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Pre-lexical phonological processing in reading Chinese characters: An ERP study

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ABSTRACT

Sinograms (i.e., Chinese characters) are usually composed of radicals which do not correspond to phonemes; instead, some radicals can occur as freestanding sinograms and have their own pronunciations. Previous research has demonstrated that the pronunciations of both radicals and sinograms are activated in reading low-frequency sinograms. However, the relative timing of activation between sinogram pronunciation and radical pronunciation has not been addressed. We examine this issue by comparing the interference effects exerted by two types of primes on the targets in an event-related potential (ERP) experiment: RADICAL-RELATED primes, which are homophonic with a radical embedded in the targets; and SINOGRAM-RELATED primes, which are homophonic with the targets. A radical interference effect is found for N170, P200 and N400 responses, whereas a sinogram interference effect is found only for N400. Our findings demonstrate that the pronunciations of radicals are activated pre-lexically, i.e., prior to those of their host sinograms. The role of this early sub-lexical phonology is discussed within an interactive activation framework, wherein two types of pronunciations—(1) the radical pronunciations and (2) the set of pronunciations associated with the sinogram's orthographical neighbors—are both present and operate interactively.

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1. Introduction

The question of how early phonological information is activated in visual word recognition is essential for understanding the role of phonology during reading. This question has been extensively studied with alphabetic scripts in which sub-lexical units (i.e., letter strings) correspond to phonemes (e.g., Jared & Seidenberg, 1991; Perfetti, Bell, & Delaney, 1988; see Frost, 1998, for a review). A general consensus is that this sub-lexical phonological information (i.e., phonemes) of alphabetic words is activated pre-lexically, i.e., prior to the access of dictionary-like lexical phonology. For example, in English, the first two phonemes of the word 'plague', /p/ and /l/, are activated before the full lexical phonology /pleig/ (Tan & Perfetti, 1998). This has been widely evidenced by behavioral studies on reading alphabetic scripts, such as English (Perfetti et al., 1988), Serbo-Croatian (Lukatela & Turvey, 1990), French (Ferrand & Grainger, 1993), Dutch (Brysbaert, 2001), and Hebrew (Gronau & Frost, 1997). Further supporting evidence comes from event-related potential (ERP) studies, which show that the properties of sub-lexical units have earlier effects on brain responses than lexical properties in reading alphabetic polysyllabic words (Barber, Vergara, & Carreiras, 2004; Carreiras, Vergara, & Barber, 2005; Chetail, Colin, & Content, 2012; Doignon-Camus, Bonnefond, Touzalin-Chretien, & Dufour, 2009; Hutzler et al., 2004). For example, Barber, Vergara, and Carreiras (2004) find that in reading disyllabic Spanish words, the frequency of the first syllable modulates both P200 and N400 responses whereas lexical frequency modulates only N400, but not P200. In particular, compared with words containing low-frequency syllables, words containing high-frequency syllables produce smaller P200 and larger (i.e., more negative-going) N400. By contrast, high-frequency words elicit a smaller N400 than low-frequency words. These results are interpreted in a two-stage framework for lexical access wherein P200 and N400 are thought to index sub-lexical and lexical processing, respectively.

In contrast, as a logographic script, Chinese characters, i.e., sinograms (Wang & Tsai, 2011), are monosyllabic, and their sub-lexical units, referred to as radicals, do not correspond to phonemes. Instead, radicals are sometimes freestanding sinograms themselves, and thus have their own pronunciations and meanings. For example, the sinogram 植 (*zhi2*[1], '*plant*') is composed of a semantic radical, 木 (*mu4*, '*wood*'), and a phonetic radical, 直 (*zhi2*, '*vertical*'). Such a sinogram is also referred to as a *phonogram*—phonograms account for around 80% of sinograms (Zhou, 1978). Moreover, because this sinogram has identical pronunciation to its phonetic radical, it is called a *regular phonogram*—regular phonograms constitute less than 30% of phonograms (Zhou & Marslen-Wilson, 1999a). By contrast, *irregular phonograms,* e.g., 贻 (pronunciation: *yi2;* phonetic radical: 台, *tai2*), are pronounced differently from their phonetic radicals in terms of both consonant and rime (Zhou & Marslen-Wilson, 1999a).

Despite the unreliability of the mapping between the pronunciations of sinograms and radicals, radical pronunciations are nonetheless activated during sinogram reading (Zhou & Marslen-Wilson, 1999b; Zhou, Peng, Zheng, Su, & Wang, 2013). Specifically, in a primed naming experiment, irregular primes (e.g., 粹, *cui4*, '*essence*') are found to facilitate the naming of targets (e.g., 族, *zu2*, '*clan*') that are homophonic with the phonetic radicals (e.g., 卒, *zu2*, '*soldier*') embedded in the primes, but only when low-frequency primes are used (Zhou & Marslen-Wilson, 1999b). Similar facilitation is also obtained in Zhou et al. (2013) when the targets (e.g., 辈, *bei4, 'generation*') are homophonic with the semantic radicals (e.g., 贝, *bei4*, *'shell*') embedded in low-frequency primes (e.g., 贻, *yi2*, '*present*'). Therefore, in reading a low-frequency sinogram, phonological processing apparently involves both the sinogram level (i.e., the host sinogram) and the radical level (i.e., radicals).

The question can be asked whether the phonological information of sub-lexical units (i.e., radicals' pronunciation) is activated earlier than that of the word as a whole (i.e., host sinograms' pronunciation) during reading low-frequency sinograms, as is the case in reading alphabetic words. Some evidence can be obtained by comparing findings of primed naming experiments that involve the use of different stimulus onset asynchronies (SOAs). Specifically, the aforementioned facilitatory effects of phonological primes that are homophonic with targets at the radical level are observed at SOAs of 57 ms (Zhou et al., 2013) and 100 ms (Zhou & Marslen-Wilson, 1999b). By contrast, the facilitatory effects of

[1] The letters represent the official Romanization of standard Chinese, that is, Pinyin, while the number indicates the corresponding tone.

phonological primes (e.g., 况, *kuang4*) that are homophonic with targets (e.g., 矿, *kuang4*) at sinogram level are reported for SOAs of 57, 85 and 115 ms (Perfetti & Tan, 1998). In terms of these results, it appears that at the SOA of 57 ms, the pronunciations of both the sinogram and radicals are activated in parallel. However, with regard to the relative timing of activation between sinogram pronunciations and radical pronunciations, these behavioral results provide no conclusive evidence.

The present study aims to address this issue using the ERP technique, which provides good temporal resolution. More importantly, ERP components can be used to index different stages of visual word recognition. For example, the N170 has been associated with orthographical detection (e.g., Wong, Gauthier, Woroch, Debuse, & Curran, 2005) and automatic connections between orthographical forms and phonological representations (e.g., Maurer & McCandliss, 2007), and the P200 with early orthographical and phonological processing (e.g., Barnea & Breznitz, 1998). In addition, the N400 is well-known for its association with semantic processing (Lau, Phillips, & Poeppel, 2008).

In connection with the interference paradigm, the ERP technique has been recruited to trace the time course of sinogram recognition at different psycholinguistic levels (Chen, Liu, Wang, Peng, & Perfetti, 2007; Liu, Perfetti, & Hart, 2003; Zhang, Zhang, & Kong, 2009). For example, to trace the time course of phonological and semantic activation during sinogram recognition, Zhang et al. (2009) use two types of related primes: phonological primes (e.g., 待, *dai4, 'wait'*), which are homophonic with targets (e.g., 袋, *dai4, 'sack'*), and semantic primes (e.g., 包, *bao1, 'bag'*), which are semantically related to targets. In the interference paradigm, the phonological relation between phonological primes and targets is irrelevant for a semantic judgment task and thus the corresponding prime-target pairs should be judged as semantically unrelated. Similarly, the semantic relation between semantic primes and target is irrelevant for a homophone judgment task and hence these prime-target pairs should be given the "no" response. Therefore, any interference effects of phonological primes in the semantic judgment task and those of semantic primes in the homophone judgment task provide evidence for the automatic phonological and semantic activation, respectively. In particular, for low-frequency targets, it is found that phonological primes elicit larger P200 and smaller N400 effects in the semantic judgment task whereas in the homophone judgment task, semantic primes modulate a reduced N400 only (Chen et al., 2007; Zhang et al., 2009; but see Liu et al., 2003). The earlier interference onset of phonological primes than semantic primes is interpreted as earlier phonological processing than semantic processing during reading low-frequency sinograms.

As far as phonology is concerned, the ERP studies have concentrated on examining interference effects at the sinogram level, thus it is as yet unclear when sub-lexical phonology is activated, and what role it might play in sinogram recognition. To provide insights for this unresolved question, we adopt the same interference paradigm in connection with the ERP technique. Specifically, in addition to using primes that are homophonic with targets at the sinogram level (i.e., sinogram interference), we also recruit primes that are homophonic with the radicals embedded in targets (i.e., radical interference). In the semantic judgment task, the phonological relation is irrelevant and these prime-target pairs should be judged as semantically unrelated. Thus any sinogram interference effects and radical interference effects provide evidence for the automatic activation of lexical and sub-lexical phonology, respectively. To trace the relative timing of activation between lexical phonology and sub-lexical phonology, we compare the sinogram interference effects and radical interference effects. If sub-lexical phonology is activated earlier than lexical phonology, the onset of radical interference effects would be earlier than that of sinogram interference effects. Alternatively, if sub-lexical and lexical phonology are activated in parallel, the effects of radical and sinogram interference will have comparable onsets.

2. Methodology

2.1. Participants

Nineteen postgraduate students (8F; mean age 26, range 23–32) of the Chinese University of Hong Kong with normal or corrected-to-normal vision took part in the ERP experiments. All participants grew up in Mainland China and are right-handed, literate, native Mandarin speakers. Data from two of them were excluded due to excessive ocular artifacts (>50%). Approval to conduct this study was obtained from the Survey and Behavioral Research Ethics Committee of The Chinese University of Hong Kong.

Table 1
Sample stimuli of prime-target pairs. The phonological relationship is highlighted in bold.

Target	Prime conditions			
	Sinogram		Radical	
	Related (SR)	Control (SC)	Related (RR)	Control (RC)
榛 ***zhen1***, '*hazelnut*' 14 strokes 1 per million (containing radicals: 木, *mu4*, '*wood*'; 秦, ***qin2***, a surname)	珍 ***zhen1***, '*treasure*' 9 strokes 108 per million	浪 *lang4*, '*wave*' 10 strokes 107 per million	琴 ***qin2***, *a musical instrument* 12 strokes 61 per million	罢 *ba4*, '*dismiss*' 10 strokes 60 per million

2.2. Materials and experimental design

The critical stimuli consisted of 72 low-frequency (below 30 per million[2], *mean* = 11.1 per million, *SD* = 9.8) irregular sinograms so that their phonology (including both consonant and rhyme) at the sinogram and radical levels differs. Each target was paired with four types of primes (see Table 1): SINOGRAM-RELATED (**SR**) primes are homophonic with the target sinogram (i.e., sinogram interference) whereas RADICAL-RELATED (**RR**) primes are homophonic with the radicals (either semantic or phonetic; equally distributed) embedded in targets (i.e., radical interference). SINOGRAM-CONTROL (**SC**) and RADICAL-CONTROL (**RC**) primes are matched with the SR and RR primes, respectively, in terms of sinogram structure[3], stroke number and sinogram frequency. The SC and RC primes have no association with targets in terms of orthography, phonology or semantics, and serve as baselines for SR and RR primes, respectively. These four types of primes correspond to two within-subject variables: prime type (SINOGRAM vs. RADICAL) and relatedness (RELATED vs. CONTROL). Another 288 semantically related prime-target pairs were selected as fillers.

To ensure that critical prime-target pairs were unrelated in semantics, a pre-test questionnaire was conducted. Eight native Mandarin speakers (4F) who did not participate in the ERP experiments rated the semantic relatedness for each pair on a 7-point scale questionnaire[4], ranging from 1 (totally unrelated) to 7 (highly related). The scores for all critical prime-target pairs were below 3, with average scores for the pairs in SR, SC, RR, and RC conditions being 1.24, 1.19, 1.18, and 1.12, respectively. Paired *t*-tests confirmed that the pairs in the RELATED and CONTROL conditions did not differ significantly in terms of semantic relatedness ($p > .4$). The average score for filler pairs was 5.5.

To exclude the possibility that the results would be biased by items for which the pronunciation was unknown to the participants, participants were asked to write down the pronunciation of targets in Pinyin on a post-test questionnaire. Only correct items were used for analysis. The average pronunciation accuracy across all participants was 89% (*SD* = 7%).

2.3. Procedure

Each trial started with a fixation cross displayed for 300 ms, followed by the prime for 140 ms. After a 360 ms blank, the target character appeared and remained on the screen for 1500 ms. The inter-trial interval was 1800–2200 ms. Both primes and targets were displayed in font Song and in white against a black background at the center of the screen. Participants were seated 60 cm from

[2] All stimuli were chosen from a word frequency database from the Centre for Chinese Linguistics at Peking University (URL: http://ccl.pku.edu.cn:8080/ccl_corpus/CCL_CC_Sta_Xiandai.pdf, downloaded on 6th May 2010).

[3] Sinogram structure refers to the relative position of phonetic and semantic radicals, e.g., a left-right structure sinogram consists of one radical on the left and the other on the right.

[4] The questionnaire included 568 sinogram pairs, including 288 critical prime-target pairs and 280 semantically related filler pairs.

the screen (visual angle: 1.9°). The task was to judge whether or not the prime and target were semantically related (synonyms, antonyms, or category coordinates[5]). A key press was required only for *yes* (i.e., semantically related) responses. In total, each participant completed 576 trials in 12 blocks. Within each block, 24 critical trials (equally distributed in the four priming conditions) and 24 filler trials were randomly presented, except that the first two trials were always fillers. Due to the within-subject design, each target, which was paired with four types of primes, was presented four times in the whole experiment. Similar designs involving target repetitions have been used in previous studies (Chen et al., 2007; Kong et al., 2010; Liu et al., 2003; Zhang et al., 2009). To control the order and carryover effects, the presentation order of targets in the four priming conditions was manipulated by a balanced Latin square (Williams, 1949), such that four presentation orders (each corresponding to a row in the 4×4 balanced Latin square) are associated with four groups of targets, respectively. For each participant, the four groups of targets are randomly assigned and of equal number. Also, there was no target repetition within any three blocks, and the repetition trials for each target in different priming conditions were separated by at least 98 trials. Participants were permitted to take a break between blocks. Prior to the formal experiment, each participant was given 20 practice trials.

2.4. ERP recordings and analyses

Electroencephalogram (EEG) data were recorded continuously at 1024 Hz using a 32-channel ActiveTwo EEG system (BioSemi B.V., Amsterdam, The Netherlands). Vertical and horizontal electro-oculograms were recorded with two additional pairs of electrodes, one placed above and one below the left eye, and the other two beside each eye.

The data were recomputed offline against average-mastoid reference, and band-passed at 0.05–30 Hz. ERPs were computed for correct trials after ocular artifact rejection. Each epoch lasted 1100 ms, including a 100 ms baseline interval prior to target onset. Mean amplitudes across 100–170, 190–270, 300–460 ms time windows, selected based on a global field power criterion (Skrandies, 2005) and previous literature, were calculated for N170, P200 and N400, respectively. The N170 amplitude at six electrodes (P3/4, PO3/4, P7/8) was submitted to a four-way ANOVA with prime type (SINOGRAM vs. RADICAL), relatedness (RELATED vs. CONTROL), laterality (LEFT vs. RIGHT), and site (P3/4, PO3/4, P7/8) as within-subject factors, since the reading-related N170 effect is prominent in these regions (Maurer, Brandeis, & McCandliss, 2005). Both the P200 and N400 responses at nine electrodes (F3/z/4, C3/z/4, P3/z/4) were analyzed with a four-way ANOVA with prime type (SINOGRAM vs. RADICAL), relatedness (RELATED vs. CONTROL), laterality (LEFT, MIDLINE, RIGHT), and site (FRONTAL, CENTRAL, PARIETAL) as four within-subject factors. Greenhouse–Geisser correction was applied to all repeated-measures with more than one degree of freedom. Any three-way interactions containing the factors of prime type and relatedness were followed by separate analyses at the SINOGRAM and RADICAL levels. Any two-way interactions were followed by simple main effect analyses and overall pair-wise comparisons across all electrodes with Bonferroni adjustment.

3. Results

Fig. 1 displays the ERP waveforms for the four experimental conditions.

3.1. N170

The four-way ANOVA reveals a main effect of relatedness [F (1, 16) = 4.567, MSE = 3.57, $p < .05$], which interacts with prime type and laterality [F (1, 16) = 8.459, MSE = 0.336, $p < .05$]. Separate analyses show that at the RADICAL level, the main effect of relatedness [F (1, 16) = 5.341, MSE = 5.545, $p < .05$] and the interaction between relatedness and laterality [F (1, 16) = 5.353, MSE = 0.622, $p < .05$]

[5] Category coordinates refer to sinogram pairs (e.g., 狗 and 猫, i.e., 'dog' and 'cat') belonging to the same semantic category (e.g., animal).

remain significant. Further analyses show that the effect of relatedness (−1.02 μV) is significant in the LEFT hemisphere ($p < .01$) but not in the RIGHT ($p = .168$): RR primes elicit significantly larger N170 amplitude (RR vs. RC: −1.91 vs. −0.89 μV) than RC primes in the left posterior region (see Fig. 1a). Further pair-wise comparisons show that the effect of relatedness is significant at P3, PO3, and P7 electrodes ($p < .05$). However, at the SINOGRAM level, neither the main effect of relatedness [F (1, 16) = .025, MSE = 2.883, p = .876] nor the interaction between relatedness and laterality [F (1, 16) = 1.189, MSE = 0.263, p = .292] is significant.

3.2. P200

The four-way ANOVA reveals a significant three-way interaction between prime type, relatedness and laterality [F (2, 29) = 4.054, MSE = 0.349, $p < .05$]. At the RADICAL level, there is a marginal main effect of relatedness [F(1, 16) = 3.691, MSE = 6.055, p = .073], which interacts with laterality [F(2, 28) =

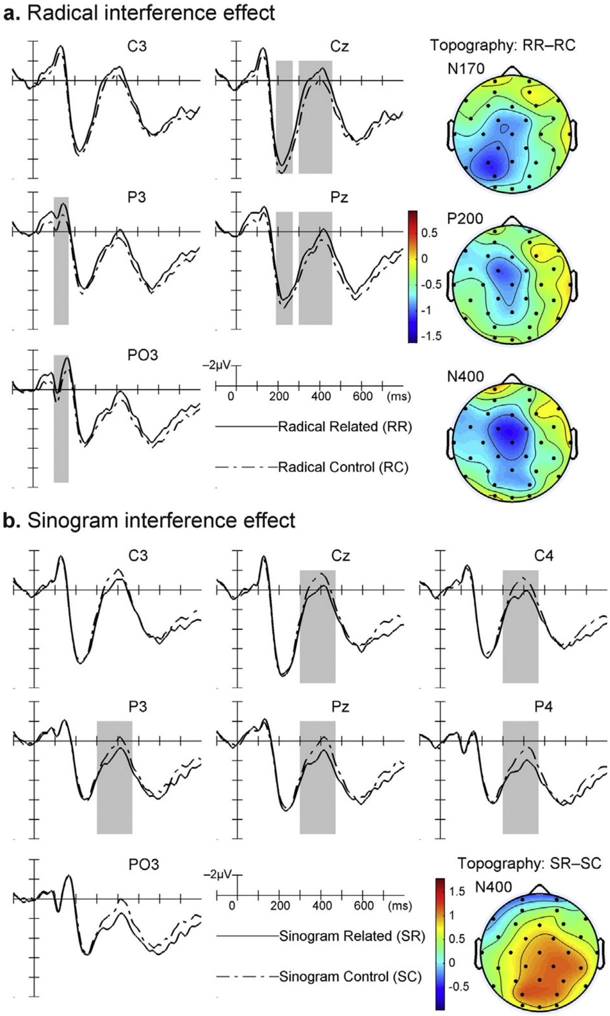

Fig. 1. Grand averaged ERPs and topology for (a) radical interference effect and (b) sinogram interference effect. For each electrode, the time windows at which significant interference effects are found are highlighted.

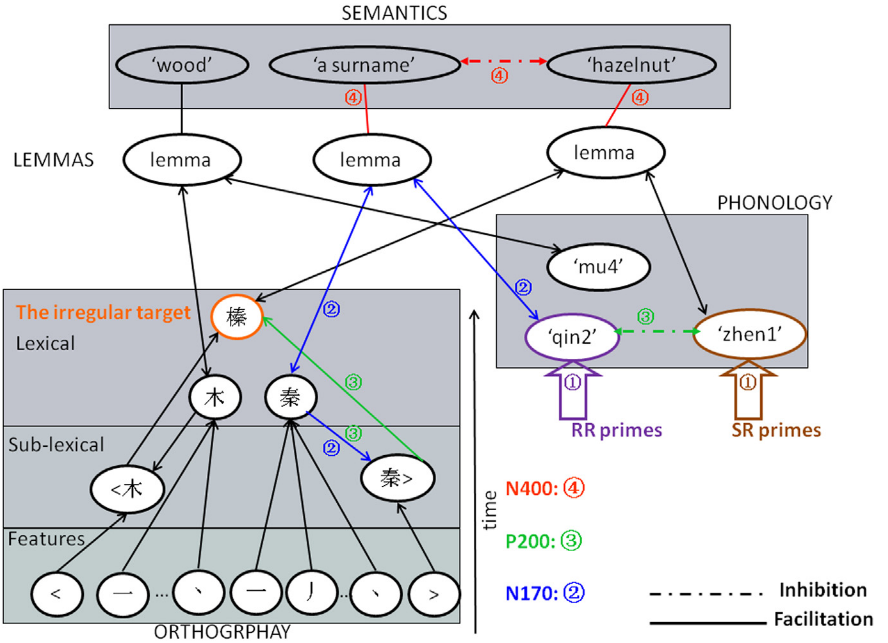

Fig. 2. Illustration of reading an irregular target based on Taft's model and the priming effects within this framework: in the orthographic system, target's representation is activated via radicals' representations during a bottom-up process. The primes pre-activate the pronunciations of either radicals or the sinogram (indexed as arrow ①), and other numbered lines correspond to the subsequent interference effects on the observed ERP components (see text for a detailed explanation).

3.977, $MSE = 0.609$, $p < .05$]. Further analyses show that the effect of relatedness (-0.78 μV) is significant in the MIDLINE region ($p < .05$): RR primes elicits smaller P200 amplitude (RR vs. RC: 7.43 vs. 8.21 μV) than RC primes (see Fig. 1a). Further pair-wise comparisons show that the effect of relatedness is significant at Cz and Pz electrodes ($p < .05$). However, at the SINOGRAM level, neither the main effect of relatedness [F (1, 16) = .061, $MSE = 11.016$, $p = .808$] nor the interaction between relatedness and laterality [F (1, 22) = .107, $MSE = 0.403$, $p = .826$] is significant.

3.3. N400

The four-way ANOVA reveals a significant three-way interaction between prime type, relatedness and laterality [F (2, 29) = 4.701, $MSE = 0.443$, $p < .05$]. In addition, the two-way interaction between prime type and relatedness is significant [F (1, 16) = 7.226, $MSE = 11.264$, $p < .05$] as well as that between relatedness and laterality [F (2, 31) = 3.613, $MSE = 0.331$, $p < .05$]. At the RADICAL level, the interaction between relatedness and laterality remains significant [F (2, 30) = 5.778, $MSE = 0.469$, $p < .05$]. Further analyses show that the effect of relatedness (-0.96 μV) is significant in the MIDLINE region ($p < .05$): RR primes elicit more negative-going N400 than RC primes (RR vs. RC: 0.72 vs. 1.68 μV; see Fig. 1a). Further pair-wise comparisons suggest that the effect of relatedness is significant at Cz and Pz electrodes ($p < .05$). At the SINOGRAM level, the main effect of relatedness ($+0.79$ μV) is significant [F (1, 16) = 5.445, $MSE = 8.751$, $p < .05$]: SR primes elicit less negative-going N400 than SC primes (SR vs. SC: 1.30 vs. 0.51 μV; see Fig. 1b). Further pair-wise comparisons suggest that the effect of relatedness is significant at Cz, C4, P3, Pz, and P4 electrodes ($p < .05$).

4. Discussion

The present study shows that phonological interference at the radical and sinogram levels has different impacts on the N170, P200 and N400 responses. Specifically, radical interference elicits enhanced (i.e., more negative) N170 in the left posterior region, reduced P200 and enhanced N400 in the midline region. In contrast, sinogram interference elicits a reduced N400 in the central-parietal electrodes, but modulates neither N170 nor P200 amplitudes. This earlier onset of radical interference effect demonstrates that, in reading a low-frequency sinogram, the pronunciation of the radical is activated pre-lexically, i.e., prior to that of the host sinogram.

From a theoretical perspective, our results can be accommodated within the model of sinogram recognition proposed by Taft and his colleagues (Taft, 2006; see also Ding, Peng, & Taft, 2004; Taft, Zhu, & Ding, 2000). Their model adopts the interactive activation framework (McClelland & Rumelhart, 1981), and assumes that there are three subsystems (orthography, phonology and semantics) and a layer of lemma units mediating these subsystems (see Fig. 2). In particular, the orthographical representation of a sinogram is activated via its radical representations during a bottom-up process. In the following, we will discuss our results regarding each ERP component in terms of this model.

4.1. Phonological interference effects

4.1.1. N170

Our main finding regarding N170 is that N170 amplitude is enhanced by radical interference in the left posterior region, but not by sinogram interference. In the literature, the N170 response elicited by visual words is significantly larger than that elicited by non-orthographic stimuli such as symbols and forms (Bentin, Mouchetant-Rostaing, Giard, Echallier, & Pernier, 1999; Maurer et al., 2005). Regarding the reading-related N170 response, there are two accounts that are not mutually exclusive. First, the perceptual expertise account suggests that it reflects orthographical detection at the initial stage of perceptual categorization (Bentin et al., 1999; Wong et al., 2005). Consistent with this account, results of previous studies on Chinese reading indicate that the N170 response is sensitive to orthographical processing of both radicals and sinograms (Hsu, Tsai, Lee, & Tzeng, 2009; Lin et al., 2011; Su, Mak, Cheung, & Law, 2012). For example, Lin et al. (2011) find that, compared with random stroke combinations, pseudo sinograms in which the radicals are (1) unpronounceable and (2) at their frequently appearing positions produce an enhanced left-lateralized N170, and this N170 response is as strong as that induced by real sinograms. Second, the phonological mapping account suggests that the reading-related N170 response reflects automatic connections between orthographical forms and phonological representations (Maurer & McCandliss, 2007; Proverbio & Zani, 2003). This view is also supported by results of previous research on Chinese reading (Hsiao, Shillcock, & Lee, 2007; Hsu et al., 2009; Lee et al., 2007). For example, Lee et al. (2007) find that phonetic consistency,[6] defined as the proportion of homophonic orthographical neighbors containing the same phonetic radical within all neighbors, modulates the N170 response. Specifically, low-consistency sinograms are found to elicit larger N170 amplitude than high-consistency sinograms.

According to the two accounts of N170, our radical interference effect for the N170 response likely reflects the automatic connections between radicals' phonological representations and orthographical representations, as well as the top-down influence on the orthographical processing of radicals: the RR primes first pre-activate the phonology of target's radicals (see Fig. 2). When the target is presented, this in turn facilitates the orthographical activation of the target's radicals by virtue of the top-down influences via the connections between phonology and orthography. The absence of an N170 effect for sinogram interference suggests that the orthographical representation of the host sinogram is not yet activated at this stage.

4.1.2. P200

Regarding P200, radical interference is found to reduce P200 magnitude in the midline region, while no effect is found for sinogram interference. Some authors suggest that P200 is associated with early orthographical and phonological processing in visual word recognition (Barnea & Breznitz, 1998;

[6] For instance, the phonetic radical 贵 (*gui4*) is included in five sinograms. Among these, 溃 (*kui4*) has three homophonic neighbors (i.e., 馈, 匮 and 篑) whereas only 遗 is pronounced as *yi2*. Hence the sinogram 溃 has a higher consistency value (i.e., 4/5 = 0.8) than 遗 (consistency value: 1/5 = 0.2; Lee, Huang, Kuo, Tsai, & Tzeng, 2010).

Liu et al., 2003). For example, in Liu et al. (2003), graphical primes sharing a radical with targets are found to reduce P200 magnitude. Additionally, in the masked priming experiment of Su et al. (2012), sinograms containing a radical (e.g., 見) at its frequently appearing position (e.g., 蜆) are found to produce a smaller P200 than those containing the same radical at its less frequently appearing position (e.g., 覓). These results suggest that P200 is influenced by the orthographical processing of radicals in Chinese reading. However, the relationship between P200 and phonological processing is less clear. In particular, while Liu et al. (2003) observe no P200 effect when the prime and target are homophonic at the lexical level, later studies find a larger P200 effect in low-frequency targets (Chen et al., 2007; Kong et al., 2010; Zhang et al., 2009). In addition, phonetic consistency is also found to modulate the P200 response (Lee et al., 2007; see also Hsu et al., 2009). Specifically, low-consistency sinograms are found to elicit larger P200 amplitude than high-consistency sinograms.

On the basis of these studies, there appear to be two possible loci—orthographical or phonological—for the reduced P200 effect observed for radical interference (see Fig. 2). First, consistent with the graphical interference effect discussed above, the reduced P200 effect may reflect the facilitated activation of radicals' orthographical representations. Second, the reduced P200 may also reflect the inhibited phonological processing of targets. Specifically, the activation of targets' phonology may be suppressed due to the pre-activation of radicals' phonology.

The absence of sinogram interference effects for P200 is consistent with the findings of Liu et al. (2003), but inconsistent with other studies (Chen et al., 2007; Kong et al., 2010; Zhang et al., 2009) in which homophonic primes elicit a larger P200 effect on low-frequency targets. This inconsistency probably arises from the difference in experimental stimuli across the various studies. In our study, all targets are irregular sinograms, but the regularity of targets is not controlled in other studies. It is possible that the phonological computation of irregular targets is slow, leading to the null effect of homophonic primes on P200 in the present study. This account is partially supported by the study of Sereno, Rayner, and Posner (1998), in which spelling-to-sound regularity in English is found to modulate P200, as well as the study of Lee et al. (2007), which suggests that the orthography-to-phonology mappings (associated with the phonetic consistency) of sinograms modulates the P200 response. However, further experimental evidence in Chinese is needed.

4.1.3. N400

N400 is well-known for its association with semantic processing (Lau, Phillips, & Poeppel, 2008). Also, the N400 response has been suggested to be associated with the integrative process among various sources of information, including phonological information (e.g., Barnea & Breznitz, 1998; Valdes-Sosa et al., 1993). Supporting evidence from studies on both alphabetic word reading (e.g., Barnea & Breznitz, 1998; Rugg & Barrett, 1987) and Chinese reading (e.g., Liu et al., 2003) shows that phonological relationships between sequentially presented word pairs can modulate the N400 response. For example, in research on English word reading, Rugg & Barrett (1987) find that, compared with non-rhyming prime-target pairs (e.g., mind and wall), rhyming prime-target pairs (e.g., loan and bone) produce a reduced N400 response. In research on Chinese reading, lexical homophonic prime-target pairs are found to produce a reduced N400 response than control prime-target pairs (Chen et al., 2007; Liu et al., 2003; Zhang et al., 2009).

In terms of these studies, there appear to be two possibilities for the N400 effects. We observe that the N400 amplitude is enhanced by radical interference. First, because the meanings of the radicals as freestanding sinograms are different from those of their host sinograms, this enhanced N400 effect likely reflects enhanced semantic competition during lexical access of the host sinogram: The pre-activation of the radicals' phonology enhances the corresponding semantic representations of radicals, causing greater competition with the semantic representation of the host sinograms (see Fig. 2). Second, the activated information (including both pronunciations and meanings) of radicals may in turn cause interference during the integrative process of lexical information of the host sinograms. This result consolidates previous studies, which show that the meanings of radicals embedded in a sinogram are activated when those radicals exist as freestanding sinograms (Lee, Tsai, Huang, Hung, & Tzeng, 2006; see also Zhou & Marslen-Wilson, 1999a; Zhou et al., 2013).

Equally important, consistent with previous studies (Chen et al., 2007; Liu et al., 2003; Zhang et al., 2009), our results also show a reduced N400 response for sinogram interference. Similarly, there are two possible accounts for this reduced N400 effect of sinogram interference. First of all, it likely reflects facilitated semantic retrieval of targets during lexical access due to the pre-activation of lexical phonology (see Fig. 2). Secondly, this reduced N400 response may further reflect facilitated integration of the lexical phonological and semantic information due to the pre-activation of lexical phonology.

4.2. Implications for the phonological processing of Chinese reading

4.2.1. An interactive competition process in the phonological system: a special role for radical pronunciation?

Our results of the radical interference effect on the N170 and P200 components suggest that phonological processing does occur at a sub-lexical stage, since N170 and P200 responses are associated with the sub-lexical stages and the N400 response with the lexical stage in general (Barber et al., 2004; Lee et al., 2007).

The early activation of the radical pronunciation calls for a deeper understanding of its role in sub-lexical phonological processing during sinogram recognition. Some previous literature suggests that sub-lexical phonological processing of a sinogram involves the activation of the pronunciations of all orthographical neighbors containing the same phonetic radical (Lee et al., 2007; see also Hsu et al., 2009). Moreover, the degree of activation of the correct pronunciation depends primarily on the consistency values of sinograms. According to this picture, the radical pronunciation plays no special role in phonological processing.

However, phonetic consistency alone cannot account for all behavioral data. For instance, in the naming experiment of Lee et al. (2005), where the phonetic consistency and regularity are factorially manipulated, a consistency effect is found only for irregular sinograms (high-consistency sinograms are named faster than low-consistency ones), but not for regular sinograms. The lack of a consistency effect for regular sinograms is especially illuminating, since it means that consistency value has no predictive power about the average naming speed of this particular group of sinograms. This suggests that alternative mechanisms must be present, causing the naming of a group of regular sinograms to be relatively independent of whether its pronunciation has a high or low number of occurrences among its orthographical neighborhood. One intuitive account is that radical pronunciations are always activated, which enhances the correct pronunciation of regular sinograms having identical pronunciations as their phonetic radicals. If this is the case, the correct pronunciation of a regular sinogram will always receive extra activation from its radicals, which will in turn suppress the other pronunciations associated with its orthographical neighborhood.

This account is partially supported by both previous studies and our present results. Using the primed naming paradigm, previous studies demonstrate the activation of radical pronunciation by showing that primes facilitate the naming of targets that are homophonic with the radicals embedded in primes (Zhou & Marslen-Wilson, 1999a; Zhou et al., 2013). Consistent with these results, using the semantic judgment task, our study demonstrates that radical pronunciations are activated even in irregular sinograms where the radical pronunciation provides invalid cues. By inference, radical pronunciations should also be activated during reading regular sinograms where radicals give valid cues. In other words, radical pronunciation will always get activated to some degree by virtue of its association with a lexical identity during reading sinograms irrespective of their regularity. More explicitly, assuming that the radical pronunciation receives some degree of activation for all sinograms, this will compete with other pronunciations associated with the sinogram's orthographical neighbors (especially those with high-consistency values, which are expected to receive strong activations according to the consistency effect). Given that the correct pronunciation of regular sinograms is the same as the radical pronunciation, this correct pronunciation will receive stronger activation compared to the case for irregular sinograms, leading to stronger suppression of the other pronunciations associated with the orthographical neighborhood. As required, this predicts that regular sinograms will be named faster than irregular ones, which is referred to as the regularity effect and is frequently reported in naming experiments (e.g., Hue, 1992).

4.2.2. Future work: under what circumstances will pre-lexical phonology occur?

Our key finding is that, in reading low-frequency irregular sinograms, the radical pronunciation is activated pre-lexically, i.e., prior to that of the host sinogram. The question can be asked under what circumstances the pre-lexical activation of phonology will occur.

In the literature, word frequency has been found to affect the activation of radical pronunciations. One line of evidence comes from primed naming experiments where the aforementioned facilitatory effects from radicals embedded in primes are found only when the primes are of low-frequency, but not when the primes are of high-frequency (Zhou & Marslen-Wilson, 1999a; Zhou et al., 2013). Another line of evidence comes from naming experiments (e.g., Hue, 1992) which found the regularity effect only for low-frequency words, but not for high-frequency words. This interaction between word frequency and regularity is also frequently reported for alphabetic word reading (e.g., Seidenberg, 1985), and is explained by the relative finishing time assumption (Coltheart & Rastle, 1994). Specifically, for high-frequency irregular words, the dictionary-like lexical phonology is accessed before the phonemes, as translated from sub-lexical units (i.e., letter strings), are assembled into an incorrect pronunciation; in this case, the incorrect pronunciation never receives sufficient activation since it is quickly suppressed by the lexical phonology. In contrast, for low-frequency irregular words, an incorrect pronunciation is assembled from phonemes in about the same interval of time as the access of the dictionary-like lexical phonology; consequently, a conflict will be created by these two candidate pronunciations, which delays the onset of articulation.

Similarly, in Chinese, for irregular sinograms, radicals generate incorrect pronunciations, which may create conflicts with the correct pronunciation of the host sinogram. By analogy with the case of alphabetic words, whether the conflict actually brings about a noticeable delay (i.e., the regularity effect) likely depends on the relative timing of activation between the pronunciation of the host sinogram and that of the radical. In our view, word frequency is not the only factor determining the activation of the radical pronunciation. In particular, along the same line of thought as the relative finishing time assumption, we think that the relative frequency between host sinograms and their radicals as freestanding sinograms may also play an important role. When the sinogram is of higher frequency than the radicals, the activation of the host sinogram's pronunciation will be very fast, suppressing the activation of radical pronunciations. By contrast, when the sinogram is of lower frequency than the radicals, the activation of the host sinogram's pronunciation is relatively slow, thus allowing the radical pronunciation to be activated pre-lexically. We notice that, in a post-hoc pair-wise *t*-test between the token frequency of radicals as freestanding sinograms and that of host sinograms, the former is significantly higher than the latter [$t(71) = 4.546$, $p < .001$], which could be a potential reason for the pre-lexical activations in our study. To further understand the role of the relative frequency between host sinograms and radicals, while it would be desirable to vary word frequency and relative frequency orthogonally and to compare the radical and sinogram interference effects, not all combinations of the two factors may have enough exemplars in the Chinese script to realize this ideal design. In particular, low-frequency sinograms containing a radical of even lower frequency are especially rare. As a remedy, medium-frequency sinograms can be selected as the targets while the frequency of radicals can be manipulated to be either relatively higher or lower than that of the targets. Along the same line of thought as the relative finishing time assumption, when the frequency of the radical is lower than that of the target, the radical pronunciation is expected to be quickly suppressed by the sinogram pronunciation, and no radical interference effect will be found; on the contrary, when the frequency of the radical is higher than that of the target, the present results will be replicated. This design thus provides a stringent test on the role of relative frequency.

5. Conclusion

Our results demonstrate that in reading a low-frequency sinogram, the pronunciation of its radical is activated prior to that of the host sinogram. This sub-lexical phonology interacts with the sinogram pronunciation in the phonological system, exerts top-down influences on orthographical processing, and in turn activates semantic information. On the whole, it is likely that the two types of pronunciations—(1) the radical pronunciations and (2) the set of pronunciations associated with the sinograms' orthographical neighbors—are both present in an interactive competition process during sinogram recognition. Further studies can be directed toward understanding how the two types of phonological information of radicals interact at different stages of reading sinograms.

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