Research Report

Orthographic and phonological processing in Chinese dynlexic children: An ERP study on sentence reading

Xiangzhi Meng[a], *Xiaomei Tian*[a], *Jie Jian*[a], *Xiaolin Zhou*[a,b,*]

[a]*Department of Psychology, Peking University, Beijing 100871, China*
[b]*State Key Laboratory of Cognitive Neuroscience and Learning, Beijing Normal University, Beijing 100875, China*

A R T I C L E I N F O

Article history:
Accepted 17 August 2007
Available online 25 August 2007

Keywords:
Developmental dyslexia
Chinese reading
Phonological processing
Orthographic processing
ERP

A B S T R A C T

An event-related potential (ERP) experiment was conducted to explore the differences between Chinese-speaking dynlexic children and normal school children in orthographic and phonological processing during Chinese sentence reading. Participants were visually presented with sentences, word-by-word and were asked to judge whether the sentences were semantically acceptable. The crucial manipulation was on the sentence-final two-character compound words, which were either correct or incorrect. For the incorrect compounds, the second characters of the base words were replaced by homophonic or orthographically similar characters. It was found that, for the normal controls, the orthographic and phonological mismatches elicited more negative ERP responses, relative to the baseline, over a relatively long time course (including the time windows for P200 and N400) at the central–posterior scalp regions. In contrast, the dyslexic children in general showed no differences between experimental conditions for P200 and N400, although the more detailed time course analyses did reveal some weak effects for the N400 component between experimental conditions. In addition, the mean amplitude of N400 in the homophonic condition was less negative-going for the dyslexics than for the controls. These findings suggest that Chinese dyslexic children have deficits in processing orthographic and phonological information conveyed by characters and, compared with normal children, they rely more on phonological information to access lexical semantics in sentence reading.

1. Introduction

It is generally accepted that developmental dyslexia is associated with neurophysiological deficits in processing auditory, visual and linguistic information in the brain. Most of the

Breznitz, 2005b; Molfese et al., 2006; Schulte-Körne et al., 2004; Taylor and Keenan, 1990, 1999; Wimmer et al., 2002). With some exceptions (see below), few studies have investigated whether dyslexic children have deficits in processing various kinds of linguistic information of the upcoming word and integrating them into prior sentential context and how these deficits would manifest in the event-related brain potentials. The main purpose of this ERP research is to examine the neural makers of orthographic and phonological processing deficits in reading Chinese sentences. Before we make an introduction to the Chinese writing system and the experimental design of this study, we first present a brief review of the earlier studies on orthographic and phonological processing and sentence comprehension in dyslexia.

Earlier ERP studies on the orthographic and phonological processing of isolated words generally observed differences in the P200 and/or P300 ERP components between dyslexic readers and the age-matched controls (e.g., Breznitz, 2003; Holcomb et al., 1985; Meyler and Breznitz, 2005b; Muller-Shaul and Breznitz, 2004; Stelmack et al., 1988). The latencies of these components were usually later for the dyslexic group than for normal readers, although controversies arose over the amplitudes of these components. Breznitz (2003), for example, found that adult dyslexics exhibited P200 and P300 with *higher* amplitudes and later latencies than normal readers in an auditory phonological similarity judgment task, and she observed no group differences in these components in an orthographic similarity judgment task (see also Taylor and Keenan, 1999). However, Meyler and Breznitz (2005b) found that the P200 had *lower* amplitude and later latency for dyslexic than for normal readers in orthographic and phonological judgment tasks. Holcomb et al. (1985) found that dyslexic children had P300 of *lower* amplitude and later latency for words compared to symbols than did normal readers.

Other studies also observed deficits in other ERP components for dyslexics as compared with normal controls in lexical processing. For example, several studies on phonological processing using rhyme judgment tasks demonstrated deficits in the N400 component for dyslexics (e.g., Ackerman et al., 1994; Lovrich et al., 1997, 2003; McPherson et al., 1996, 1998). These studies generally observed stronger N400 components for dyslexics than for the controls except Lovrich et al. (2003) who observed an opposite pattern. For Chinese, Liu et al. (2003) presented character pairs and asked Chinese adult participants to make phonological or semantic judgment to these pairs. They found that, compared with dissimilar pairs, orthographically similar pairs produced a smaller P200 component in the phonological task and a smaller N400 component in the semantic task. Homophonic pairs produced a reduced N400 component compared with non-homophonic pairs in the semantic task. Valdes-Sosa et al. (1993) also observed a reduced N400 component for homophonic pairs in a phonological judgment task. It is not clear, however, how dyslexics in Chinese would perform in these tasks.

The few studies on sentence comprehension in dyslexic or language-impaired individuals focused either on the semantic aspect of lexical processing (Brandeis et al., 1994; Helenius et al., 1999; Neville et al., 1993; Robichon et al., 2002; Sabisch et al., 2006) or on syntactic processing (Breznitz and Leikin, 2000, Leilin and Breznitz, 2001; Leilin, 2002; Rispens et al., 2006). Neville et al. (1993) recorded ERPs to each word in visually presented sentences that ended either with semantically congruent or incongruent words. The N400 effect for the incongruent words was larger for language-impaired children than for normal children over the posterior regions of the scalp. Interestingly, language impaired children tended to have larger N400 components for both the congruent and incongruent words than normal children. Similarly, Robichon et al. (2002) compared the performance of dyslexic and normal adult participants in reading sentences ending with semantically congruent or incongruent words. ERP results revealed larger N400 components and a larger N400 effect for dyslexics than for the controls at a slow presentation rate. A recent study by Sabisch et al. (2006), however, found that the lexical-semantic violation elicited similar N400 effects for dyslexic and normal children in auditory sentence comprehension (see also Helenius et al., 1999 for visually presented sentences), although they showed remarkable differences in the early syntactic processes of phrase structure building. Studies on syntactic processing in sentence comprehension in general demonstrated also deficits in dyslexics. Again, it is not clear whether dyslexics in Chinese would show similar deficits in their lexical, semantic or syntactic processing in sentence comprehension.

The Chinese language uses a logographic writing system in which the basic orthographic units, the characters, correspond directly to morphemic meanings and to syllables in the spoken language. With some exceptions, each character represents one morpheme and has one pronunciation, although different characters may have the same pronunciations. Because the number of syllables used in the language is limited to about 1300 whereas the number of commonly used morphemes is about 5000, Mandarin Chinese has a great many homophonic morphemes and homophonic characters. These homophones may or may not have similar orthographic forms. For example, 因 (*because of*) and 阴 (*negative*) have the same pronunciation, /yin1/ (with the number indicating the lexical tone), but their visual forms are different; 诚 (*honest*) and 城 (*city*) share the pronunciation, /cheng2/, and part of the visual forms (i.e., the radical 成, /cheng2/, *success*, which is a meaningful character by itself). Orthographically similar characters, however, may or may not have similar pronunciations (e.g., 服 /fu2/, *clothes*, and 报/bao4/, *newspaper,* having different pronunciations; 诚 (*honest*) and 城 (*city*) having the same pronunciation). Moreover, homophonic or orthographically similar characters usually have no semantic relations between them.

Several behavioral studies demonstrated that Chinese dys-
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Table 1 – Experimental design and sample stimuli

Condition	Sentence example
A. Orthographic	过新年，孩子们都穿上漂亮的衣报（衣服）. Guoxinnian, haizimen dou chuanshang piaoliang de yibao (yifu). In the new year's day, children all dress up with beautiful YIBAO (CLOTHES).
B. Homophonic	节假日，人们喜欢到郊外观赏自然风井（风景）. Jiejianri, renmen xihuan dao jiaowai guanshang ziran fengjing (fengjing). In holidays, people like to go out of town to enjoy the natural FENGJING (SCENE).
C. Baseline	刮大风时，我出门都要穿挡风的风衣. Guadafengshi, wo chumen douyao chuan dangfeng de fengyi. In windy days, I will dress an OVERCOAT.

Words in brackets were the base compound words from which the critical nonwords were created.

orthographic skills and in rapid naming. At the neurophysiological level, Meng et al. (2005) showed that Chinese dyslexic children have smaller mismatch negativities (MMNs) than normal controls to auditory stimuli deviating in initial consonants or vowels from the standard syllables and to stimuli deviating in temporal information.

In order to investigate the neurophysiological markers of the potential deficits in processing orthographic and phonological information in sentence reading, we recorded ERPs when Chinese-speaking dyslexic children and the matched normal controls were presented, word-by-word, with sentences that ended with the critical two-character compound words. The crucial manipulation was on the second characters of these compounds (see Table 1), such that the correct characters were replaced by characters which were orthographically similar to, but phonologically different from the base characters (in the orthographic condition), or by characters which were homophonic to, but orthographically different from the base characters (in the homophonic condition). This manipulation resulted in sentences ending with compound nonwords. Although the incorrect input characters by themselves would be able to access the corresponding morphemic representations in the lexicon (Zhou and Marslen-Wilson, 2000a; Zhou et al., 1999), the combinations of the first, correct characters and the second, incorrect characters in the homophonic and orthographic conditions could not activate strongly the semantic representations of the base words in the lexicon and this would result in difficulties in integrating the current input with the prior sentential context. Moreover, because the base words, the morphemes corresponding to the input characters and the morphemes corresponding to the replaced critical characters in the base words were all nouns (see the Method section), the morphological processes involved in processing the compound nonwords in the homophonic and orthographic conditions should be similar and any differential ERP effects between the conditions could only be attributed to the impact of orthographic and phonological mismatches between the input characters and the base words upon semantic processes. Given the previous studies concerning the processing of semantically incongruent words in Western languages or scripts for dyslexics or language-impaired individuals (e.g., Helenius et al., 1999; Neville et al., 1993; Robichon et al., 2002; Sabisch et al., 2006) and given the findings in Liu et al. (2003) and Valdes-Sosa et al. (1993) for Chinese orthographic and phonological processing in individually presented words, we predicted that, for both the dyslexic and the normal participants, the N400 component for the critical stimuli should be more negative-going for the orthographic and homophonic conditions than for the baseline condition. Importantly, depending on whether the orthographic or phonological information is used predominantly to constrain access to lexical semantics (Zhou and Marslen-Wilson, 1999, 2000b), the orthographic or phonological mismatch between the input words and the base words could elicit differential N400 effects between the experimental conditions for the two groups of participants. There could also be differences in the P200 component between the conditions and between the participant groups.

2. Results

2.1. Behavioral data

For reaction times (RTs) and error rates (see Table 2) in the semantic acceptability judgment task, 2 (dyslexic vs. normal) × 3 (orthographic vs. homophonic vs. baseline) ANOVAs were conducted. For RTs, the main effect of participant group was significant, $F(1, 25) = 4.54$, $p < 0.05$. RTs for the dyslexic group (1428 ms) were significantly slower than for the control group (1248 ms). The main effect of experimental condition was not significant, $F(2, 50) = 1.91$, $p > 0.1$. However, the interaction between participant group and experimental condition was significant, $F(2, 50) = 4.06$, $p < 0.05$. Further test showed that RTs in the orthographic and homophonic conditions for the dyslexic group were significantly slower ($p < 0.01$) than RTs for the control group. For error rates, the main effect of participant group was significant, $F(1, 25) = 18.98$, $p < 0.001$, with more errors committed by the dyslexic group (29%) than by the control group (15%). The interaction between participant group and experimental condition was significant, $F(2, 50) = 4.77$, $p < 0.05$. Further tests showed that

Table 2 – Mean RTs and error percentages, with standard deviations (in parenthesis), for the control and the dyslexic groups

	Mean RT (ms)		Error (%)	
	Control	Dyslexic	Control	Dyslexic
Orthographic	1216 (173)	1467 (251)	15 (11)	31 (12)
Homophonic	1261 (214)	1472 (264)	14 (13)	33 (13)
Baseline	1266 (208)	1346 (294)	16 (7)	22 (10)

Sentences in the baseline condition required "yes" responses while sentences in the orthographic and the homophonic conditions required "no" responses in the semantic acceptability judgment.

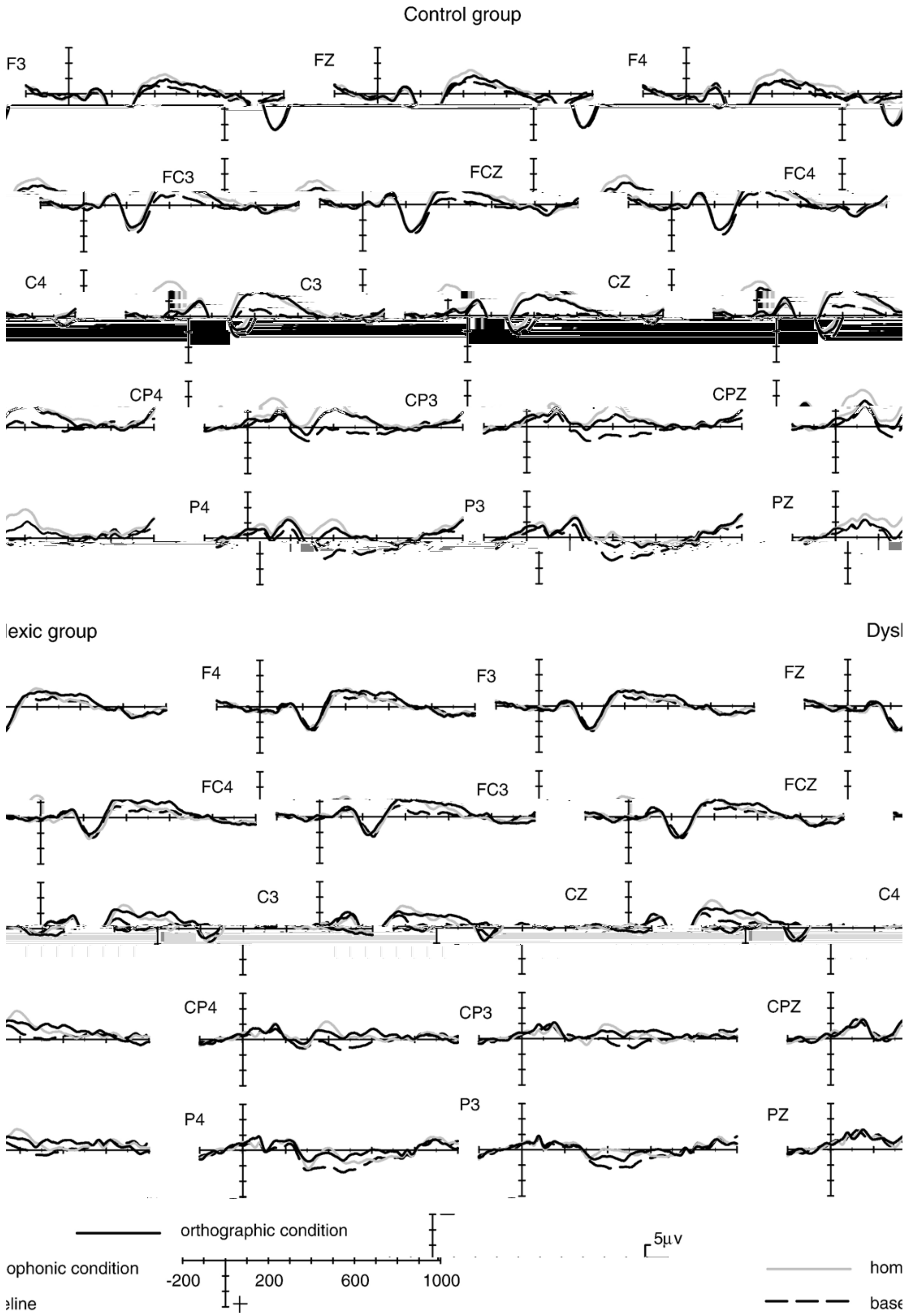

Fig. 1 – Grand average ERPs for the two participant groups at 15 exemplar electrodes. The solid line represents the orthographic condition, the grey line for the homophonic condition and the broken line for the baseline condition.

the dyslexic children had higher error rates than the normal controls in the orthographic ($p<0.01$) and the homophonic ($p<0.01$) conditions, but not in the baseline condition. Moreover, while the error rates did not differ between the three experimental conditions for the normal controls ($p>0.1$), the error rates in the orthographic and homophonic conditions were significantly higher than in the baseline condition ($p<0.05$) for the dyslexic children. These findings demonstrated that the dyslexic participants have deficits in detecting orthographic and phonological anomalies of individual characters in sentences.

2.2. ERP data

We investigated the general morphology of ERPs by averaging ERP responses to the critical sentence-ending stimuli in different conditions. In both the orthographic and the homophonic conditions, the character mismatches elicited an N100-P200-N400 pattern at all electrodes, with the 50- to 150-ms time window for the early negativity (N100, peaking at 129 ms); the 150- to 300-ms time window for the positivity (P200, peaking at 244 ms); the 300- to 500-ms time window for the N400 component (peaking at 406 ms; see Fig. 1). Statistical analyses were conducted separately for the peak amplitudes and peak latencies of N100 and P200 and for the mean amplitudes in the time window of 300–500 ms. The participant group was treated as a between-participant factor and the experimental condition, anterior/posterior location (FC3, F3, FCz, Fz, FC4, F4/ CP3, P3, CPz, Pz, CP4, P4), laterality (left: FC3, F3, CP3, P3; midline: FCz, Fz, CPz, Pz; right: FC4, F4 CP4, P4) and electrode were treated as four within-participant factors. The time course of differential effects between experimental conditions and between participant groups were also examined. The average number of trials included in the ERP analysis, after rejecting judgment errors and ERP artifacts, was 41 (35–50), 39 (33–53), 45 (38–55), respectively, in the orthographic, homophonic and baseline conditions for the dyslexic group and 49 (33–58), 49 (34–57), 49 (44–54) for the control group. Since the statistical analyses for N100 did not produce any significant results, we did not report them here.

2.2.1. P200

ANOVA for the peak amplitudes revealed no main effect of participant group, $F(1, 25) < 1$, nor a main effect of experimental condition, $F(2, 50) = 1.11$, $p > 0.1$, but a main effect of anterior/posterior location, $F(1, 25) = 101.95$, $p < 0.001$. The interaction between experimental condition and anterior/posterior location was significant, $F(2, 50) = 6.07$, $p < 0.01$. Further tests showed that the peak amplitude for the homophonic condition was less positive ($p = 0.054$) than the amplitude for the baseline condition in the posterior regions (CP3, P3, CPz, Pz, CP4, P4).

ANOVA for the peak latencies found a significant main effect of experimental condition, $F(2, 50) = 5.01$, $p < 0.005$, with the peak for the homophonic condition appeared earlier (235 ms) than the peak for the baseline condition (245 ms). The peak latency for the orthographic condition (241 ms) did not differ significantly from either of the two conditions. No other significant results were obtained.

2.2.2. N400

ANOVA conducted for the average amplitudes in the N400 window found a significant main effect of experimental condition, $F(2, 50) = 13.17$, $p < 0.001$, with the overall mean amplitudes most negative for the homophonic condition (−4.24 μV), less so for the orthographic condition (−3.17 μV) and even less so for the

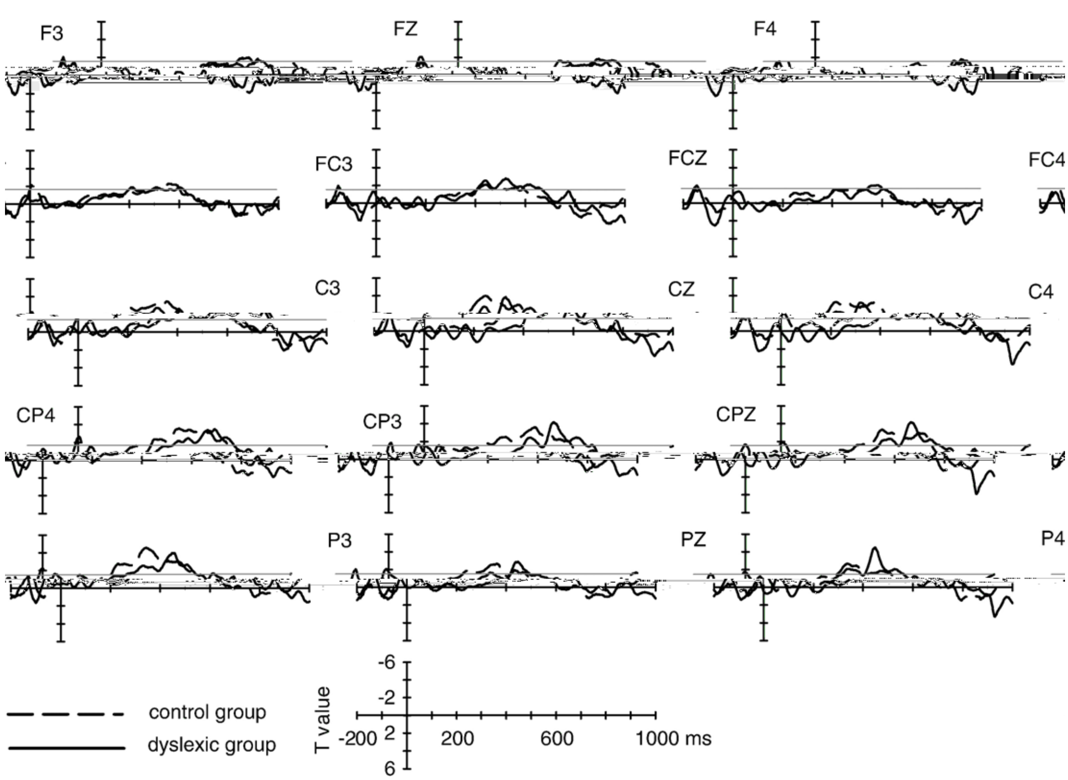

Fig. 2 – Point-by-point *t*-tests contrasting the orthographic condition and the baseline for the control group (broken line) and the dyslexic group (solid line), time-locked to stimulus onset. Note that the vertical calibration bar represents *t* value; the line above horizontal calibration bar marks the 0.05 significance level.

baseline condition (−0.39 μV). The main effect of anterior/posterior location was significant, $F(1, 25)=23.48$, $p<$

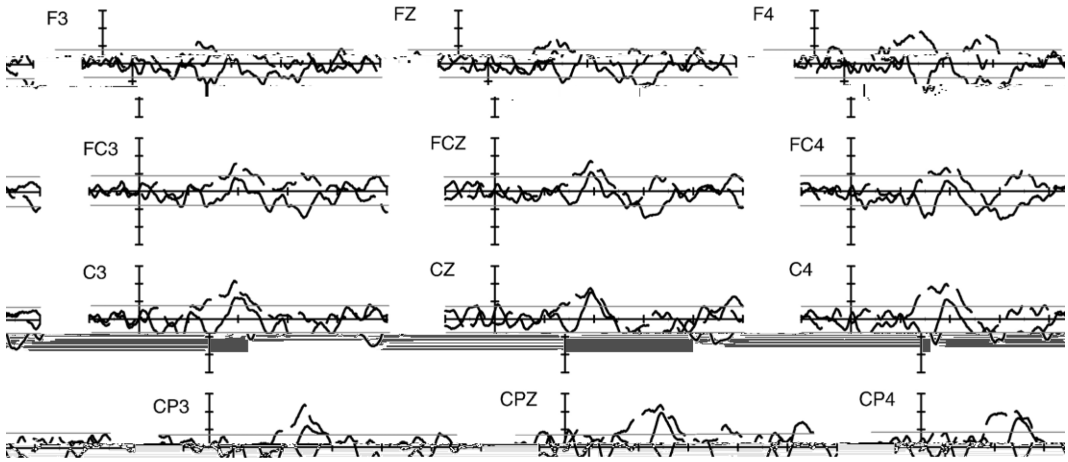

Fig. 4 – Point-by-point *t*-tests contrasting the homophonic and the orthographic conditions for the control group (broken line) and the dyslexic group (solid line), time-locked to stimulus onset. Note that the vertical calibration bar represents *t* value, the line above and down *x*-axis marks the 0.05 significance level. The negative *t* indicates that the homophonic condition was more negative than the orthographic condition, and the positive *t* indicates that the orthographic condition was more negative than the homophonic condition.

Similarly, the contrast between the homophonic and the baseline conditions showed significant negative *t* values for approximately 300 ms for the normal controls, beginning at about 274 ms and ending at about 573 ms poststimulus onset (Fig. 3). However, for the dyslexic group, the same contrast had a much narrower span (approximately 100 ms) of significant negative *t* values, beginning at about 369 ms and ending at about 488 ms poststimulus onset. It is also clear from Fig. 4 that while the homophonic and the orthographic conditions showed little difference in the mean ERP amplitudes for the dyslexic group (except between 372 and 423 ms), the homophonic condition was more negative than the orthographic condition for the control group in the time window of 274–452 ms. But in a later time window of 531–676 ms, the orthographic condition was more negative than the homophonic condition for the dyslexic group, although not for the control group. These results suggested the functioning of orthographic and phonological information in Chinese sentence reading has different time courses for normal and dyslexic children.

The above point-by-point tests did not allow us to evaluate statistically the between-group differences in the timing of the onset and offset of the differential effects between experimental conditions. We therefore applied a jackknife procedure (Miller et al., 1998; Ulrich and Miller, 2001) to the averaged mean amplitudes across electrodes at the central–posterior regions (C3, CZ, C4, CP3, CPZ, CP4, P3, PZ, P4) and defined the criteria for statistical significance in relative terms (Miller et al., 1998). The onset and offset of the differential effects reaching significance were thus defined as the points equal to the half of the peak amplitudes of the differential effects. This procedure was carried out for the potential differential effects in the time window of 0–1000 ms, using unweighted means ANOVA and the corrected *F* (Keselman et al., 1995; Miller et al., 1998; Ulrich and Miller, 2001). Although this procedure did not give us the onsets and offsets of differential effects with exactly the same timing as the above point-by-point *t*-tests, the general patterns were the same for the two ways of time course analysis.

With this procedure, the onsets for the differential effect contrasting the homophonic and the baseline conditions were 288 ms and 379 ms, respectively, for the control and the dyslexic groups. The difference between the two onsets were statistically significant, $F(1, 25) = 7.32$, $p < 0.05$. The offsets for the differential effect contrasting the homophonic and the baseline conditions were 540 ms and 524 ms, respectively, for the control and the dyslexic groups. But the difference here was not significant, $F(1, 25) < 1$. For the differential effect between the orthographic and the baseline conditions, the onsets were 301 ms and 413 ms, respectively, for the control and the dyslexic groups, and the difference here was significant, $F(1, 25) = 11.14$, $p < 0.01$. The offsets were 596 ms and 650 ms, respectively, for the two groups, with no significant difference between them, $F(1, 25) = 2.5$, $p > 0.1$.

3. Discussion

Taking into account the analyses of both peak amplitudes, peak latencies and mean amplitudes over different time windows, we summarize the findings as follows. In the time window (150–300 ms) defined for P200, we found no overall differential effects between the two groups of participants, although across the two groups, the peak amplitude for the homophonic condition tended to be less positive than that for the baseline condition in the posterior regions (CP3, P3, CPz, Pz, CP4, P4) and the peak latencies tended to be increasingly longer over the homophonic, orthographic and baseline conditions. In the time window (300–500 ms) defined for N400, while the dyslexic children in general showed no differences between experimental conditions, for the control group, the mean amplitudes were increasingly more negative-going over the baseline, orthographic and homophonic conditions. Moreover, the mean amplitude of the N400 component in the homophonic condition was less negative-going for the dyslexics than for the controls. In the more detailed time course analyses, relative to the baseline, the negative effects for both the orthographic and the homophonic conditions appeared later, at the central–posterior regions and for the N400 component, for the dyslexics than for the controls, but these differential effects ended at approximately the same times for the two groups of participants. Moreover, while the homophonic condition was more negative-going than the orthographic condition for the controls in the time window of 274–452 ms, this effect was observed at fewer electrodes for the dyslexic children and in a narrower time window (372–423 ms); additionally, the orthographic condition was more negative-going than the homophonic condition for the dyslexic children in a later time window of 531–676 ms.

The ERP patterns for orthographic and phonological processing in the normal controls demonstrate that, compared with the phonological information, the orthographic information plays a more important role in constraining initial lexical processing and access to lexical semantics (Cho and Chen, 1999; Zhou and Marslen-Wilson, 1999, 2000b). As we reviewed earlier, in a phonological judgment task, Liu et al. (2003) found that orthographically similar, but phonologically unrelated pairs of Chinese characters produced a smaller P200 than the completely unrelated pairs, suggesting that P200 is sensitive to early orthographic processing. In this study, we found that, at central–posterior electrodes, the critical characters in the homophonic condition, which differed from the base characters in orthographic forms, showed a less positive P200 component and an earlier peak latency than the characters in the baseline condition. On the other hand, the phonological mismatch between the critical and the base characters in the orthographic condition did not show a P200 effect at all in this experiment, consistent with Liu et al. (2003) who did not find an earlier effect for the homophonic, but orthographically unrelated pairs in a semantic judgment task. Taken together, these results on P200 suggest that in reading logographic Chinese, compared with the phonological mismatch, the orthographic mismatch between the input and the underlying representation is generally detected earlier by the brain.

Indeed, the stronger orthographic constraints on lexical processing may continue to function at the later stage of semantic processing. Both the mismatch in orthographic information and the mismatch in phonological information between the critical characters and the base characters produced N400 effects for the normal readers in this study. However, the homophonic condition, which had the orthographic mismatch, produced a stronger N400 effect than the orthographic condition, which had mostly the phonological mismatch. The very existence of the N400 effects for the orthographic and homophonic conditions indicates that the incorrect orthographic or phonological input causes difficulties in accessing and integrating the lexical semantics of the compound words (for a review, see Kutas and Federmeier, 2000). The stronger N400 effect for the homophonic condition than for the orthographic condition suggests further that constraints on lexical-semantic processing are stronger from the orthographic information provided by the homophonic characters than from the phonological information provided by the orthographically similar characters. The orthographic information plays a stronger role than the phonological information in lexical processing in reading Chinese, even though orthographic and phonological processing are usually interactive in constraining access to lexical semantics (Zhou and Marslen-Wilson, 1999, 2000b).

More pertinent to the main purpose of this study, we found differential ERP responses to the orthographic and phonological mismatches between the critical and the base characters for the two groups of participants. While the homophonic and orthographic conditions produced significant effects, relative to the baseline, for the normal controls on the P200 and N400 components, such effects were generally absent for the dyslexic children. Although the more detailed time course analyses did reveal differential effects for the dyslexics between the experimental conditions at the central–posterior regions, these effects (over the N400 time window) were generally weaker, and with later onsets, than the effects for the controls. The weaker responses in the dyslexic children to orthographic and homophonic mismatches suggested that, compared with normal children, dyslexic children have deficits in detecting misinformation conveyed by the input characters during sentential comprehension. It is possible that Chinese dyslexic children have less stable orthographic and phonological representations in the lexicon, as demonstrated in behavioral studies (Meng, 2000; Shu et al., 2003a). With less well specified links between orthographic, phonological and semantic representations in the lexicon, the (slightly) distorted orthographic or phonological input is able to activate the underlying representations, hence causing no strong N400 effects.

Although Chinese dyslexic children, compared with normal children, are not efficient in initial phonological and orthographic processing, they comparatively rely more on phonological than on orthographic information to access lexical semantics, in opposite to normal children. This argument was supported by the comparison between ERP responses in the homophonic and orthographic conditions. While the two groups of participants did not differ in the mean amplitudes of N400 for the orthographic condition, which had the phonological mismatch between the input and the base words, the dyslexic children showed less negative-going N400 component than the normal controls in the homophonic condition, which had the orthographic mismatch. This dissociation suggests that, comparatively, the dyslexic children had less severe deficits in phonological processing than in orthographic processing. Moreover, in a later time window of 531–676 ms, the homophonic condition was actually less negative-going than the orthographic condition for the dyslexic children, suggesting that the phonological information concerning the base characters provided by the input characters in the homophonic condition helped the dyslexic children to access the semantics of the base words and hence to reduce the magnitude of the negativity in the later time window.

The present findings of weak negative effects (e.g., N400) for the homophonic and orthographic conditions for the dyslexic group than for the control group appear to be inconsistent with previous studies on dyslexics in alphabetic scripts. Using rhyme judgment tasks, a number of studies (e.g., Ackerman et al., 1994; Lovrich et al., 1997; McPherson et al., 1996, 1998) observed *stronger* N400 components for the dyslexics than for the controls (but see Lovrich et al., 2003). However, the apparent inconsistency was likely to be caused by the experimental tasks which tap into different levels of lexical processing. On the other hand, in sentence comprehension, Robichon et al. (2002) found that the semantically incongruent words elicited larger N400 components and a larger N400 effect for dyslexics than for the controls (also Neville et al., 1993 for language-impaired children; but see Helenius et al., 1999), suggesting that dyslexic readers have difficulties in integrating word meaning into sentence representation. Given the characteristics of the experimental design, the weak or general absence of the N400 effect for the orthographic and the homophonic conditions for the dyslexic children in this study demonstrates their deficits in using phonological and orthographic information to constrain lexical access. It would be interesting to conduct further experiments in Chinese, in which the input mismatches the underlying representation along both orthographic and phonological dimensions, as the above studies with alphabetic scripts. It would also be interesting to conduct experiments with alphabetic scripts, in which the phonological and orthographic correspondences with the underlying representations are systematically manipulated and the relative deficits in dyslexic readers in using phonological and orthographic information to constrain lexical processing can be compared (see Connolly et al., 1995; Helenius et al., 1999; Niznikiewicz and Squires, 1996 for the initial efforts).

To conclude, by using the ERP technique to measure brain responses to the mismatches between orthographic and phonological input and the underlying representations in the lexicon, we demonstrate that Chinese dyslexic children have deficits in processing orthographic and phonological information conveyed by the characters and, compared with normal children, and they rely more on phonological information to constrain access to lexical semantics.

4. Experimental procedures

4.1. *Participants*

Seventeen dyslexic children and 13 normal school children were selected and tested. They were screened from several primary schools in Beijing. None of the participants had a history of neurological or emotional disorders. All the participants were right-handed and had normal hearing and normal or corrected-to-normal vision. The parents of all the participants gave their informed consent for the children to take part in the experiment. These children were accompanied by their parents to the ERP laboratory. The data of three participants had to be excluded from further analysis because one participant showed anomalous EEG waveforms throughout the experiment, one committed too much response errors (67%) and one had too many artifacts in the EEG data.

The dyslexic children were selected according to a number of tests: vocabulary size, reading fluency and Raven's Standard Progressive Matrices tests (see also Shu et al., 2006). In the standardized *vocabulary test* (Wang and Tao, 1996), 210 Chinese characters (i.e., morphemes) were divided into 10 levels according to their frequencies in usage and were administered to 924 fourth and fifth grade school children. These children were asked to write down a compound word based on a constituent morpheme provided orally. The performance was measured by the total number of correct characters (morphemes) that the participants could make use of in word-composition. The *Reading fluency test* included 95 sentences or short paragraphs, each paired with 5 pictures describing some events. The participants were asked to read each sentence and to select one picture that best described the meaning of the sentence. They were encouraged to complete as many sentences as possible within 10 min. The Chinese city version of Raven's Standard Progressive Matrices test (Zhang and Wang, 1985) was also administered to the school children to examine their nonlinguistic reasoning ability.

The criteria for selecting dyslexic children were that their scores on the vocabulary test were at least one and a half grade below the norm and their scores on the reading fluency test were lower than the mean scores of their grades. Moreover, they should have normal IQs, as measured by the Raven test. By these criteria, 50 out of the 924 children tested (about 5.4%) were classified as dyslexics. The age- and grade-matched normal children were selected from the dyslexic children's peers. Table 3 shows the average scores in the three tests for the two groups of participants. In addition, we conducted

Table 3 – The characteristics of the dyslexic and normal children participating in the experiment

	Dyslexic ($n=14$)	Control ($n=13$)
Age	10 years and 6 months (9 years 9 months to 12 years 4 months)	10 years and 6 months (9 years 6 months to 11 years 4 months)
Sex (male)	6	7
Handedness (right)	14	13
Raven	81% (50–95%)	83% (50–95%)
Vocabulary	1732 (989–2470)	2839 (2592–3248)
Reading fluency	33 (7–51)	60 (46–85)

The two groups of children had equivalent scores in the Raven test, but they differed significantly ($p<0.001$) in the vocabulary and reading fluency tests.

t-tests to examine the possible gender differences in Raven, reading fluency and vocabulary tests and found no differences between the dyslexic girls and the dyslexic boys ($p > 0.1$) or between the normal control girls and the control boys ($p > 0.1$).

4.2. Stimuli

4.2.1. Stimuli and design

The experiment had three conditions: the orthographic condition; the homophonic condition; and the correct, baseline condition. In the former two conditions, the second characters (morphemes) of two-character compound words that could fit with the sentence context were replaced with characters that were orthographically similar or homophonic to the original characters, resulting in compound nonwords. All the correct or incorrect words were embedded at the end of sentences (see Table 1).

Most of the critical characters in the orthographic condition shared their phonetic radicals with the base characters (e.g., 服, /fu2/, *clothes*, 报, /bao4/, *newspaper*), although a few other critical characters showed their orthographical similarity to the base characters by having similar writing patterns (e.g., 龟, /gui1/, *tortoise*, 电, /dian4/, electricity). These orthographic pairs were phonologically dissimilar (with only a few exceptions in which they had the same lexical tones) and had no semantic relations between them. The base characters and the replacing characters in the homophonic condition shared the same onset, rime and lexical tone in their pronunciation (e.g., 尘, /chen2/, *dust*, 晨, /chen2/, *morning*), but they had no orthographic or semantic relations between them. Moreover, the replacing characters, the base characters, and the base words were all nouns.

Sixty sentences were included in each of the three experimental conditions after pretests (see below). The mean frequencies of the base words from which the critical compound nonwords in the orthographic and homophonic conditions were derived and the frequency of critical words in the baseline conditions were 43, 66 and 115 per million, respectively. The character frequencies for the initial characters of the two-character words or nonwords were 1357, 1200 and 1011 per million, respectively, for the three conditions. The visual complexity, in terms of the number of strokes, was also matched for the initial characters of the three groups of compound (non)words, with the mean scores of 7.3, 7.4 and 7.5 per character respectively. The properties of the critical, second characters are summarized in Table 4. All the words and characters were selected from a corpus based on the textbooks used in primary schools in Beijing (Shu et al., 2003b).

Table 4 – The mean frequencies (per million) and numbers of strokes for the critical characters and the characters in the original base words

Conditions	Character frequency		Number of stroke	
	Original	Critical	Original	Critical
Orthographic	478	465	8.0	8.3
Homophonic	427	491	8.9	8.1
Baseline	440	440	8.4	8.4

4.2.2. Pretests of stimuli

Prior to the selection of the final set of sentences included in the experiment, the potential stimuli underwent two pretests. The cloze probability test was to make sure that the base words in the three conditions were equally predictable. The orthographic similarity judgment test was to assess the degree of orthographic similarity between the original characters and the replacing characters in the orthographic condition.

In the cloze probability test, the potential sentences for the three conditions were printed in random order, with the final compound words omitted. Fifty-three school children who did not participate in the ERP test were asked to complete the sentences as soon as possible with words that come into their minds. The predictability for the base words was 72%, 76% and 71%, respectively, for the orthographic, the homophonic and the baseline conditions. For the orthographic similarity judgment, the 60 pairs of the replacing characters and their base characters and 60 pairs of orthographic dissimilar filler characters were printed in random orders and the 53 participants who were asked to judge, by circling a number on a 5-point scale, the similarity between the pairs of characters. The number "5" represented "very similar" while the number "1" represented "totally dissimilar". The mean score for the 60 pairs of the base characters and the replacing characters in the orthographic condition was 3.5.

4.3. Procedure

Participants were tested individually in a sound-attenuating and electrically shielded booth. They were seated in a comfortable sofa in front of a computer monitor. Before the experiment started, the participants performed a practice block of 15 sentences and they were told to relax as much as possible without moving their heads. Sentences were presented at the center of the computer screen word by word. Each word was presented for 500 ms. The sentence-final critical word (nonword) was presented together with the mark of full stop. Participants had 2500 ms to make the acceptability judgment for the sentence. The experiment consisted of 8 testing blocks, with each block having 40 sentences. Sentences from different conditions and the filler sentences were randomized before being presented to the participants. The whole experiment lasted for about 2 h.

Participants were asked to judge whether each sentence was semantically acceptable. In order to balance the potential "yes" and "no" responses, 100 correct and 40 semantically unacceptable sentences were added to the critical sentences. The unacceptable filler sentences had incorrect characters in the middle of sentences to prevent the participants from forming response strategies based on the position of critical words in sentences.

4.4. EEG recording and data analyses

The EEG data were recorded and analyzed by NeuroScan 4.3.1. The EGG was recorded with 32 electrodes based on the advanced International 10–20 system. The vertical electrooculogram (VEOG) was recorded from electrodes placed above and below the right eye. The horizontal EOG (HEOG) was recorded from electrodes placed 1.5 cm lateral to the left and right external canthi. The linked bilateral mastoids served as reference points and the AFz electrode on the cap served as ground. Electrode impedance was kept below 5 kΩ. The EEG was amplified (band pass 0.05–70 Hz) and digitized at a sampling rate of 500 Hz. The continuous EEG recordings were epoched off-line (−200 to 1000 ms), with the onset of the final word in each sentence as 0 ms. They were averaged separately off-line for each condition. Any trails with EOG artifacts greater than ±75 μV were excluded from further analysis.

For the statistical analysis of the ERP effects, only trials with correct responses in the sentence acceptability judgment were analyzed. Peak amplitudes and latencies of P200 were obtained in the 150- to 300-ms time window and the mean amplitudes of N400 were calculated for the window of 300–500 ms. The data were entered into the mixed-design analyses of variance (ANOVAs), with participant group (dyslexic vs. control) as a between-participant factor, experimental condition (orthographic vs. homophonic vs. baseline), anterior/posterior location, laterality (left vs. midline vs. right) and electrode as four within-participant factors. The electrodes selected were grouped into anterior left (FC3, F3), anterior midline (FCz, Fz), anterior right (FC4, F4), posterior left (CP3, P3), posterior midline (CPz, Pz) and posterior right (CP4, P4). Furthermore, to examine the time course of the differential effects between experimental conditions, we conducted point-by-point *t*-tests at each selected electrode from the onset of stimulus presentation. The Greenhouse–Geisser correction was applied when appropriate.

Acknowledgments

This study was supported by grants from China National science Foundation (30200078, 30070260, 30470569, 60435010). We thank Drs. Phillip J. Holcomb and Marianna Eddy for their suggestions on data analyses and two anonymous reviewers for their constructive comments on an earlier version of the manuscript.

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