,825 (300)	73.46	<0.001
Reading fl enc	36 (12)	59 (7)	62.17	<0.001
Phonological a areness	7 (2)	11 (2)	77.43	<0.001
STA	32.02 (5)	33.39 (6)	0.88	>0.1
MOT	16.68 (7)	12.84 (4)	6.47	<0.05

For age, the n mbers are the mean months for d sle ic and control gro ps. For the Ra en, the n mbers are the mean percentiles for d sle ic and control gro ps. For 1-min reading, ord reading, ord dictation, reading fl enc , and phonological a areness, the n mbers represent means of items that the d sle ic and control gro ps ans ered correctl . For ocab lar , the n mbers are the n mbers of characters children co ld se correctl in ord composition. For static pattern detection (*STA*) and cohere motion detection (*MOT*), the n mbers are the percentages of dots forming the patterns

Psychometric tests

Raven's Standard Progressive Matrices were used to measure children's nonverbal IQ. There were five sets of 12 items each in the test. Each item consisted of a target matrix with one missing part. Children were asked to select, from six to eight alternatives, the part that best completed the matrix. Scoring procedures were based on the Chinese norm (Zhang & Wang, 1985).

A number of reading tests were administered, with three of them modeled after the Hong Kong test of specific learning difficulties in reading and writing (Ho, Chan, Tsang, & Lee, 2000). In the Chinese *word reading test*, children were asked to read aloud 150 Chinese two-character words in order of increasing difficulty. The test was discontinued when the child failed consecutively to read 15 words. The *1-min reading test* consisted of 90 two-character words, and children were asked to read aloud each word as quickly and as accurately as possible within 1 min. The third test was a *word-dictation test*, in which children were asked to take a dictation of 48 Chinese two-character words. This test was discontinued when a child failed consecutively to write correctly eight words. The number of correctly produced words in each of the three tests was taken as the score for a particular participant in that test. These literacy tests were to measure children's reading, writing, and decoding fluency abilities.

The written *vocabulary test* was a standardized test (Wang & Tao, 1996) in which 210 characters were divided into 10 groups based on their reading difficulties. Participants were asked to write down a compound word based on a constituent morpheme provided on the sheet. The performance was measured by the total number of correct characters (morphemes) the participants could make use of in word-composition. Participants had to know with whom the provided morpheme can be combined to form a compound word.

The *reading fluency test* was a reading comprehension test which had 95 sentences, each sentence paired with five picture choices. Participants were asked to read each sentence and select from the five pictures the one that best reflected the meaning of the sentence. Children were encouraged to complete as many paragraphs as possible within a 10-min time period. The performance was measured by the total number of sentences the participants could understand. Rapid retrieval and retention of lexical information and construction of sentential representation are needed to complete the task.

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

Visual perception tasks

Two psychophysic tests, a coherent motion detection test and a static visual pattern detection test (Talcott et al., 2000; Witton et al., 1998), were administered to the two groups of children. In the coherent motion detection task, two patches of randomly moving white dots were presented on the left and right sides of screen with dark background. One patch had a certain percentage of dots moving coherently leftward and rightward. Participants had to judge which patch had such coherently moving dots. The percentage of these dots was varied adaptively to decide participants' detection threshold. In the static pattern detection task, two patches of static dots were also presented on the screen, with one patch having a certain percentage of dots forming a circle. Participants had to indicate which patch had

Experiment 2

Experiment 1 suggested that there is apparent relationship between poor performance in reading Chinese and deficits in dynamic visual perception and possibly its neural substrates. The purpose of Experiment 2 was to investigate whether the impact of dynamic visual perception on reading Chinese can be related to certain cognitive processes in reading Chinese. Specifically, we wanted to examine whether perception of dynamic visual information has specific impact upon orthographic processing in reading Chinese, as suggested by Meng et al. (2002).

Method

Participants

One hundred fifth-grade children from a primary school in Beijing were tested on a number of linguistic and visual perception tasks. These children were randomly selected, and hence their reading skills ranged from excellent to poor.

Psychometric and visual perception tests

A battery of linguistic and visual perception tests were administered. The two visual perception tasks and the written vocabulary, reading fluency, and phonological awareness tests were the same as in Experiment 1. In addition, this experiment tested participants with three on-line tasks: *character naming*, *orthographic similarity judgment*, and *picture naming*. The written vocabulary test, reading fluency test, and phonological awareness test were administered in groups. Character naming, orthographic similarity judgment, picture naming, and visual perception tests were administered individually in a quiet room.

In the *character-naming task*, 100 characters were presented one by one on the screen, and participants were asked to name the characters into a microphone as quickly and as accurately as possible. Each character was presented for 400 ms (Meng, 2000). Naming latencies were recorded by the DMDX system (Forster & Forster, 2003), and naming errors were recorded by an experimenter. The characters were all complex characters, each composed of a semantic radical and phonetic radical (Zhou & Marslen-Wilson, 1999). According to whether the whole character was pronounced in the same way as its phonetic radical, a character could be categorized as "regular" or "irregular." For example, the character 球 (/ 2/, *ball*) a, a a 求 (*to ask*) a a a a a a; a a 滑 (/ a2/, *slippery*) a, a a 骨 (/ 3/, *bone*) a a a. T 50 a a 50 a a a, a a a y - y (109/) a - y (20/). T a a a a a a a a a a. I a a a y a y a a a.

In the *orthographic similarity judgment task*, children had to judge whether a pair of consecutively presented characters were orthographically similar. Orthographic similarity was defined in the way that simple characters had similar visual form (e.g., 甲 / a3/, *first* a 龟/ 1/, *turtle*) a a a a a a a (. ., 徒 / 2/, *apprentice* a □ / 3/, *steep*). F a a, a a a 400 , y a 100- a a. T a a a 400 , a a a a a "y ", " " a y a a a a y a .

P a a a , , a, a a a
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y a C .

In the *picture-naming task*, 100 pictures, selected from Shu, Cheng, and Zhang (1989), were presented one by one on the computer screen, and participants were asked to name each picture as quickly and as accurately as possible. Half of the objects depicted by these pictures were commonly seen while another half were less common. Each picture was presented for 500 ms, 100 ms longer than the presentation of a character for naming, as our previous study (Meng et al., 2002) showed that the naming latency for pictures was approximately 100 ms longer than that for characters. Naming latencies were recorded by the DMDX system, and naming errors were monitored by an experimenter. This test was done to test the efficiency of visual form analysis and the efficiency of accessing phonological codes from meaning.

Results and discussion

Correlation coefficients between various tests are presented in Table 2. It can be seen from the table that scores in phonological awareness tests correlated significantly with a number of reading tests, such as vocabulary and reading fluency, consistent with other studies demonstrating the contribution of phonological awareness to Chinese reading (Ho & Bryant, 1997; McBride-Chang & Ho, 2000).

Also consistent with many previous studies, children responded faster and more accurately in naming high-frequency characters and pictures than that in naming low-frequency ones. They were also faster in answering yes to orthographically similar character pairs of high frequency than to pairs of low frequency. Furthermore, regular characters were named faster and more accurately than irregular characters (Table 3).

More importantly to the present purpose, this experiment found no correlation between the threshold of static pattern perception and linguistic tests, suggesting that perceptual tasks that do not rely on the magnocellular pathway do not tap into processes involved in reading. On the other hand, the coherent motion detection threshold correlated significantly to measures of phonological awareness, the speed of orthographic similarity judgment, and the error rate in orthographic similarity judgment and in picture naming, suggesting that the magnocellular pathway is substantially implicated in Chinese reading.

Hierarchical regression analyses showed that the coherent motion detection threshold could independently account for 11% of the variance in the speed of orthographic similarity judgment after nonverbal IQ, vocabulary size, character-naming speed, and phonological awareness scores were controlled (Table 4). On the other hand, although there was a significant correlation between the coherent motion detection threshold and the error rate in orthographic similarity judgment, the coherent motion detection threshold could account for 4% ($p<0.05$) of variance in the error rate for only low-frequency characters after nonverbal IQ, vocabulary size, character-naming error rate, and phonological awareness scores were controlled (see Table 5). The correlation between the coherent motion detection threshold

Table 2 Correlation matrix between various measures in Experiment 2

	1	2	3	4	5	6	7	8	9	10	11	12
RAV		0.24*	0.21*	0.27**	0.04	−0.35**	0.12	−0.18	0.02	−0.20*	−0.00	−0.09
VOC			0.36**	0.50**	−0.18	−0.05	−0.23*	−0.13	−0.34**	−0.35**	0.02	−0.16
FLU				0.25*	−0.28**	0.04	−0.28**	−0.02	−0.40**	−0.16	−0.07	0.04
PHO					−0.20*	−0.26**	−0.11	−0.29**	−0.13	−0.30**	−0.16	−0.29*
ORT_RT						0.07	0.26**	0.19	0.37**	0.00	0.03	0.36**
ORT_ER							−0.15	0.36**	0.04	0.12	−0.00	0.21*
PIC_RT								−0.03	0.67**	−0.10	−0.02	−0.16
PIC_ER									0.00	0.52**	0.11	0.36**
CHA_RT										0.07	−0.10	−0.00
CHA_ER											−0.11	0.17
STA												0.28**
MOT												

RAV Raven Standard Progressive Matrices, VOC vocabulary, *FLU* reading fluency, *PHO* phonological awareness, *ORT_RT* orthographic similarity judgment latency, *ORT_ER* orthographic similarity judgment error rate, *PIC_RT* picture-naming latency, *PIC_ER* picture-naming error rate, *CHA_RT* character-naming latency, *CHA_ER* character-naming error rate, *STA* static pattern detection, *MOT* coherent motion detection

*$p<0.05$; **$p<0.01$

Table 3 Paired *t* tests for character and picture frequency effects and for character regularity effect in response time and error rate, with standard deviation in parenthesis

Variable_1	Means	Variable_2	Means	*T*	*p*
ORT_L_RT	683 (142)ms	ORT_H_RT	660 (133)ms	4.96	<0.001
ORT_L_ER	0.06 (0.05)	ORT_H_ER	0.054 (0.05)	1.11	>0.1
PIC_L_RT	874 (134)ms	PIC_H_RT	816 (119)ms	11.85	<0.001
PIC_L_ER	0.04 (0.05)	PIC_H_ER	0.02 (0.03)	4.53	<0.001
REG_RT	719 (161)ms	IREG_RT	804 (189)ms	−18	<0.001
REG_ER	0.04 (0.06)	IREG_ER	0.08 (0.09)	−6.9	<0.001
CHA_L_RT	804 (194)ms	CHA_H_RT	719 (156)ms	12	<0.001
CHA_L_ER	0.10 (0.09)	CHA_H_ER	0.06 (0.06)	7.12	<0.001

ORT_L_RT orthographic similarity judgment reaction time for low-frequency characters, *ORT_H_RT* orthographic similarity judgment reaction time for high-frequency characters, *ORT_L_ER* orthographic similarity judgment error rate for low-frequency characters, *ORT_H_ER* orthographic similarity judgment error rate for high-frequency characters, *PIC_L_RT* picture-naming latency for low-frequency objects, *PIC_H_RT* picture-naming latency for high-frequency objects, *PIC_L_ER* picture-naming error rate for low-frequency objects, *PIC_H_ER* picture-naming error rate for high-frequency objects, *REG_RT* naming latency for regular characters, *IREG_RT* entIRp229c48409.0.52850TJ/F49J/F3TD5F490n(804)/F30imeTf9.46050TD(IREG_Ranc

and the error rate in orthographic similarity judgment was significant for low-frequency characters (r=0.29, p<0.01), but not for high-frequency characters (r=0.05, p>0.1) when the characters were grouped according to their frequencies.

Furthermore, hierarchical regression analyses showed that the coherent motion detection threshold could also account for 12% of the variance in picture-naming error rate after nonverbal IQ and vocabulary size were controlled (Table 6; see also Meng et al., 2002 for a similar pattern). Regression analyses did not find significant contributions of coherent motion threshold to other linguistic measures.

We believe that both orthographic similarity judgment and picture-naming tap into speeded visual form analysis, which may rely partly on the magnocellular pathway.

General discussion

The main purpose of this study was to investigate to what extent developmental dyslexia and reading development in Chinese depend on the development of dynamic visual

Table 5 Hierarchical regression predicting the speed of orthographic similarity judgment

Dependent variable	Independent variables	R^2	R_{ch}^2	F
ORT_L_ER	RAV	0.08	0.08	0.007
	VOC	0.081	0.001	0.78
	CHA_ER	0.11	0.02	0.32
	PHO	0.19	0.09	0.035
	MOT	0.23	0.04	0.042

perception and its neural substrates. Experiment 1 found that the Chinese dyslexic group had a higher threshold in detecting coherent motion than normal controls did. Further deviance analysis showed that about 52% of the dyslexic children, as opposed to only 13% of the controls, had dynamic visual perception deficits, suggesting that substantial amount of Chinese dyslexics are impaired in dynamic visual perception, a function of the magnocellular pathway. Moreover, the regression analyses in Experiment 2 showed that dynamic visual perception threshold could account for 11%, 12%, and 4% of the variance in, respectively, the speed of orthographic similarity judgment, the error rate in picture naming, and the error rate in orthographic similarity judgment for low-frequency characters after IQ and vocabulary were controlled. These results demonstrate that the impact of dynamic visual perception on Chinese reading could be related specifically to orthographic processing and hence provide evidence for a link between dynamic visual processing and the development of reading skills in Chinese.

Note that the prevalence of dyslexic children having dynamic visual perception deficit in the present study (52%) was higher than the percentage reported for English counterparts (30% in Conlon et al., 2009, or even less in Ramus et al., 2003). This difference may result from the logographic nature of Chinese writing system, in which the reader relies more heavily on visual–orthographic route in lexical access (Zhou & Marslen-Wilson., 1999, 2000) and in learning to read (Huang & Hanley, 1994; Leck, Weeks, & Chen, 1995; Tzeng & Wang, 1983; Meng, Jian, Shu, Tian, & Zhou, 2008). The present findings suggest that although dynamic visual perception and its underlying neural substrates are important in learning to read across different writing systems, the extent of its impact upon reading development and developmental dyslexia may depend partly on the role of orthography in lexical processing for a particular writing system.

Findings in the present study are consistent with Witton et al. (1998) who demonstrated that English dyslexic adults have lower sensitivity to dynamic sensory information than normal controls, and with Talcott et al. (2000) who found that after controlling for intelligence and overall reading ability, for normal children, dynamic motion sensitivity explains independent variance in orthographic skill but not phonological ability, while auditory sensitivity in frequency modulation explains independent variance in phonological skill but not in orthographic skill. These results suggest that there are common

Table 6 Hierarchical regression predicting the picture-naming error rate

Dependent Variable	Independent variables	R^2	R_{ch}^2	F
PIC_ER	RAV	0.32	0.03	0.09
	VOC	0.04	0.01	0.36
	MOT	0.17	0.12	0.003

underlying causes of development dyslexia across different cultures and different writing systems, and deficits in the magnocellular pathway is one of them.

Stein and Talcott (1999) suggested that accurate visual coding is needed to identify a word and to retrieve the correct pronunciation of that word. Eden, Van Meter, Rumsey, and Zeffiro (1996) also suggested that one way in which the visual deficiency could influence reading processes would be through interfering with the uptake of crucial visual information required for the formation of spelling-to-sound correspondences. In the present study, both orthographic similarity judgment and picture naming need accurate analyses and extraction of stimuli's configural information, and the ability to do this may depend on the more basic functions of magnocellular pathway. In contrast, the present study did not find correlation between coherent motion detection threshold and vocabulary size or reading fluency, although Meng et al. (2002) did find that the dynamic visual detection threshold accounted for 7% (4% in this study) of variance in reading fluency. The absence of stable correlations for these tasks may be due to the fact that these tasks tap into more complex cognitive processes rather than the simple visual–orthographic processing. It has been suggested that the possible effect of dynamic visual perception is not on the whole processes of reading or vocabulary development, but on a specific aspect of orthographic processing (Talcott et al., 2000).

The present study observed a significant correlation between coherent motion detection threshold and the measurement of phonological awareness (see also Conlon et al., 2009; Ben-Shachar, Dougherty, Deutsch, & Wandell, 2007; Borsting, Ridder, Dideck, Kelley, Matsui, & Motoyama, 1996; Johnson, Bruno, Watanabe, Quansah, Patel, Daskin, et al., 2008; Meng et al., 2002; Ridder, Borsting, & Banton, 2001; Slaghuis & Lovegrove, 1985; Slaghuis & Ryan, 1999; Talcott et al., 1998, 2000; Witton et al., 1998), which was taken by Vidyassagar and Pammer, (2009) as evidence that phonological problems experienced by dyslexics arise from impairment of the dorsal visual stream, which is responsible for visual processing of graphemes, their translation into phonemes, and the development of phonemic awareness. However, given that this correlation did not survive in the regression analysis after general cognitive ability and reading skills were removed (see also Talcott et al., 2000), further studies are needed to explore to what extent the deficit in dynamic visual perception contributes to the deficit in phonological skills.

It is noted that in the present study the coherent motion detection threshold correlated with both the speed and the error rate in orthographic similarity judgment, but correlated with only the error rate in picture naming. This difference might come from the difference in the processes underlying the two tasks. Orthographic similarity judgment is a task tapping mostly into the visual–orthographic process in visual word recognition. This process may be intrinsically related to dynamic visual perception. Picture naming, on the other hand, involves more complex processes including visual analysis of configural information, activating a specific concept, and mapping the concept onto a specific phonological code. While the speed of picture naming may measure all these processes, the error rate reflects mostly the processes of visual form analysis and the activation of concept using configural information. Almost all the errors were naming a visually (and semantically) similar object for the target (e.g., naming "orange" for "apple"). It is no wonder that the error rate in picture naming correlated to the threshold of coherent motion detection. Similarly, the stronger correlation between the coherent motion detection threshold and the error rate in orthographic similarity judgment for low frequency than for high-frequency characters may be due to the fact the visual–orthographic analysis for low-frequency characters is more demanding and relies more on the dynamic visual perception and the magnocellular pathway.

To summarize, by using a coherent motion detection task that taps into the functions of the magnocellular pathway, the present study demonstrates that a large proportion (over 50%) of Chinese dyslexic children have deficits in dynamic visual perception and that this deficit affects specific cognitive processes in reading. Thus, reading development in Chinese depends to a certain extent on the development of dynamic visual perception and its underlying neural pathway, and the impact of visual development can be specifically related to orthographic processing in reading Chinese characters.

Acknowledgment This study was supported by grants from the Natural Science Foundation of China (30770712, 30970889) and a research grant from The Joint PekingU-PolyU Center for Child Development and Learning. We thank the anonymous reviewers for their constructive comments and suggestions.

References

Ben-Shachar, M., Dougherty, R. F., Deutsch, G. K., & Wandell, B. A. (2007). Contrast responsivity in MT+ correlates with phonological awareness and reading measures in children. *Neuroimage, 37*, 1396–1406.

Boden, C., & Giaschi, D. (2007). M-stream deficits and reading-related visual processes in developmental dyslexia. *Psychological Bulletin, 133*, 346–366.

Boets, B., Wouters, J., van Wieringen, A., et al. (2006). Auditory temporal information processing in preschool children at family risk for dyslexia: Relations with phonological abilities and developing literacy skills. *Brain and Language, 97*, 64–79.

Borsting, E., Ridder, W. H., III, Dideck, K., Kelley, C., Matsui, L., & Motoyama, J. (1996). The presence of a magnocellular deficit depends on the type of dyslexia. *Vision Research, 36*, 1047–1053.

Bosse, M. L., Tainturier, M. J., & Valdois, S. (2007). Developmental dyslexia: The visual attention span deficit hypothesis. *Cognition, 104*, 198–203.

Bradley, L. L., & Brayant, P. (1978). Difficulties in auditory organization as a possible cause of reading backwardness. *Nature, 271*, 746–747.

Bradley, L. L., & Brayant, P. (1983). Categorizing sounds and learning to read: A causal connexion. *Nature, 301*, 419.

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

Bruck, M. (1992). Persistence of dyslexics' phonological deficits. *Developmental Psychology, 28*, 874–886.

Casco, C., & Prunetti, E. (1996). Visual search of good and poor readers: effects with targets having single and combined features. *Perceptual Motor Skills, 82*, 1155–1167.

Cheng, K., Fujita, H., Kanno, I., Miura, S., & Tanaka, K. (1995). Human cortical regions activated by wide-field visual motion: an H2(15)O PET study. *Journal of Neurophysiology, 74*, 413–427.

Chung, K. K. H., McBride-Chang, C., Wong, S. W. L., Cheung, H., Penney, T. B., & Ho, C. (2008). The role of visual and auditory temporal processing for Chinese children with developmental dyslexia. *Annals of Dyslexia, 58*, 15–35.

Conlon, E., Sanders, M., & Zapart, S. (2004). Temporal processing in poor adult readers. *Neuropsychologia, 42*, 142–157.

Conlon, E. G., Sanders, M. A., & Wright, C. M. (2009). Relationships between global motion and global form processing, practice, cognitive and visual processing in adults with dyslexia or visual discomfort. *Neuropsychologia, 47*, 907–915.

Cornelissen, P., & Hansen, P. (1998). Motion detection, letter position encoding, and single word reading. *Annals of Dyslexia, 48*, 155–188.

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

Demb, J. B., Boynton, G. M., Best, M., & Heeger, D. (1998). Psychophysical evidence for a magnocellular deficit in dyslexia. *Vision research, 38*, 1555–1559.

Eden, G. F., Van Meter, J. W., Rumsey, J. M., & Zeffiro, T. A. (1996). The visual deficit theory of developmental dyslexia. *Neuroimage, 4*, S108–S117.

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

Edwards, V. T., Giaschi, D. E., Dougherty, R. F., Edgell, D., Bjornson, B. H., Lyons, C., et al. (2004). Psychophysical indexes of temporal processing abnormalities in children with developmental dyslexia. *Developmental Neuropsychology, 25*, 321–354.

Facoetti, A., Paganoni, P., Turatto, M., Marzola, V., & Mascetti, G. G. (2000). Visual–spatial attention in developmental dyslexia. *Cortex, 36*, 109–123.

Facoetti, A., Trussardi, A. N., Ruffino, M., et al. (2010). Multisensory spatial attention deficits are predictive of phonological decoding skills in developmental dyslexia. *Journal of Cognitive Neuroscience, 22*, 1011–1025.

Fischer, B., & Hartnegg, K. (2000). Effects of visual training on saccade control in dyslexia. *Perception, 29*, 531–542.

Forster, I. K., & Forster, C. J. (2003). DMDX: A Windows display program with millisecond accuracy. *Behavior Research Methods, Instruments, & Computers, 35*, 116–124.

Frith, U. (1981). Experimental approaches to developmental dyslexia: An introduction. *Psychological Research, 43*, 97–109.

Goodale, M. A., & Milner, A. D. (1992). Separate visual pathways for perception and action. *Trends in Neuroscience, 15*, 20–25.

Hansen, P. C. (2001). *Global form and global motion processing programs*. London: Department of Physiology, Oxford University.

Hansen, P. C., Stein, J. F., Orde, S. R., Winter, J. L., & Talcott, J. B. (2001). Are dyslexics' visual deficits limited to measures of dorsal stream function? *NeuroReport, 12*, 1527–1530.

Hari, R., Valta, M., & Uutela, K. (1999). Prolonged attentional dwell time in dyslexic adults. *Neuroscience Letters, 271*, 202–204.

Ho, C. (1997). The importance of phonological awareness and verbal short-term memory to children's success in learning to read Chinese. *Psychologia, 40*, 211–219.

Ho, C., & Bryant, P. (1997). Phonological skills are important in learning to read Chinese. *Developmental Psychology, 33*, 946–951.

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

Ho, C., Chan, D., Tsang, S., & Lee, S. (2000). *The Hong Kong test of specific learning-difficulties in reading and writing (HKT-SpLD), August* (Researchth ed.). Hong Kong: Hong Kong Specific Learning Difficulties Research Team.

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

Hu, C. F., & Catts, H. W. (1998). The role of phonological processing in early reading ability: what we can learn from Chinese. *Scientific Studies of Reading, 2*, 55–79.

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

Huang, H. S., & Hanley, J. R. (1995). Phonological awareness and visual skills in learning to read Chinese and English. *Cognition, 54*, 73–98.

Huang, H. S., & Hanley, J. R. (1997). A longitudinal study of phonological awareness, visual skills and Chinese reading acquisition among first graders in Taiwan. *International Journal of Behavioral Development, 20*(2), 249–268.

Hulslander, J., Talcott, J., Witton, C., DeFries, J., Pennington, B., Wadsworth, S., et al. (2004). Sensory processing, reading, IQ, and attention. *Journal of Experimental Child Psychology, 88*, 274–295.

Johnson, A., Bruno, A., Watanabe, J., Quansah, B., Patel, N., Dakin, S., et al. (2008). Visually-based temporal distortion in dyslexia. *Vision Research, 48*, 1852–1858.

Kevan, A., & Pammer, K. (2008). Visual processing deficits in preliterate children at familial risk for dyslexia. *Vision Research, 48*, 2835–2839.

Kevan, A., & Pammer, K. (2009). Predicting early reading skills from pre-reading measures of dorsal stream functioning. *Neuropsychologia, 47*, 3174–3181.

Laycock, R., & Crewther, S. G. (2008). Towards an understanding of the role of the magnocellular advantage in fluent reading. *Neuroscience & Biobehavioral Reviews, 32*(8), 1494–1506.

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.

Levy, T., Walsh, V., & Lavidor, M. (2010). Dorsal stream modulation of visual word recognition in skilled readers. *Vision Research, 50*, 883–888.

Lovegrove, W. J., Bowling, A., Badcock, D., & Blackwood, M. (1980). Specific reading disability: Differences in contrast sensitivity as a function of spatial frequency. *Science, 210*, 439–440.

Lundberg, I., Frost, J., & Petersen, O. (1988). Effects of an extensive program for stimulating phonological awareness in preschool children. *Reading Research Quarterly, 23*, 263–284.

Manis, F. R., Custodio, R., & Szeszulski, P. A. (1993). Development of phonological and orthographic skill: a two-year longitudinal study of dyslexic children. *Journal of Experimental Child Psychology, 56*, 64–86.

McBride-Chang, C. (2004). *Children's literacy development*. London: Arnold.

McBride-Chang, C., & Chang, L. (1995). Memory, print exposure, and metacognition: components of reading in Chinese children. *International Journal of Psychology, 30*(5), 607–616.

McBride-Chang, C., & Ho, C. (2000). Developmental issues in Chinese children's character acquisition. *Journal of Educational Psychology, 92*, 50–55.

Meng, X. (2000). *The lexical representation and processing in Chinese-speaking developmental dyslexia*. Doctoral dissertation: Beijing Normal University.

Meng, X., Zhou, X., Zeng, B., Kong, R., & Zhuang, J. (2002). Visual perceptual skills and reading abilities in Chinese-speaking children (in Chinese). *Acta Psychologica Sinica, 34*(1), 16–22.

Meng, X., Tian, X., Jian, J., & Zhou, X. (2007). Orthographic and phonological processing in Chinese dyslexic children: An ERP study on sentence reading. *Brain Research, 1179*, 119–130.

Meng, X., Jian, J., Shu, H., Tian, X., & Zhou, X. (2008). ERP correlates of the development of orthographical and phonological processing during Chinese sentence reading. *Brain Research, 1219*, 91–102.

Pellicano, E., & Gibson, L. Y. (2008). Investigating the functional integrity of the dorsal visual pathway in autism and dyslexia. *Neuropsychologia, 46*, 2593–2596.

Ramus, F. (2004). Neurobiology of dyslexia? A reinterpretation of the data. *Trends in Neurosciences, 27*, 720–726.

Ramus, F., Rosen, S., Dakin, S. C., Day, B. L., Catelotte, J. M., White, S., et al. (2003). Theories of developmental dyslexia: Insights from a multiple case study of dyslexic adults. *Brain, 126*, 841–865.

Reid, A. A., Szczerbinski, M., Iskierka-Kasperek, E., & Hansen, P. (2007). Cognitive profiles of adult developmental dyslexics: Theoretical implications. *Dyslexia, 13*, 1–24.

Ridder, W. H., Borsting, E., & Banton, T. (2001). All developmental dyslexia subtypes display an elevated motion coherence threshold. *Optometry and Vision Science, 78*, 510–517.

Shu, H., Cheng, Y. S., & Zhang, H. C. (1989). The naming consistency, familiarity, representation consistency and visual complexity of 235 pictures (in Chinese). *Acta Psychologica Sinica, 21*(4), 389–396.

Shu, H., Chen, X., Anderson, R. C., Wu, N., & Xuan, X. (2003). Properties of school Chinese: implications for learning to read. *Child Development, 74*(1), 27–48.

Siok, W. T., & Fletcher, P. (2001). The role of phonological awareness and visual–orthographic skills in Chinese reading acquisition. *Developmental Psychology, 37*(6), 886–899.

Slaghuis, W. L., & Lovegrove, W. J. (1985). Spatial-frequency-dependent visible persistence and specific reading disability. *Brain and Cognition, 4*, 219–240.

Slaghuis, W. L., & Ryan, J. F. (1999). Spatio-temporal contrast sensitivity, coherent motion, and visible persistence in developmental dyslexia. *Vision Research, 39*, 651–668.

Song, H., Zhang, H., & Shu, H. (1995). The role of phonology and orthography and its development in Chinese reading. *Acta Psychologica Sinica, 27*, 139–141.

Stanovich, K. E., Siegel, L. S., Gottardo, A., Chiappe, P., & Sidhu, R. (1997). Subtypes of developmental dyslexia: differences in phonological and orthographic coding. In B. Blachman (Ed.), *Foundations of reading acquisition and dyslexia* (pp. 115–142). London: Lawrence Erlbaum.

Stein, J. F. (1994). A visual defect in dyslexics? In A. Fawcett & R. Nicolson (Eds.), *Dyslexia in children: Multidisciplinary perspectives* (pp. 137–156). Hemel Hempstead: Harvester Wheatsheaf.

Stein, J. F., & Talcott, J. (1999). Impaired neuronal timing in developmental dyslexia—The magnocellular hypothesis. *Dyslexia, 5*, 59–77.

Stein, J. F., & Walsh, V. (1997). To see but not to read: the magnocellular theory of dyslexia. *Trend in Neurological Science, 20*, 147–152.

Stein, J. F., Richardson, A. J., & Fowler, M. S. (2000). Monocular occlusion can improve binocular control and reading in dyslexics. *Brain, 123*, 164–170.

Stevenson, H. W., Stigler, J. W., Lucker, G. W., Hsu, C. C., & Kitamura, S. (1982). Reading disabilities: the case of Chinese, Japanese and English. *Child Development, 53*, 1164–1181.

Talcott, J. B., Hansen, P. C., Willis-Owen, C., McKinnell, I. W., Richardson, A. J., & Stein, J. F. (1998). Visual magnocellular impairment in adult developmental dyslexics. *Neuro-Opthalmology, 20*, 187–201.

Talcott, T. B., Witton, C., McLean, M. F., Hansen, P. C., Rees, A., Green, G. G. R., et al. (2000). Dynamic sensory sensitivity and children's word decoding skills. *Proceedings of the National Academy of Sciences, 97*, 2952–2957.

Tzeng, O. J. L., & Wang, W. S. Y. (1983). The first two R's. *Scientific American, 71*, 238–243.
Vaina, L. M., Lemay, M., Bienfang, D. C., Choi, A. Y., & Nakayama, K. (1990). Intact "biological motion" and "structure from motion" perception in a patient with impaired motion mechanisms: A case study. *Visual Neuroscience, 5*, 353–369.
Vidyasagar, T. R., & Pammer, K. (1999). Impaired visual search in dyslexia relates to the role of the magnocellular pathway in attention. *Neuroreport, 10*, 1283–1287.
Vidyassagar, T. R., & Pammer, K. (2009). Dyslexia: A deficit in visual–spatial attention, not in phonological processing. *Trends in Cognitive Sciences, 14*, 57–63.
Wagner, R. K., Torgesen, J. K., & Rashotte, C. A. (1994). Development of reading-related phonological processing abilities: New evidence of bidirectional causality from a latent variable longitudinal study. *Developmental Psychology, 30*, 73–87.
Wang, X. L., & Tao, B. P. (1996). *The scale and assessment of vocabulary for primary school (in Chinese)*. Shanghai: Shanghai Educational.
White, S., Milne, E., Rosen, S., Hansen, P., Swettenham, J., Frith, U., et al. (2006). The role of sensorimotor impairments in dyslexia: A multiple case study of dyslexic children. *Developmental Science, 9*, 237–269.
Williams, M. J., Stuart, G. W., Castles, A., & McAnally, K. I. (2003). Contrast sensitivity in subgroups of developmental dyslexia. *Vision Research, 43*, 467–477.
Witton, C., Talcott, J. B., Hansen, P. C., Richardson, A. J., Griffiths, T. D., Rees, A., et al. (1998). Sensitivity to dynamic auditory and visual stimuli predicts nonword reading ability in both dyslexic and normal readers. *Current Biology, 8*, 791–797.
Zeki, S., Watson, J. D. G., Lueck, C. J., Friston, K. J., Kennard, C., & Frackowiak, R. S. J. (1991). A direct demonstration of functional specialization in human visual cortex. *The Journal of Neuroscience, 11*, 641–649.
Zhang, H. C., & Wang, X. P. (1985). *Raven standard progressive matrices: Chinese city revision*. Beijing: The National Revision Collaborative Group.
Zhang, C. F., Zhang, J. H., Chang, S., Zhou, J., & Yin, R. (1998). A study of cognitive profiles of Chinese learners' reading disabilities. *Acta Psychologica Sinica (in Chinese), 30*, 50–55.
Zhou, Y. G. (1978). To what degree are the 'phonetics' of present-day Chinese characters still phonetic? *(in Chinese) Zhongguo Yuwen, 146*, 172–177.
Zhou, X., & Marslen-Wilson, W. (1999). Phonology, orthography, and lexical semantic activation in reading Chinese. *Journal of Memory and Language, 41*, 579–606.
Zhou, X., & Marslen-Wilson, W. (2000). The relative time course of semantic and phonological activation in reading Chinese. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 26*, 1245–1265.