available at www.sciencedirect.com

ScienceDirect

www.elsevier.com/locate/brainres

BRAIN RESEARCH

Research Report

ERP correlates of the development of orthographical and phonological processing during Chinese sentence reading

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

[a]*Department of Psychology, Peking University, Beijing 100871, China*
[b]*State Key Laboratory of Cognitive Neuroscience and Learning, Beijing Normal University, Beijing 100875, China*
[c]*Learning and Cognition Laboratory, Capital Normal University, Beijing 100037, China*

ARTICLE INFO

Article history:
Accepted 16 April 2008
Available online 27 April 2008

Keywords:
Chinese reading
Phonological processing
Orthographic processing
ERP
N400
Semantic access

ABSTRACT

An event-related potential (ERP) experiment was conducted to investigate the development of orthographic and phonological processing during Chinese sentence reading between school children and adult readers. 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. ERP results showed that, across participant groups, the peak of P200 appeared earlier for the homophonic condition than for the orthographic and the baseline conditions. Importantly, for both child and adult readers, relative to the baseline, both orthographic mismatch in the homophonic condition and phonological mismatch in the orthographic condition elicited N400 effects. While for adults these effects appeared to be equal in size, the peak of the N400 component appeared earlier for orthographic mismatch than for phonological mismatch. For children the N400 effect was larger for orthographic mismatch than for phonological mismatch. The N400 component was also more negative for children than for adults in the homophonic condition, and its peak appeared later for children than for adults in the homophonic and the baseline conditions. Moreover, the offset of the N400 effects appeared earlier for adults than for children and for orthographic mismatch than for phonological mismatch. These findings suggest that both Chinese adult readers and school children rely more on orthographic information than on phonological information to access lexical semantics in reading Chinese sentences. However, the differential effects between orthography and phonology may have different ERP manifestations in adults and children.

1. Introduction

The event-related potential (ERP) technique has been extensively used to investigate the neurophysiological mechanisms of language development, from infants' language acquisition (Friedrich and Friederici, 2006; Friederici and Hahne, 2001; Hahne et al., 2004; Mills et al., 1994; Molfese, 1990; see Friederici, 2006 for a review) to school children's auditory or visual language comprehension (Breznitz and Leikin, 2000; Holcomb et al., 1992; Holcomb and Neville, 1990, 1991; Neville et al., 1993). Such

* *Corresponding author*. Department of Psychology, Peking University, Beijing, 100871, China. Fax: +86 10 6276 1081.
E-mail address: xz104@pku.edu.cn (X. Zhou).

0006-8993/$ – see front matter
doi:10.1016/j.brainres.2008.04.052

studies demonstrate clear developmental courses from children to adults in phonological (Bonte and Blomert, 2004; Brem et al., 2006; Coch et al., 2002, 2005; Grossi et al., 2001; Licht et al., 1988), semantic (Atchley et al., 2006; Holcomb et al., 1992; Juttonen et al., 1996) and syntactic processes (Oberecker et al., 2005; Weber-Fox and Neville, 1998; Weber-Fox et al., 2006). In this study, we examine the neurophysiological correlates of the development of orthographic and phonological processing during Chinese sentence reading by comparing, between school children and adult readers, ERP responses to orthographic and phonological mismatches between the input Chinese characters and the base characters embedded in sentence-final words. This study continues our earlier investigation into the ERP manifestation of the deficits in orthographic and phonological processing in Chinese dyslexic children (Meng et al., 2007).

The Chinese language uses a logographic writing system in which the basic orthographic units, the characters, correspond directly to morphemic meanings and to syllables in the spoken language. With some exceptions, each character represents one morpheme and has one pronunciation in isolation, although different characters may have the same pronunciations. Homophonic characters may or may not share graphical forms. For example, 因 (*because of*) and 阴 (*negative*) have the same pronunciation, /yin1/, 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*). Moreover, homophonic or orthographically similar characters usually have no semantic relations between them. These properties of the Chinese writing system allow us to tear apart the roles of orthographic and phonological processes in access to lexical semantics and in semantic integration during sentence reading.

Indeed, these characteristics of the Chinese writing system have been exploited in behavioral studies manipulating orthographic and phonological similarities in stimulus sets and experimental designs (e.g., Chua, 1999; Feng et al., 2001; Perfetti and Zhang, 1995; Xu et al., 1999; Zhou and Marslen-Wilson, 2000a, accepted). These studies, however, produced two schools of thought concerning the role of orthographic and phonological information in processing logographic Chinese. One view, adopted from studies on reading alphabetic scripts, argues that phonology plays a dominant role over orthography in constraining access to lexical semantics in reading Chinese. Unfortunately, the experiments supporting this argument are mostly not replicable (see, for example, Chen and Shu, 2001; Xie and Zhou, 2003). Another view suggests that access to lexical semantics in reading Chinese is driven by both orthographic and phonological information. However, phonologically mediated access is not the predominant or default mechanism for linking visual input with lexical semantic representation. Rather, the two routes – phonological mediation and direct orthographic access – interact with each other in access to semantics even though orthographic information may play a stronger role than phonological information in driving semantic activation (Chen and Shu, 2001; Feng et al., 2001; Xie and Zhou, 2003; Zhou and Marslen-Wilson, 1999, 2000a, accepted).

The latter view is supported by a large number of experiments, including developmental studies examining the relative roles of orthographic and phonological processing in reading Chinese. For example, using an off-line proof reading task in which the crucial characters in the text were replaced with homophonic or orthographically similar characters, Song et al. (1995) observed that school children missed more erroneous homophonic than orthographically similar characters whereas college students showed the opposite pattern. These results imply that Chinese school children may depend more on phonological information than on orthographic information in reading but direct access from orthography to semantic becomes increasingly dominant with the development of reading skills. Similar findings were also obtained for Chinese school children when good and poor readers were compared. When judging the semantic relatedness of a pair of consecutively presented Chinese characters (e.g., *far–near*), a homophone interference effect was found when one of the original, semantically related characters was replaced with orthographically dissimilar homophonic character (see Xu et al., 1999). However, this effect correlated significantly with the level of children's reading skill, with no effect for good readers and a large effect for poor readers (Wang et al., 2000). Another line of research also demonstrated the differential uses of orthographic and phonological information in driving semantic activation. Cho and Chen (1999) asked Korean readers to carry out a semantic categorization task on logographic *Hanja* (Chinese characters) and alphabetic *Hangul* scripts. While less-skilled Hanja readers produced more false positive categorization responses on homophone foils as well as on visually similar foils than their corresponding controls, skilled readers produced only a visual similarity effect but no homophonic effect. For Hangul, both groups of participants displayed homophonic effects. Thus both language proficiency and script difference determine the role of orthographic and/or phonological information in lexical processing.

In the present cross sectional study, we aim to examine the impact of orthographic and phonological information upon lexical semantic activation and its developmental profile by recording ERP responses to orthographic and phonological mismatches between the input characters and the base characters during sentence reading. School children and adult readers 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, base 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, 2000b, accepted; 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 base compounds in the lexicon and this would result in difficulties in integrating the current

Table 1 – Design and sample stimuli

Conditions	Sentence examples
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 (FENGJING).
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 original words from which the critical nonwords were created.

input with the prior sentential context. Moreover, because the base compounds, the morphemes corresponding to the input characters and the morphemes corresponding to the replaced critical characters in the base compounds were all nouns, 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 orthographic and phonological mismatches between the input characters and the base characters upon semantic processes.

Previous studies that manipulated the semantic, phonological, or orthographic properties of the final words in English sentence reading have generally found enhanced N400 components for such mismatches or violations (Connolly et al., 1995; Holcomb et al., 1992; Neville et al., 1993; Niznikiewicz and Squires, 1996). Using the same design and sentences as here, we also observed that orthographic and phonological mismatches elicited more negative-going N400 components, relative to the baseline, at the central-posterior scalp regions for both normal and dyslexic school children (Meng et al., 2007). We therefore predicted that such N400 effects should be observed for both children and adult readers. Indeed it was shown that, for normal school children, 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 and the N400 effect was larger for orthographic mismatch than for phonological mismatch. The crucial question now is to what extent the pattern of ERP effects would be modulated by the proficiency of reading skills.

2. Results

2.1. *Behavioral data*

The participants were asked to judgment whether the sentences they just read were semantically acceptable. Mean reaction times (RTs) and response error rates are shown in Table 2. A 2 (children vs. adults) by 3 (baseline vs. orthographic vs. phonological) ANOVA for RTs found a significant main effect of participant group, $F(1, 24)=21.25$, $p<0.001$, with adults (929 ms) responding faster than children (1248 ms). For error rates, the main effect of participant group was significant, $F(1, 24)=11.98$, $p<0.01$, with children (15.30%) committed more errors than adults (6.50%). No other effects were obtained in either RT or error rate analysis.

2.2. *ERP data*

The number of trials included in the orthographic, the homophonic, and the baseline conditions after rejecting judgment errors and ERP artifacts was 53 (39–58), 53 (45–58), 53 (45–59), and 49 (33–58), 49 (34–57), 49 (44–54) for adult and children groups, respectively. This made sure that the statistical powers concerning the potential effects were roughly equivalent across the two groups of participants and across experimental conditions.

We investigated the general morphology of ERPs by averaging ERP responses to the critical sentence-ending targets in different conditions (see Figs. 1 and 2). The difference waves for the orthographic and homophonic conditions, relative to the baselines, are presented in Fig. 3. In both the orthographic and the homophonic conditions, the character violations elicited a N100–P200–N400 pattern. Statistical analyses were conducted separately for the peak amplitudes of P200 and for the mean amplitudes in the 300–500 ms time window. The peak latencies for P200 and N400 were also examined. 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. Statistical analyses were conducted for both the original data and the normalized data controlling for the typically larger ERP amplitudes in children (see Experimental procedures).

2.2.1. *P200*

ANOVA for the peak amplitudes found no main effect of participant group, $F(1, 24)<1$, but a significant main effect of experimental condition, $F(2, 48)=7.67$, $p<0.01$. Further tests showed that the peak amplitudes for the orthographic (7.26 μV) and the homophonic (6.74 μV) conditions were significantly less positive ($0.05<p<0.1$, $p<0.01$ respectively) than for the baseline condition (8.14 μV). The main effect of anterior/posterior

Table 2 – Mean of RTs (in milliseconds) and error percentages for the adult and child readers

	Mean RT		% Error	
	Adults	Children	Adults	Children
Orthographic	927 (187)	1216 (173)	6.8 (3.6)	15.4 (11.4)
Homophonic	901 (167)	1261 (214)	6.9 (3.9)	14.1 (13.9)
Baseline	961 (187)	1266 (208)	5.8 (6.8)	16.3 (6.7)

Standard deviations are presented in brackets.
Sentences in the baseline condition required "yes" responses while sentences in the orthographic and the homophonic conditions required "no" responses.

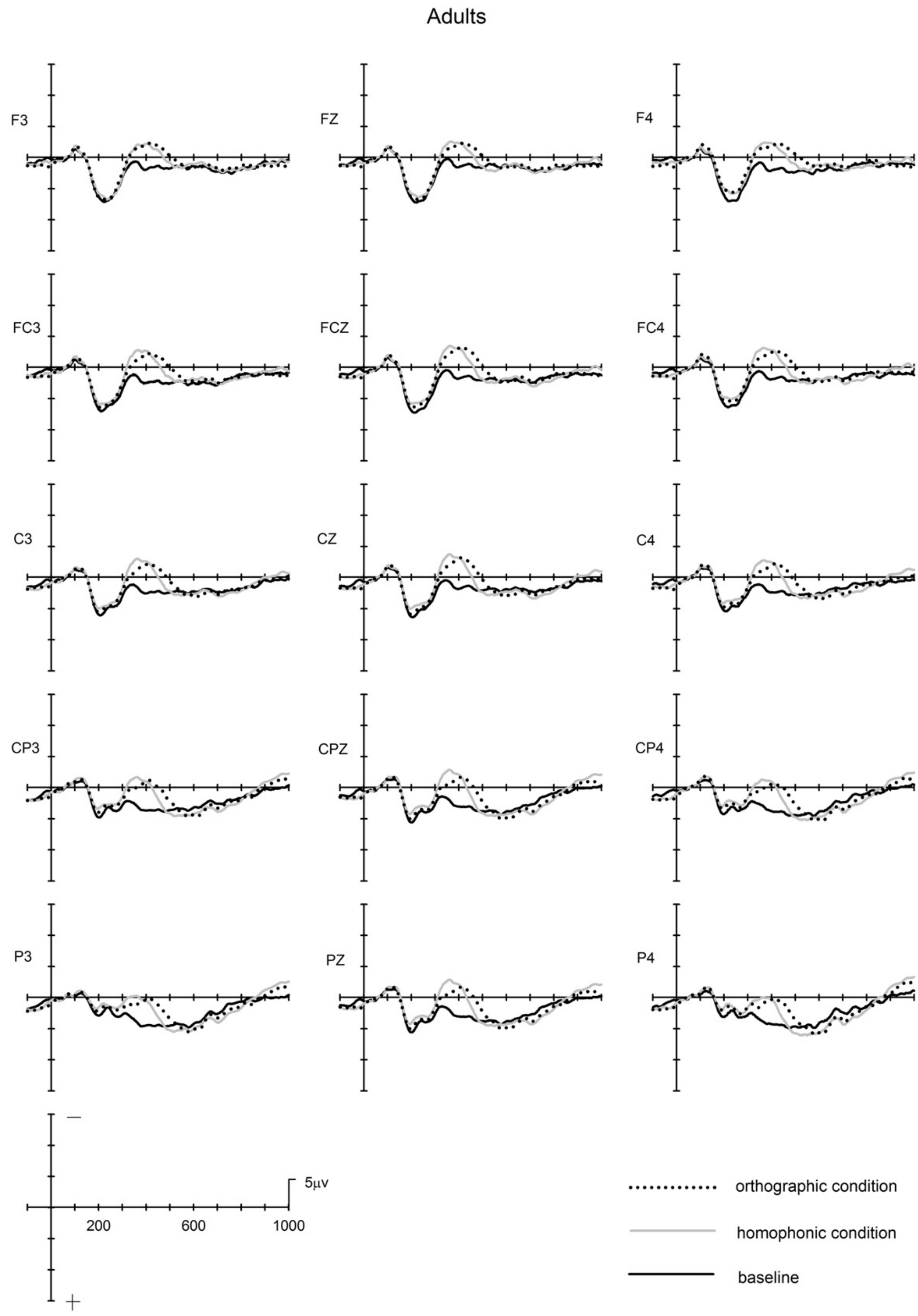

Fig. 1 – Grand average ERPs for the adult participants at 15 typical electrodes. The solid line was for the baseline condition, the dotted line for the orthographic condition, and the gray line for the homophonic condition.

location was significant, $F(1, 24)=28.98$, $p<0.001$, with the anterior regions (9.14 μV) significantly more positive than the posterior regions (5.63 μV). Importantly, the interaction between condition and anterior/posterior location was significant, $F(2, 48)=9.28$, $p<0.001$, so the three-way interaction between participant group, condition, and anterior/posterior location,

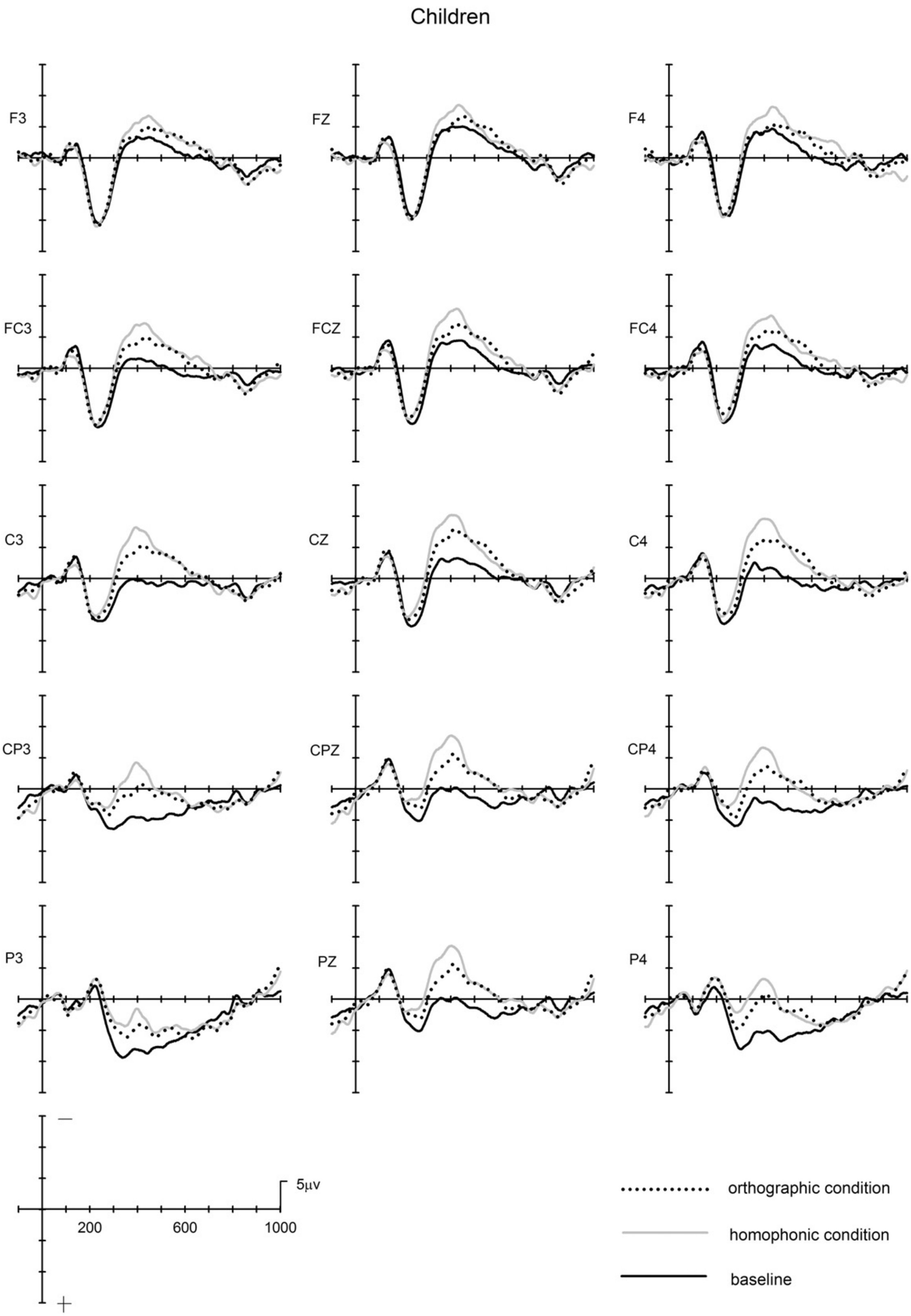

Fig. 2 – Grand average ERPs for the child participants at 15 typical electrodes. The solid line was for the baseline condition, the dotted line for the orthographic condition, and the gray line for the homophonic condition.

$F(2, 48)=7.09$, $p<0.01$. Further tests indicated that, for children, and at posterior regions, the peak amplitudes for the orthographic (5.68 μV) and the homophonic (4.57 μV) conditions were significantly less positive ($p<0.01$) than for the baseline condition (7.76 μV). For adults, only the difference between the homophonic (4.59 μV) and the baseline (5.80 μV) conditions at

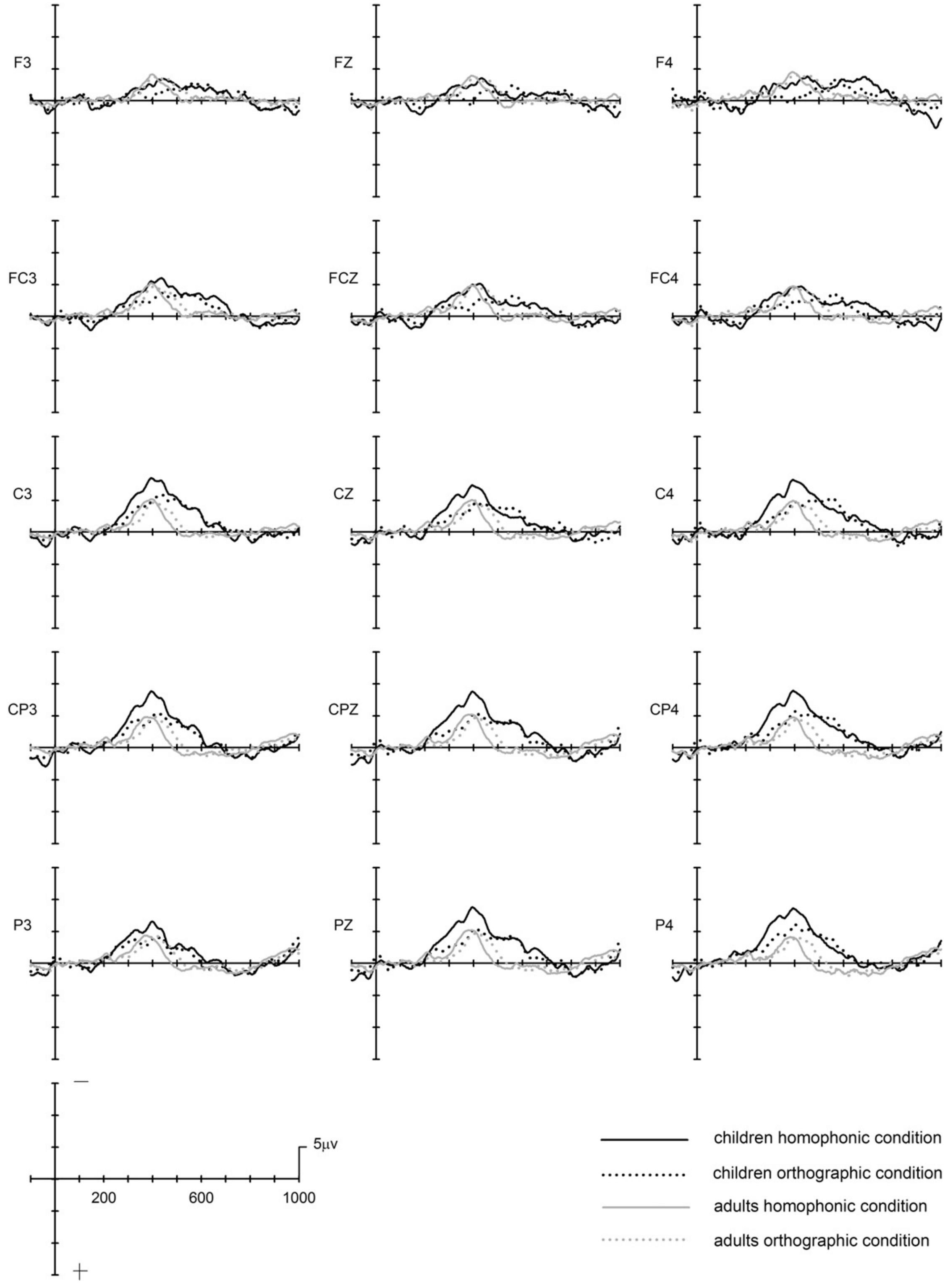

Fig. 3 – Difference waveforms contrasting the homophonic and the baseline conditions and contrasting the orthographic and the baseline conditions for the adult and the child participants.

posterior regions was marginally significant ($0.05<p<0.1$), although the peak amplitude showed a similar trend of increasing over the homophonic, the orthographic and the baseline conditions.

Analyses of the normalized data produced essentially the same pattern of effects. There was no main effect of participant group, F (1, 24) <1, but a main effect of condition, $F(2, 48)=7.66$, $p<0.001$. Further tests showed that the peak amplitudes for the orthographic (5.52 μV) and the homophonic (5.00 μV) conditions were significantly less positive ($p<.05$ or $p<0.01$) than for the baseline condition (6.40 μV). The main effect of anterior/posterior was significant, $F(1, 24)=28.98$, $p<0.001$. Moreover, the interaction between condition and anterior/posterior location was significant, $F(2, 48)=9.28$, $p<0.001$, so the three-way interaction between participant group, condition, and anterior/posterior location, $F(2, 48)=7.09$, $p<0.01$. Further tests found that, for the child participants, the peak amplitudes increased linearly over the homophonic (5.00 μV), the orthographic (5.52 μV) and the baseline (5.85 μV) conditions at posterior regions, with a significant difference between the homophonic and the baseline conditions ($p<0.01$). The adult readers showed a similar trend, with the difference between the homophonic (3.02 μV) and the baseline (4.23 μV) conditions at posterior regions being marginally significant ($0.05<p<0.1$).

Analyses of the peak latencies found a significant main effect of experimental conditions, $F(2, 48)=3.96$, $p<0.05$, with the peak for the homophonic condition (230 ms) appearing earlier ($p<.05$) than the peak for the baseline condition (241 ms). The difference between the homophonic and the baseline condition (243 ms) was more clearly seen at posterior midline sites(222 and 243 ms respectively), as revealed by the three-way interaction between experimental condition, anterior/posterior, and laterality, $F(4, 96)-2.91$, $p<0.05$.

2.2.2. N400

The N400 effects for the orthographic and homophonic conditions, relative to the baselines, can be seen clearly in the difference waves (Fig. 3) and the topographic map (Fig. 4). ANOVA conducted for the mean amplitudes in the N400 window found a significant main effect of participant group, $F(1, 24)=5.31$, $p<0.05$, with the mean amplitude more negative for children (−1.69 μV) than for adults (0.72 μV). Importantly, the main effect of experimental condition was significant, $F(2, 48)=50.95$, $p<0.001$, with the mean amplitude being increasingly more negative over the baseline (1.71 μV), the orthographic (−1.15 μV), and the homophonic (−2.02 μV) conditions ($p<0.01$). Moreover, the interaction between experimental condition and participant group was significant, $F(2, 48)=5.39$, $p<0.01$. Further tests showed that, while both participant groups showed the N400 effects for the orthographic and the homophonic conditions, relative to the baselines (Figs. 3 and 4), only the child group had a significantly more negative mean amplitude for the homophonic condition (−3.96 μV) than for the orthographic condition (−1.96 μV; $p<0.01$), suggesting a larger N400 effect for the former than for the latter condition relative to the baseline (see also Fig. 3); moreover, the mean amplitude in the homophonic condition was significantly more negative for the child participants (−3.96 μV) than for the adults (−0.08 μV; $p<0.01$).

The main effect of anterior/posterior was significant, $F(1, 24)=32.03$, $p<0.001$, with the anterior regions (−2.23 μV) significantly more negative than the posterior regions (1.26 μV). The main effect of laterality was also significant, $F(2, 48)=15.44$, $p<.001$, with the left side (0.54 μV) and the right side (−0.55 μV) significantly less negative than the midline (−1.43 μV). Importantly, the three-way interaction between participant group, experimental condition and anterior/posterior location was significant, $F(2, 48)=5.41$, $p<0.01$. Further tests demonstrated that the differential effect between the two participant groups in the homophonic condition appeared at both anterior and posterior regions ($p<0.01$) and children showed also more negativity than adults in the baseline condition at anterior sites ($p<0.01$). The three-way interaction between participant group, experimental condition and laterality was not significant, $F(4, 96)<1$.

Analyses with the normalized data observed the same pattern of effects, with a marginally significant main effect of participant group, $F(1, 24)=3.11$, $0.05<p<0.1$, and a significant main effect of experimental condition, $F(2, 48)=50.95$, $p<0.001$. Further tests showed that, across the participant groups, the amplitudes for the orthographic (−0.98 μV) and the homophonic (−1.85 μV) conditions were more negative

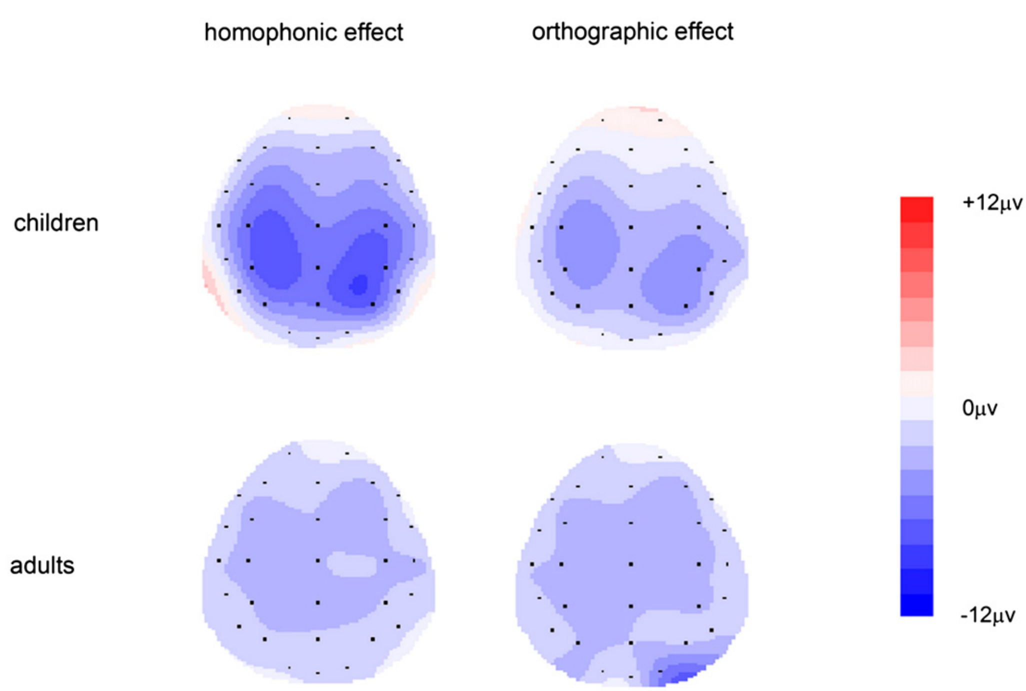

Fig. 4 – Topographic maps for the averaged N400 effects in the 300–500 ms time window for the child and adult participants, contrasting the homophonic or the orthographic condition with the baseline.

($p<0.01$) than the amplitude for the baseline condition (1.88 μV); the difference between the orthographic and the homophonic conditions was marginally significant ($0.05<p<0.1$). Importantly, the interaction between participant group and experimental condition was significant, $F(2, 48)=5.39$, $p<0.01$. Further tests showed that the mean amplitude in the homophonic condition was significantly more negative ($p<0.01$) for children (−3.50 μV) than for adults (−0.19 μV). Moreover, while the amplitudes in the orthographic and the homophonic conditions were more negative ($p<0.01$) than the baselines for both participant groups, showing the N400 effects, only for the child group was the amplitude in the homophonic condition (−3.50 μV) more negative ($p<0.001$) than the amplitude in the orthographic condition (−1.50 μV), indicating a larger N400 effect for the former than for the latter condition. The main effect of anterior/posterior location was significant, $F(1, 24)=32.03$, $p<0.0001$, with more negative ERP responses at anterior regions (−2.06 μV) than at posterior regions (1.43 μV). The interaction between participant group, experiment condition and anterior/posterior location was significant, $F(2, 48)=5.41$, $p<0.01$. Further test showed that the above difference between the two participant groups in the homophonic condition appeared at both anterior and posterior regions ($p<0.05$), while at the same time the child participants showed also more negativity than the adult readers for the baseline condition at anterior sites ($p<0.01$). The main effect of laterality was significant, $F(2, 48)=15.44$, $p<0.001$, with the most negative ERP responses in the midline (−1.27 μV) than at the left (0.71 μV) or right (−0.39 μV) side.

In the analysis of peak latencies, the main effect of participant group was significant, $F(1, 24)=6.51$, $p<0.05$, with the peak appeared earlier for adults (381 ms) than for children (413 ms). The main effect of experimental condition was also significant, $F(2, 48)=4.22$, $p<0.05$, indicating that, relative to the baseline (389 ms), the appearance of the peak was delayed less severely by orthographic mismatch in the homophonic condition (393 ms) than by phonological mismatch in the orthographic condition (409 ms). Importantly, the interaction between participant group and experimental condition was significant, $F(2, 48)=3.83$, $p<0.05$. Further tests showed that the peak appeared earlier for adults than for children in the baseline ($p<0.01$) and the homophonic ($p<0.05$) conditions, but not in the orthographic condition ($p>0.1$). Moreover, for adults, the peak appeared earlier for the homophonic (379 ms) and the baseline (362 ms) conditions ($p<0.05$ or 0.01) than for the orthographic condition (403 ms). The main effect of anterior/posterior location was significant, $F(1, 24)=18.53$, $p<0.001$, with the peak appeared earlier at posterior regions (387 ms) than at anterior regions (407 ms).

In addition, we used the Jackknife-based procedure (Miller et al., 1998; Ulrich and Miller, 2001) to evaluate whether the onsets and offsets of the N400 effects for the orthographic and homophonic conditions differed between the adult and the child participants. The onset and offset of the differential effects reaching significance were defined as the points equating to 60% of the peak amplitudes of the differential effects (Fig. 3), taking into account the starting points of the N400 components illustrated in Figs. 1 and 2. Thus for the child and the adult readers respectively, the onsets of the differential effects contrasting the homophonic and the baseline conditions were 302 ms and 330 ms, and the onsets of the differential effects between the orthographic and the baseline conditions were 327 ms and 363 ms. ANOVA with participant group (adults vs. children) as a between-participant factor and experimental condition (orthographic vs. homophonic) as a within-participant factor found neither a significant main effect of participant group, $F(1, 24)=1.88$, $p>0.1$, nor interaction between participant group and experimental condition, $F<1$, although the main effect of experimental condition was marginally significant, $F(1, 24)=3.11$, $0.05<p<0.1$. These findings suggested that while the differential N400 effects starts at essentially the same time points for the child and the adult readers, the effect for orthographic mismatch in the homophonic condition appeared somewhat earlier than the effect for phonological mismatch in the orthographic condition.

On the other hand, for the child and the adult readers respectively, the offsets of the differential effects contrasting the homophonic and the baseline conditions were 472 ms and 431 ms, and the offsets of the differential effects contrasting the orthographic and the baseline conditions were 567 ms and 477 ms. ANOVA found a significant main effect of participant group, $F(1, 24)=27.71$, $p<0.001$ and a significant main effect of experimental condition, $F(1, 24)=31.75$, $p<0.001$. The interaction between these two factors was marginally significant, $F(1, 24)=3.84$, $0.05<p<0.1$. These findings suggested that it is easier for adult readers than for children to recover from the difficulties in semantic integration led by orthographic or phonological mismatch and it is easier for the processing system to recover from the difficulties led by orthographic mismatch in the homophonic condition than from the difficulties led by phonological mismatch in the orthographic condition.

3. Discussion

ERP results of this cross sectional study on the development of orthographic and phonological processing in Chinese sentence reading can be summarized as follows. The P200 peak amplitude was increasingly more positive over the homophonic, the orthographic, and the baseline condition. This was especially true for children at posterior regions, although the adult participants showed a similar pattern. Across the participant groups, the peak latency was shorter for the homophonic condition than for the baseline, suggesting that orthographic mismatch between the input characters and the base characters can be detected very early. In the 300–500 ms time window, although both orthographic mismatch in the homophonic condition and phonological mismatch in the orthographic condition elicited N400 effects relative to the baselines, these effects showed different patterns for children and adults. For adults, while the orthographic and the phonological effects were equal in size in mean amplitudes, the peak of the N400 component was delayed, relative to the baseline, more severely by phonological mismatch in the orthographic condition than by orthographic mismatch in the homophonic condition. For children, the effect of orthographic mismatch in the homophonic condition was evidently larger than the effect of phonological mismatch in the orthographic condition. Between the participant groups, the mean amplitude of the N400 component in the homophonic condition was more negative for children than for adults, and the peaks of this component in the baseline and the homophonic conditions appeared earlier for adults than for children. Moreover, although the onsets of the N400 effects did not differ between the participant groups, the offsets were much earlier for adults than for children. Across the participant groups, the offsets of the N400 effects were also earlier for orthographic mismatch in the homophonic condition than for phonological mismatch in the orthographic condition. These findings demonstrate differential roles of orthographic and phonological processes in driving semantic activation in both child and adult readers and show clearly the developmental courses of orthographic and phonological processing in reading logographic Chinese.

The differential effects in the P200 component between experimental conditions suggest that this component is related to the orthographic processes in lexical processing and sentence reading. Indeed, the graded effects over the homophonic, the orthographic and the baseline conditions for both groups of the participants demonstrate that the P200 is sensitive to the degree of orthographic mismatch between the input and the underlying representation. Relative to the baseline, the small orthographic mismatch in the orthographic condition elicited a non-significant effect on P200, while the more severe orthographic mismatch in the homophonic condition elicited a larger effect on P200. This interpretation is consistent with earlier studies linking the P200 to lexical processing in reading alphabetic scripts (Barnea and Breznitz, 1998; Carreiras et al., 2005; Dambacher et al., 2006; Martin et al., 2006; Meyler and Breznitz, 2005) and to orthographic processing in reading logographic Chinese (Lee et al., 2007; Liu et al., 2003). Liu et al. (2003), for example, 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.

For both child and adult readers, we observed N400 effects for both the orthographic and the homophonic conditions, relative to the baselines. Given that the N400 effect is commonly thought as reflecting the difficulty in access to semantic representation of the target words and/or in integrating lexical semantics into the sentential or discourse representation (see Kutas and Federmeier, 2000 for a review), the N400 effects observed here show the difficulty of activating the semantic representations of the base words from the incorrect orthographic input. Thus, the difficulty in mapping orthographic (and phonological) input onto the underlying representations of the base words led not only to the earlier P200 effect, reflecting orthographic processing, but also to the later N400 effect, reflecting semantic processing. Here the order of effects in different ERP components over time seems to correspond to the level and time course of lexical processing in reading Chinese (Zhou and Marslen-Wilson, 2000a).

More specifically, for adult readers, we observed equal N400 effects in mean amplitudes for orthographic mismatch in the homophonic condition and for phonological mismatch in the orthographic condition. This may be taken as evidence that orthographic information and phonological information functions in equivalent ways in constraining access to lexical semantics in reading Chinese. However, the finding that the orthographic effect appeared earlier than the phonological effect, both in terms of the peak of the N400 component and in terms of the onset of the N400 effect, suggest that constraints on lexical semantic processing are faster and more efficient from orthographic information provided by the homophonic characters than from phonological information provided by the orthographically similar characters. This argument is consistent with the earlier behavioral studies showing that direct orthographic access dominates over phonological mediation in access to lexical semantics (Chen and Shu, 2001; Cho and Chen, 1999; Zhou and Marslen-Wilson, 1999, 2000a, accepted).

The N400 effects for child participants demonstrated also the importance of orthographic processing in reading for meaning. Instead of the difference in peak latencies, here the N400 effect in mean amplitude was substantially larger for orthographic mismatch in the homophonic condition than for phonological mismatch in the orthographic condition. This difference between the two conditions suggests that activation of lexical semantics is driven more strongly by orthographic information than by phonological information in reading Chinese. Direct orthographic access is led astray by incorrect orthographic input, causing more difficulties in activating and integrating semantics of the base words. Note that the findings here are somewhat different from behavioral studies demonstrating the differential use of orthographic information between school children and adults (Song et al., 1995) or between good and poor child readers (Wang et al., 2000).

While the mean amplitudes of the N400 component did not differ between children and adult readers in the orthographic and the baseline conditions, the N400 in the homophonic condition was more negative for children than for adults. This may be taken as evidence that, compared with adults, Chinese school children have more difficulties in accessing the base words from the (mismatched) orthographic information provided by homophonic characters. While the ability to use phonological information to access lexical semantics is relatively stable over the time span we studied, (for normal readers but not for dyslexics, see Meng et al., 2007), the ability to use orthographic information and access directly semantic representations develops over reading experience.

Differences in the offset of the N400 effects between children and adult readers and between the orthographic and the homophonic conditions demonstrate that, after the failure of initial access to semantic representations of the base words, it takes less time or effort for adults than for children to recover from the misleading input and/or to construct appropriate sentential representations; moreover, it takes less time or effort for adults (and possibly children as well) to recover from orthographic mismatch in the homophonic condition than from phonological mismatch in the orthographic condition. It has been shown in an eye movement tracking study (Feng et al., 2001) that, while there is no evidence for early phonological activation in reading Chinese text containing orthographic errors, phonology helps readers recover from the disruptive effects of errors, as revealed by measures sensitive to the later-stage lexical processing. It is possible that, when the direct orthography-to-semantics mapping fails to activate the base words, phonological information provided by the homophonic input characters comes up to play a role in the recovery process, allowing the processing system to search for a solution in a well-defined, often explicitly taught homophonic set.

To conclude, by measuring ERP responses to mismatches between orthographic or phonological input and the underlying representations in the lexicon and by comparing children with adult readers, we demonstrate that both Chinese adult readers and school children rely more on orthographic information than on phonological information to access lexical semantics in reading for meaning during sentence comprehension, but the differential effects between orthography and phonology may have different ERP manifestations in adults and children. Further, longitudinal studies are needed to confirm and extend these findings.

4. Experimental procedures

4.1. *Participants*

Thirteen undergraduate students (5 female and 8 male, aging between 19–24 years old) from Peking University took part in the experiment. They received 50 Chinese yuan (about 8 US dollars) for their participation. In addition, 13 fourth and fifth grade school children, with a mean age of 10 years and 6 months, participated in the study. They were screened from several primary schools in Beijing, originally as control participants for our earlier study on orthographic and phonological processing in Chinese dyslexic children (Meng et al., 2007). Raven's standard progressive matrices (IQ test), reading fluency, and vocabulary test showed that these children's IQ and reading ability were normal. Parents of all the child participants gave their informed consent for the children to participate in the experiment. The children were accompanied by their parents to the ERP laboratory. All the participants were right-handed and had normal or corrected-to-normal vision. None of the participants had a history of neurological or emotional disorders.

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).

The orthographic similarity between the replacing characters and the base characters in the orthographic condition was mostly achieved by they having the same phonetic radicals (e.g., 服, /fu2/, *clothes*, 报, /bao4/, *newspaper*), although a few other characters achieved the orthographical similarity by having similar writing patterns to the base characters (e.g., 龟, /gui1/, *tortoise*, 电, /dian4/, *power*). These orthographic pairs were phonologically dissimilar (with only a few exceptions in which they had the same lexical tones) and had no

Table 3 – The mean frequencies (per million) and the 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

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 frequencies of the base words from which the critical incorrect words in the orthographic and homophonic conditions were derived and the correct 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 (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 three groups of compound (non-)words, with the mean scores of 7.3, 7.4, and 7.5 per character respectively. Properties of the critical, second characters were summarized in Table 3. All the words and characters were selected from a corpus based on the textbooks used in primary schools in Beijing (Shu et al., 2003).

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 critical 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 missing. Fifty-three school children and 50 undergraduate students who did not participate in the ERP test were asked to complete the sentences quickly as possible with words that came into their minds. The predictability for the base words was 72%, 76%, and 71% for children and 76%, 76%, and 77% for adults, respectively for the orthographic, the homophonic, and the baseline conditions. For the orthographic similarity judgment, the 60 pairs of orthographically similar critical characters and their base characters and 60 pairs of orthographically dissimilar filler characters were printed in random orders and the 53 children and 50 undergraduate students were asked to judge, by circling a number on the 5-point scale, the similarity between 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 and 3.9 respectively for children and adults.

4.3. *Procedure*

The 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 (non-word) was presented together with the mark of full stop. The 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 sentences were 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.

4.4. *EEG recording and data analyses*

The EEG data was 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 (−200–1000 ms). Any trail with EOG artifacts greater than ±75 mV was excluded from further analysis. The ERPs were recorded from the onset of the final word in each sentence. They were averaged separately off-line for each condition.

For the statistical analysis of the ERP effects, only trials with correct responses in the sentence acceptability judgment were analyzed. Because the preceding words before the critical targets were different between conditions, we used the ERPs in the 0–100 ms for baseline correction to control for the potential influence of the preceding words on ERP responses to the critical words. It turned out that the results had no substantial difference from the results with −200–0 ms ERPs for baseline correction, as we have reported for the child participants (Meng et al., 2007). Peak amplitudes and latencies of N100 and P200 were obtained in the 50–150 ms, and 150–300 ms time window, respectively, and the mean amplitudes of N400 were calculated for the window 300–500 ms. Peak latencies of N400 were also obtained in this time window.

In addition, to control for the typically the larger ERP amplitudes in children than for adults, the amplitude data were normalized with the formula (score−mean/SD), where score was an ERP average amplitude value (one for each condition and scalp site for each participant), mean was the mean amplitude across all the participants in a particular age group, and SD was the standard deviation of the mean amplitude (Coch et al., 2002, 2005; Holcomb et al., 1992). The data were entered into the mixed-design analyses of variance (ANOVAs), with participant group (children vs. adults) 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). The Greenhouse–Geisser correction was applied when appropriate.

Acknowledgments

This study was supported by China Natural Science Foundation (grant no. 30200078, 30470574, 30470569, 30770712, and 60435010) and by Beijing Key Laboratory of Learning and Cognition, Capital Normal University. 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.

REFERENCES

Atchley, R.A., Rice, M.L., Betz, S.K., Kwasny, K.M., Sereno, J.A., Jongman, A., 2006. A comparison of semantic and syntactic event related potentials generated by children and adults. Brain Lang. 99, 236–246.

Barnea, A., Breznitz, Z., 1998. Phonological and orthographic processing of Hebrew words: electrophysiological aspects. J. Gen. Psych. 159 (4), 492–504.

Bonte, M., Blomert, L., 2004. Developmental changes in ERP correlates of spoken word recognition during early school years: a phonological priming study. Clin. Neurophysiol. 115, 409–423.

Brem, S., Bucher, K., Halder, P., Summers, P., Dietrich, T., Martin, E., Brandeis, D., 2006. Evidence for developmental changes in the visual word processing network beyond adolescence. NeuroImage 29, 822–837.

Breznitz, Z., Leikin, M., 2000. Syntactic processing of Hebrew sentences in normal and dyslexic readers: electrophysiological evidence. J. Gen. Psych. 161, 359–380.

Carreiras, M., Vergara, M., Barber, H., 2005. Early event-related potential effects of syllabic processing during visual word recognition. J. Cogn. Neurosci. 17 (11), 1803–1817.

Chen, H.-C., Shu, H., 2001. Lexical activation during the recognition of Chinese characters: evidence against early phonological activation. Psychol. Bull. Rev. 8, 511–518.

Cho, J.-R., Chen, H.-C., 1999. Orthographic and phonological activation in the semantic processing of Korean Hanja and Hangul. Lang. Cogn. Processes 14, 481–502.

Chua, F.K., 1999. Phonological recoding in Chinese logograph recognition. J. Exp. Psychol., Learn., Mem., Cogn. 25, 876–891.

Coch, D., Grossi, G., Coffey-Corina, S., Holcomb, P.J., Neville, H.J., 2002. A developmental investigation of ERP auditory rhyming effects. Dev. Sci. 5, 467–489.
Coch, D., Grossi, G., Skendzel, W., Neville, H.J., 2005. ERP nonword rhyming effects in children and adults. J. Cogn. Neurosci. 17, 168–182.
Connolly, J.F., Phillips, N.A., Forbes, K.A.K., 1995. The effects of phonological and semantic features of sentence-ending words on visual event-related brain potentials. EEG. Clin. Neurophysiol. 94, 276–287.
Dambacher, M., Kliegl, R., Hofmann, M., Jacobs, A.M., 2006. Frequency and predictability effects on event-related potentials during reading. Brain Res. 1084, 89–103.
Feng, G., Miller, K., Shu, H., Zhang, H., 2001. Rowed to recovery: the use of phonological and orthographic information in reading Chinese and English. J. Exp. Psychol. Learn. Mem. Cogn. 27, 1079–1100.
Friederici, A.D., 2006. The neural basis of language development and its impairment. Neuron 52, 941–952.
Friederici, A.D., Hahne, A., 2001. Developmental patterns of brain activity for semantic and syntactic processes. In: HÖhle, B., Weissenborn, J. (Eds.), Approaches to Bootstrapping in Early Language Development. John Benjamins, Amsterdam/Philadelphia, pp. 231–246.
Friedrich, M., Friederici, A.D., 2006. Early N400 development and later language acquisition. Psychophysiology 43, 1–12.
Grossi, G., Coch, D., Coffey-Corina, S., Holcomb, P.J., Neville, H.J., 2001. Phonological processing in visual rhyming: a developmental ERP study. J. Cogn. Neurosci. 13 (5), 610–625.
Hahne, A., Eckstein, K., Friederici, A.D., 2004. Brain signatures of syntactic and semantic processes during children's language development. J. Cogn. Neurosci. 16, 1302–1318.
Holcomb, P.J., Neville, H.J., 1990. Auditory and visual semantic priming in lexical decision: a comparison using event-related brain potentials. Lang. Cogn. Processes 5, 281–312.
Holcomb, P.J., Neville, H.J., 1991. Natural sentence processing: an analysis using event-related brain potentials. Psychobiology 19, 286–300.
Holcomb, P.J., Coffey, S.A., Neville, H.J., 1992. Visual and auditory sentence processing: a developmental analysis using event-related brain potentials. Dev. Neuropsychol. 8 (2 and 3), 203–241.
Juttonen, K., Revonsuo, A., Lang, H., 1996. Dissimilar age influences on two ERP waveforms (LPC and N400) reflecting semantic context effect. Cogn. Brain Res. 4, 99–107.
Kutas, M., Federmeier, K.D., 2000. Electrophysiology reveals semantic memory use in language comprehension. Trends Cogn. Sci. 4, 463–470.
Lee, C.Y., Tsai, J.L., Chan, W.H., Hsu, C.H., Hung, D.L., Tzeng, O.J.L., 2007. Temporal dynamics of the consistency effect in reading Chinese: an event-related potentials study. Neuroreport 18 (2), 147–151.
Licht, R., Bakker, D.J., Kok, A., Bouma, A., 1988. The development of lateral event-related potentials (ERPs) related to word naming: a four-year longitudinal study. Neuropsychologia 26, 327–340.
Liu, Y., Perfetti, C.A., Hart, L., 2003. ERP evidence for the time course of graphic, phonological, and semantic information in Chinese meaning and pronunciation decisions. J. Exp. Psychol. Learn., Mem., Cogn. 29, 1231–1247.
Martin, F.H., Kaine, A., Kirby, M., 2006. Event-related brain potentials elicited during word recognition by adult good and poor phonological decoders. Brain Lang. 96 (1), 1–13.
Meng, X., Tian, X., Jian, J., Zhou, X., 2007. Orthographic and phonological processing in Chinese dyslexic children: an ERP study on sentence reading. Brain Res. 1179, 119–130.
Meyler, A., Breznitz, Z., 2005. Impaired phonological and orthographic word representations among adult dyslexic readers: evidence from event-related potentials. J. Gen. Psych. 166 (2), 215–238.
Miller, J., Patterson, T., Ulrich, R., 1998. Jackknife-based method for measuring LRP onset latency differences. Psychophysiol. 35, 99–115.
Mills, D.L., Coffey-Corina, S.A., Neville, H.J., 1994. Variability in cerebral organization during primary language acquisition. In: Dawson, G., Fischer, K.W. (Eds.), Human Behavior and the Developing Brain. Guilford Press, New York, pp. 427–455.
Molfese, D., 1990. Auditory evoked responses recorded from 16-month-old human infants to words they did and did not know. Brain Lang. 38, 345–363.
Neville, H.J., Coffey, S.A., Holcomb, P.J., Tallal, P., 1993. The neurobiology of sensory and language processing in language impaired children. J. Cogn. Neurosci. 5, 235–253.
Niznikiewicz, M., Squires, N.K., 1996. Phonological processing and the role of strategy in silent reading: Behavioral and electrophysiological evidence. Brain Lang. 52, 342–364.
Oberecker, R., Friedrich, M., Friederici, A.D., 2005. Neural correlates of syntactic processing in two-year-olds. J. Cogn. Neurosci. 17, 1667–1678.
Perfetti, C.A., Zhang, S., 1995. Very early phonological activation in Chinese reading. J. Exp. Psychol. Learn., Mem., Cogn. 21, 24–33.
Shu, H., Chen, X., Anderson, R.C., Wu, N., Xuan, Y., 2003. Properties of school Chinese: implications for learning to read. Child Dev. 74, 27–48.
Song, H., Zhang, H.C., Shu, H., 1995. The role of phonology and orthography and its development in Chinese reading. Acta Psychol. Sin. 27, 139–141.
Ulrich, R., Miller, J., 2001. Using the jackknife-based scoring method for measuring LRP onset effects in factorial designs. Psychophysiol 38, 816–827.
Wang, M., Meng, X., Zhou, X., 2000. Phonology in semantic activation in reading Chinese: Comparing skilled and poor school children readers. Int. J. Psychol. 35(3–4), 59.
Weber-Fox, C., Hart, L.J., Spruill III, J.E., 2006. Effects of grammatical categories on children's visual language processing: evidence from event-related brain potentials. Brain lang. 98, 26–39.
Weber-Fox, C., Neville, H.J., 1998. Maturational constraints on functional specializations for language processing: ERP and behavioral evidence in bilingual speakers. J. Cogn. Neurosci. 8, 231–256.
Xie, D., Zhou, X., 2003. Earlier phonological activation in semantic activation in reading Chinese? A replication study. Acta Psychol. Sin. 14–22 special issue.
Xu, Y., Pollatsek, A., Potter, M.C., 1999. The activation of phonology during silent Chinese word reading. J. Exp. Psychol. Learn., Mem., Cogn. 25, 838–857.
Zhou, X., Marslen-Wilson, W., 1999. Phonology, orthography, and lexical semantic activation in reading Chinese. J. Mem. Lang. 41, 579–606.
Zhou, X., Marslen-Wilson, W., 2000a. The relative time course of semantic and phonological activation in reading Chinese. J. Exp. Psychol. Learn. Mem. Cogn. 26, 1245–1265.
Zhou, X., Marslen-Wilson, W., 2000b. Lexical representation of compound words: Cross-linguistic evidence. Psychologia 43, 47–66.
Zhou, X., Marslen-Wilson, W., accepted. Pseudohomophone effects in processing Chinese compound words. Lang. Cogn. Process.
Zhou, X., Marslen-Wilson, W., Taft, M., Shu, H., 1999. Morphology, orthography, and phonology in reading Chinese. Lang. Cogn. Processes 14, 525–565.