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Electrophysiological evidence of sublexical phonological access in character processing by L2 Chinese learners of L1 alphabetic scripts

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Abstract While Chinese character reading relies more on addressed phonology relative to alphabetic scripts, skilled Chinese readers also access sublexical phonological units during recognition of phonograms. However, sublexical orthography-to-phonology mapping has not been found among beginning second language (L2) Chinese learners. This study investigated character reading in more advanced Chinese learners whose native writing system is alphabetic. Phonological regularity and consistency were examined in behavioral responses and event-related potentials (ERPs) in lexical decision and delayed naming tasks. Participants were 18 native English speakers who acquired written Chinese after age 5 years and reached grade 4 Chinese reading level. Behaviorally, regular characters were named more accurately than irregular characters, but consistency had no effect. Similar to native Chinese readers, regularity effects emerged early with regular characters eliciting a greater N170 than irregular characters. Regular characters also elicited greater frontal P200 and smaller N400 than irregular characters in phonograms of low consistency. Additionally, regular-consistent characters and irregular-inconsistent characters had more negative amplitudes than irregular-consistent characters in the N400 and LPC time windows. The overall pattern of brain activities revealed distinct regularity and consistency effects in both tasks. Although orthographic neighbors are activated in character processing of L2 Chinese readers, the timing of their impact seems delayed compared with native Chinese readers. The time courses of regularity and consistency effects across ERP components suggest both assimilation and accommodation of the reading network in learning to read a typologically distinct second orthographic system.

Keywords L2 Chinese reading · Phonological regularity · Phonological consistency · Event-related potential (ERP) · N170 · P200 · N400 · LPC

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Writing systems across the world vary fundamentally in the visual form of writing units and the mapping between orthographic and other linguistic units, including phonological units, grammatical morphemes, and semantic features. For instance, words in most alphabetic scripts are formed by linear arrangement of letters, while characters in Chinese, widely considered a morphosyllabic script (DeFrancis, 1989), are square-shaped consisting of components referred to as radicals. For mapping from orthography to phonology, the correspondence can be between graphemes and phonemes (e.g., English, French, and Korean hangul), between graphemes and consonants only (e.g., Hebrew), between a symbol and a mora in Japanese katakana and hiragana, or between a character and a syllable in Chinese. In today's globalized world, communicating in spoken and/or written form in two or more languages in different contexts on a daily basis is a way of life. The questions of how different scripts can be processed at relative ease by bilingual or multilingual speakers and how the characteristics of these systems may interact at the brain level have fascinated psycholinguists and cognitive neuroscientists in recent decades (see a review in Lemh fer et al., 2008; also Kim, Yoon, & Park, 2004; Liu & Perfetti, 2003; Zhao et al., 2012).

While bilingual or multilingual research in reading is generally concerned with the impact of first language (L1) on second language (L2) learning, it is restricted by the fact that the majority of the studies have involved L2 English learners of different L1 alphabetic scripts (Lemh fer et al., 2008). Several investigations have examined word recognition in L2 English learners who are native readers of different writing systems (e.g., Chinese, Japanese, and Persian in Akamatsu, 2002; Chinese and Korean in Wang, Koda, & Perfetti, 2003). The present study focused on Chinese character recognition of bilingual individuals who read English as L1 and have reached intermediate proficiency in reading Chinese as L2. The English and Chinese systems represent, respectively, the most widely learned alphabetic and logographic scripts, and differ dramatically not only in appearance but also in orthography-phonology mapping. Perfetti, Cao, and Booth (2013) have discussed in detail the specific challenges L1 English speakers may face when learning to read Chinese. Investigation into how the bilingual English-Chinese brain represents and processes the two scripts can greatly benefit from a good understanding of how these systems are processed among individuals who learn them as L1s. As pointed out in Perfetti et al. (2013), much of the science of reading since the 1970s has centered on reading English. Consequently, a great deal is already known about L1 English reading. This introduction first briefly reviews studies of orthography-phonology correspondence in English, then focuses on the same aspect in the Chinese script and its impact on processing as revealed in behavioral and imaging measures. Where appropriate, the contrasts between the Chinese and English systems are highlighted. The background allows us to consider previous works on word reading in Chinese-English bilingual individuals.

Orthography-to-phonology mapping in English

The orthography-phonology relationships in English can be characterized in terms of regularity and consistency, depending on the theoretical approach. The regularity of a word is determined by whether its pronunciation conforms to grapheme-phoneme correspondence (GPC) rules of the language (e.g., regular words such as *raid*, *pink* vs. irregular words such as *pint*, *have*; Coltheart, Curtis, Atkins, & Haller, 1993; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001), while the consistency of a word depends on the strength of spelling-sound connections derived from the properties of the pronunciations of the "body" of other similarly spelled words (e.g., consistent words such as *bust*, *dust*, *gust*, *just*, *lust*, *must*, *rust* vs. inconsistent words such as *cost*, *host*, *lost*, *most*, *post*; Plaut, McClelland, Seidenberg, & Patterson, 1996; Seidenberg and McClelland, 1989). Both regularity and consistency have been shown to affect naming latency. Irregular words take longer to name than regular words (e.g., Baron and Strawson, 1976; Gough and Cosky, 1977; Stanovich and Bauer, 1978), and the effect is more pronounced in low frequency words (e.g., Andrews, 1982; Seidenberg, Waters, Barnes, & Tanenhaus, 1984; Waters, Seidenberg, & Bruck, 1984). Readers are also slower to read aloud inconsistent than consistent lexical items (Glushko, 1979). However, regularity and consistency are not easily distinguishable. Irregular or exception words are often inconsistent; moreover, in some studies regularity is defined in terms of neighborhood characteristics such as the relative numbers of friends (e.g., peak-teak) and enemies (e.g., peak-pear) (see for example Peereman, 1995). In the few studies that have manipulated both regularity and consistency, effects of consistency are robust while those of regularity are unclear or limited (Andrews, 1982; Kay and Bishop, 1987; Cortese and Simpson, 2000; Jared, 2002). This has raised the question of whether regularity effects conceptualized as GPC knowledge have important impact on reading alphabetic scripts.

ERP studies examining the regularity/consistency effects in English have traditionally focused on late components, the N400 and the following late positive complex (LPC), which occurs between 500–800 ms over the left centro-parietal region and is generally interpreted as reflecting conflict resolution and word recognition memory (see Rugg & Curren, 2007; Van Patten & Luka, 2012 for review). This is probably due to the fact that whole-word phonology is only available upon or after lexical access, which is believed to take place at the N400 time window (see Kutas & Federmeier, 2011; Lau, Phillips, & Poeppel, 2008 for review). The interaction between phonology and orthography reflected in N400 has been reported in Newman and Connolly (2004). They found comparable facilitative effects in N400 for pseudohomophones and semantically related words, compared with semantically incongruent words and pseudowords, in the context of semantically constrained sentences. More recently, Fischer-Baum, Dickson, and Federmeier (2014) have obtained larger LPC for irregular than regular English words, and the effect is restricted to low frequency words.

Orthography-to-phonology mapping in the Chinese writing system

Although the Chinese writing system is generally considered logographic, the notions of regularity and consistency have been shown to be highly relevant to reading, and they are theoretically more distinct. Almost all Chinese characters are monosyllabic and correspond to morphemes. There are no elements within a character that are linked to phonemes or tones. Orthographically, Chinese characters are made up of spatial arrangements of strokes, which combine to form larger units called radicals. Radicals may further combine to form complex characters or phonograms. More than 80 % of all Chinese characters are phonograms consisting of a semantic radical and a phonetic radical which provide clues to the meaning and the pronunciation of a character at the syllabic level, respectively. For instance, the character 趾 *zi2* "toe" has a semantic radical 足 on the left meaning "foot" and a phonetic radical 止 *zi2* on the right. (Phonetic transcriptions of Chinese characters are given in *jyutping*, a romanization system of Cantonese Chinese developed by the Linguistics Society of Hong Kong. The number in the transcription represents the tone.) About 34–40 % of phonograms are "regular" characters (Law, Weekes, Wong, & Chiu, 2009) with pronunciations segmentally identical (regardless of tone) to the pronunciation of their phonetic radical when it occurs as a character (e.g., 湖 *wu4* and 胡 *wu4*). Another 30 % are "partially regular" phonograms sharing at least the same rime as their phonetic radical (e.g., 他 *taa1* and 也 *jaa5*), and the rest are "irregular" with no phonological relationship with their phonetic radical (e.g. 路 *lou6* and 各 *gok3*).

Besides regularity, the phonological property of a character can also be described in terms of consistency. It refers to the extent to which the phonetic radical serves as a reliable cue to the pronunciations of the phonograms containing it. A character of high consistency is one that sounds the same as most, if not all, phonograms with the same phonetic radical (e.g., 驅 *keoi1*, 軀 *keoi1*, 嶇*keoi1*, 敺*keoi1*, 鰸*keoi1*, 嘔 *ngau2*), and a low consistency character is one that shares the phonetic radical with phonograms that sound differently (e.g., 油 *jau4*, 宙, *zau6*, 迪 *dik6*, 笛 *dek6*, 軸 *zuk6*). In other words, regularity is defined by the phonological distance between a phonogram and its phonetic radical and only applicable to phonograms with phonetic radicals that exist as standalone characters, while consistency is determined by the different phonological forms associated with a family or neighborhood of phonograms having a common phonetic radical. Therefore, consistency in Chinese is comparable to that in alphabetic scripts (Lee, 2008), whereas regularity in relation to the phonetic radical is unique to the Chinese writing system.

Psycholinguistic studies of character naming using a behavioral measure of response latency have consistently found an interaction between regularity and character frequency, where low frequency regular phonograms, but not high frequency ones, have significantly shorter reading latencies than irregular phonograms (e.g., Fang, Horng, & Tzeng, 1986; Lee, Tsai, Su, Tzeng, & Hung, 2005; Wu, Chou, & Liu, 1994). When regularity, consistency, and frequency were independently manipulated, a significant interaction was observed between regularity and consistency for low frequency characters (Lee et al., 2005; also see Yang, McCandliss, Shu, & Zevin, 2009 for a computational model that correctly predicted behavioral naming results). More specifically, Lee et al. (2005) found that among irregular phonograms, high consistency characters were named faster than low consistency characters.

Neuroimaging data showed that the right inferior frontal gyrus and bilateral medial frontal gyri were more active when viewing briefly presented irregular compared to regular characters if they were low frequency (Peng et al., 2004). This paralleled the behavioral pattern of frequency by regularity interaction. ERP studies further demonstrated that effects of regularity and consistency seem to emerge during the earliest stage of word recognition, suggesting highly efficient phonological recoding at the character and sub-character (or sublexical) levels among skilled readers. ERP components associated with regularity were first reported in Lee, Tsai, Huang, Hung, and Tzeng (2006). In a probe recognition task, significant N400 semantic priming effects were elicited by regular phonograms when contrasted with the unrelated control condition. The results suggest that the phonological forms of the phonogram and its phonetic radical have modulating effects on semantic processing during the N400 time window. Lee et al. (2007) found consistency effects in N170 in the temporo-occipital region, P200 in the frontal region, and N400 in the central region in homophone judgment. In particular, greater negativity in N170 and greater positivity in P200 were elicited by inconsistent characters compared with consistent ones, while greater N400 was found for consistent than inconsistent characters (Lee et al., 2007). The effects at N170 and P200 were interpreted as early extraction of phonological information from the phonetic radical, whereas effects at N400 were taken to reveal post-lexical processing resulting from competition among activated representations at the lexical level. When consistency was manipulated with neighborhood size taken into consideration, consistent characters were shown to exhibit greater negativity in N170, smaller P200, and greater N400 compared with inconsistent stimuli (Hsu, Tsai, Lee, & Tzeng, 2009), but these effects were restricted to characters from large orthographic neighborhoods ($N > 10$) compared with small ones ($N < 4$). One noteworthy point is that the consistency contrast in Hsu et al. (2009) and Lee et al. (2007) was between extreme values, with high consistency stimuli having an average consistency rating approaching 1. This extreme contrast, in combination with the lack of information on the regularity status of the stimuli, may raise the question whether consistency was confounded with regularity in these studies.

The possible confounding between regularity and consistency in previous studies was recently addressed in Yum, Law, Su, Lau, and Mo (2014), which examined the two effects simultaneously in a lexical decision task and a delayed naming task. Effects of regularity and consistency in ERPs were only found in delayed naming (see also Fischer-Baum et al., 2014, reporting effects of regularity and lexical frequency as a function of task demands). Importantly, regularity effects showed an earlier onset and were longer lasting than those of consistency. Regular characters elicited larger N170, smaller P200, and larger N400 compared to irregular characters. In contrast, significant effects of consistency were only seen at the P200 with consistent characters exhibiting a greater P200 than inconsistent characters. The regularity effect in N170 reflects the presence of conflict between phonological forms in irregular phonograms, i.e. those of the phonogram and its phonetic radical. Stronger P200 may be interpreted as more effortful processing due to competition between two phonological forms, and more negative N400 as greater processing effort when different word meanings are mapped onto the same phonological form. The consistency effects in P200 can be explained in terms of competition among orthographic neighbors induced by the phonetic radical of the target phonogram. Although Yum, Law et al. (2014) did not examine the interaction of regularity and consistency, both the time course and the direction of the effects indicate that the two variables have distinct effects. In sum, the ERP findings of early occurrence of phonological effects among Chinese skilled readers indicated highly efficient visual analyses of orthographic units and synchronous access to orthography and lexical phonology.

Orthographic and phonological processing in L2 Chinese reading

The similarities and differences in neural regions and the distinctive time courses associated with cognitive processes during visual word recognition in L1 readers of English and Chinese constitute a unique context for the examination of how learning to read one of these scripts as L2 is influenced by having the other script as L1. Chinese is well known for its prevalence of homophony at the single character level, which has led to the hypothesis that orthography is more reliable than phonology in character recognition (Perfetti et al., 2007; Yum, Midgley, Holcomb, & Grainger, 2014), in contrast to alphabetic and syllabic systems where phonological information is integral to lexical access (Grainger & Holcomb, 2009). Findings compatible with this view include Wang et al. (2003), in which L1 speakers of Korean misclassified homophones of English targets (*stare* instead of *stair*) more often than graphemic controls (e.g., *stars*), whereas L1 Chinese speakers did not show this pattern (see also Muljani, Koda, & Moates, 1998, of native readers of Indonesian). However, Akamatsu (2002) examined L2 learners of English who are L1 speakers of Chinese, Japanese, and Persian, and found no difference in effects of lexical frequency and phonological regularity in patterns of L2 English word naming.

In a series of studies involving beginning learners of Chinese who were native English speakers, Perfetti and colleagues observed early sensitivity to visual-orthographic forms of Chinese characters. For instance, English speakers who learned Chinese as L2 for one year showed activities in the left fusiform gyrus while viewing English words, but recruited the right fusiform gyrus while viewing Chinese characters (Nelson, Liu, Fiez, & Perfetti, 2009). Training studies of native English speakers with limited exposure to the script revealed similar patterns (Deng, Booth, Chou, Ding, & Peng, 2008; Deng, Chou, Ding, Peng, & Booth, 2011; Liu, Dunlap, Fiez, & Perfetti, 2007). These previous findings showed that visual-orthographic processing of Chinese characters was prominent during the very early stage of Chinese learning, which required support through recruiting the right occipital area. However, there has been little evidence for sublexical orthography-to-phonology mapping during character recognition among beginning Chinese learners. Given the relatively low proficiency in Chinese of the bilingual participants in those studies and previous demonstration of how the pattern of processing in L2 may approach that in L1 when proficiency increases (e.g., Geyer, Holcomb, Midgley, & Grainger, 2011; Ng & Wicha, 2013; Sebastian, Laird, & Kiran, 2011), it is a theoretically significant question whether access to phonological representations of Chinese characters may differ in more advanced L2 Chinese learners, in light of the fundamental differences in orthographic forms of the two writing systems and the nature of orthography-phonology mapping.

The present study examined online access to orthographic and phonological representations of Chinese characters in L2 Chinese readers who are proficient in spoken Cantonese and have constant exposure to both the English and Chinese scripts in their daily life. These individuals thus differed importantly from most L2 Chinese participants in previous studies in terms of the extent of their exposure to the Chinese script and the command of the spoken language. We recruited L2 Chinese learners who had reached the Chinese reading level of Grade 4 of primary schools in Hong Kong. The requirement of a minimum reading level of Primary 4 was motivated by previous findings in developing L1 Chinese readers. It has been repeatedly reported that effects of regularity were observed as early as Primary 1, while effects of consistency only emerged in Primary 4 and among pupils with high reading abilities (see Chen, Shu, Wu, & Anderson, 2003, for a review; Shu, Zhou, & Wu, 2000).

Using a similar design to Yum, Law et al. (2014), the L2 Chinese participants took part in lexical decision (LD) and delayed naming (DN) tasks. As described before, observations of effects of regularity and consistency were confined to DN among native readers, plausibly because they are able to make lexicality judgment based solely on the orthographic form without access to phonology. These two tasks were applied in the current study to examine whether similar effects of task demand would be found among relatively proficient L2 Chinese learners. However, unlike Yum, Law et al. in which different, although overlapping, sets of characters served as stimuli for investigating the regularity and consistency effects separately, this study used a fully-crossed factorial design to examine the temporal dynamics of phonological regularity and consistency. Furthermore, since subjective lexical frequency tends to be low among L2 readers relative to L1 readers, we did not manipulate this variable, but instead matched the cumulative frequency of characters across conditions.

Effects of regularity and consistency and their interaction are revealed by brain activities reflected in the N170, P200, N400, and LPC components. Our interest in the N170, P200, and N400 is apparent as both phonological effects have been reported at these components in L1 Chinese character recognition. The LPC component is also examined because regularity/consistency effects have been observed among English readers (Fischer-Baum et al., 2014). Demonstration of such effects would entail analysis of phonograms into constituent sub-character units which access the associated phonological information. The occurrence of the two effects and their time courses across the ERP components may reflect accommodation (i.e., modifications of the L1 system to accommodate the demands particular to L2) and assimilation (i.e., processing of L2 reveals characteristics similar to those of L1) in L2 literacy development (Perfetti et al., 2007), albeit more from a processing standpoint. Specifically, the presence of regularity effects would suggest accommodation especially if they emerge early on, since the relationship between a phonogram and its phonetic radical is specific to Chinese and must be developed during L2 acquisition. Phonological effects in LPC may reflect assimilation as they have not been found in Chinese character processing but reported in reading in English.

Based on prior observations of L1 young and adult Chinese readers and L2 Chinese learners, we predict that effects of regularity and consistency would occur among L2 Chinese readers at the Primary 4 reading level. We further expect that phonological effects would appear before N400, as beginning L2 Chinese learners already show sensitivity to the visual-orthographic structures of characters, and that the effects would be stronger in the naming task. In contrast, since we know of no prior ERP work examining these phonological effects in L2 learners, we hesitate to make predictions about how early the effects may emerge and how long they last.

Method

Participants

Eighteen native English speakers (12 female) aged 15–29 years (M = 19.9, SD = 3.5) participated in the study. All were right-handed and had a normal neurological profile and visual acuity. All participants acquired written Chinese (traditional script) as L2 after age 5 years and were around Grade 4 Chinese reading level in Hong Kong with reference to the reading age of 9;00 to 10;00 (equivalent to Grade 4), with z-scores ranging between −0.33 to +2 SDs as assessed by the word reading subtest of the Hong Kong Test of Specific Learning Disabilities (HKT-SpLD; Ho, Chan, Tsang, & Lee, 2000). For details of participants' language background, refer to Table 1. Written informed consent was obtained from all participants and the experiments were approved by the Human Research Ethics Committee for Non-Clinical Faculties of the University of Hong Kong. All participants were paid for their participation in the study.

Materials

The stimuli consisted of 160 real phonograms learned by Grade 2 (Leung & Lee, 2002) and 160 pseudo-characters created by re-combining the phonetic and semantic radicals of the real character stimuli in accordance with orthographic rules. Each character contained one phonetic radical and one semantic radical in left-right or top-bottom configurations.

Character stimuli were divided into four conditions by manipulating consistency (consistent vs. inconsistent) and regularity (regular vs. irregular). Consistency was calculated as the sum frequency of "friends" (orthographic neighbors with the same phonetic radical and pronunciation) divided by the total frequency of characters containing the phonetic radical. To match the reading level of the participants, cumulative frequency values of the characters at Grade 4 were used. Following Yum, Law et al. (2014), we did not include the phonetic radical as a simple character in our calculations of consistency values; this diverged from some previous studies (e.g., Hsu et al., 2009; Lee et al., 2005, 2007). By definition, characters low in consistency had phonetic radicals that were associated with more syllables than characters high in consistency. Low consistency characters also tended to have more orthographic

Table 1 Participants' background for Cantonese Chinese as a non-native language

	Range	Mean (SD)
Self-rated proficiency (out of 5)		
Speaking	2–5	3.9 (0.8)
Listening	3–5	3.9 (0.8)
Reading	2–5	3.3 (0.9)
Writing	1–4	2.5 (0.9)
Percentage of daily usage		
Speaking and listening	5–70 %	36.1 % (21.7)
Reading and writing	0–40 %	17.5 % (13.1)
Age of first exposure (in years)		
Spoken	2–10	5.2 (2.3)
Written	5–18	8.0 (3.4)
HKT-SpLD word reading z-score (z-score relative to Grade 4)	−0.33 to +2	+0.5 (0.7)

neighbors sharing their phonetic radicals than those with high consistency. Regular characters in our stimuli shared both onsets and rimes with their phonetic radicals irrespective of tones, while irregular characters did not meet this criterion. Regular and irregular characters were matched in token consistency. Phonetic radicals did not overlap across the four conditions, but within a condition, a phonetic radical appeared at most three times in combination with different semantic radicals. Stimuli were matched across the four conditions in stroke number, lexical frequency, and total orthographic neighborhood size (total number of neighbors sharing phonetic or semantic radicals with the stimuli). The number of homophones was higher in regular compared to irregular characters, which was expected because regular characters are homophonic with their phonetic radicals. Stimuli properties and example stimuli are given in Table 2.

Procedure

All participants first completed screening tasks and questionnaires about their language background. They then performed a lexical decision (LD) task followed by a delayed naming (DN) task in a sound-attenuated and electrically shielded booth. As the same set of real characters was employed in the two tasks, task order was fixed to reduce priming effects which might influence lexical judgment. A practice block was provided prior to each task. Stimuli were presented as yellow characters (100 × 90 pixels) on a black background on a computer screen approximately 60 cm away. The experiments were presented with a different random sequence of stimuli delivered by E-Prime (Psychology Software Tools Inc., USA), with the response buttons counterbalanced across participants.

In LD, each trial started with a fixation cross (500 ms) followed by a blank screen (1,000–1,200 ms), the target stimulus (800 ms), and another blank screen (1,100–1,300 ms). Participants were instructed to press different response buttons to indicate whether the character was real or not as soon as they made a decision. In DN, each trial started with a fixation cross (500 ms) followed by a blank screen (1,000–1,200 ms) and a character (800 ms), which was replaced by three asterisks until a naming response was made. Participants read aloud the character upon seeing the asterisks which served to minimize muscle artifacts generated by verbal production in the time window of visual word recognition.

Electroencephalographic recordings

The electroencephalographic (EEG) data were recorded from 64 silver-silver chloride sintered electrodes (10–20 system) with a vertex reference electrode and the ground positioned anterior to electrode Fz. Vertical and horizontal eye movements were monitored by bipolar electrodes placed on the supra- and infra-orbital ridges of the left eye and bipolar electrodes placed on the left and right side of the lateral orbital rim. Electrode impedance was kept below 5 kΩ. Data were digitized online at 1 kHz with a band pass filter of 0.05–200 Hz using SynAmps2® (Neuroscan, Inc., El Paso, TX, USA) amplifiers.

Event-related potential (ERP) data processing

ERP data were filtered offline using Neuroscan 4.5 software (Compumedics Ltd., Charlotte, NC, USA) with a zero-phase shift band-pass filter of 0.05–30 Hz (12 dB/ octave slopes). Channels affected by eye blink artifacts were corrected using an ocular artifact reduction model implemented in Neuroscan 4.5, with a minimum of 100 eyeblink artifacts for each participant. Epochs of −200 to 1,000 ms after stimulus onset were obtained, then baseline corrected using the pre-stimulus interval and re-referenced to the average of the two mastoid electrodes.

Table 2 Example stimuli and means (standard deviations) of stimuli properties in the four conditions: RC = Regular-Consistent, RIC = Regular-Inconsistent, IRC = Irregular-Consistent, and IRIC = Irregular-Inconsistent

	High consistency		Low consistency		*p* value
	RC	IRC	RIC	IRIC	
Character	蛛 *zyu1*	渾 *wan6*	惜 *sik1*	堵 *dou2*	
Phonetic radical	朱 *zyu1*	軍 *gwan1*	昔 *sik1*	者 *dze2*	
Stroke number	11.6 (3.06)	12.8 (2.98)	11.7 (3.50)	12.1 (3.53)	.330
Cumulative character frequency	100.9 (110.6)	107.7 (121.5)	99.8 (106.3)	112.3 (124.3)	.958
Cumulative phonetic radical frequency	144.1 (282.6)	201.5 (615.6)	152.9 (222.2)	114.1 (145.8)	.755
Total orthographic neighborhood size	194.7 (111.1)	165.6 (124.4)	145.0 (103.5)	151.0 (121.8)	.224
Token consistency	.90 (.10)	.87 (.09)	.21 (.13)	.22 (.14)	< .001
Phonetic radical neighborhood size	3.9 (1.0)	3.6 (0.9)	7.0 (2.6)	7.8 (2.8)	< .001
No. of associated syllables for phonetic radical	1.9 (0.7)	2.4 (0.7)	5.1 (1.3)	6.0 (1.7)	< .001
No. of homophones	5.4 (2.8)	4.0 (2.8)	4.9 (3.9)	3.3 (2.5)	.015

Trials contaminated with artifacts, with incorrect responses, response latencies exceeding 2,000 ms, or voltage exceeding ±100 μV were excluded. Grand average waveforms for each condition were then computed from individual channels.

Statistical analyses

Behavioral accuracy of each task was separately measured using two-way ANOVAs with Regularity and Consistency as independent variables. Regularity and Consistency were treated as within-subject variables in the analysis by participants (F_1) and between-item variables in the analysis by items (F_2). Due to the response delay in DN, RT results were only reported for LD, again using two-way ANOVAs. Response time (RT) analysis was only performed on correct responses that fell between ±3 SDs on an individual basis. For LD, an additional contrast of lexicality on accuracy and RT to real and pseudo-characters was done using *t*-tests.

For the ERP data, mean amplitudes at the N170 (110–190 ms), P200 (190–270 ms), N400 (270–450 ms), and LPC (500–800 ms) were analyzed statistically. The N170 analyses were performed at parietal and occipital sites (PO5, PO6, PO7, and PO8). The P200 was measured at frontocentral sites (F3, F4, FC3, FC4, C3, and C4). The N400 and LPC analyses were performed at midline electrodes (Fz, FCz, Cz, CPz, and Pz) and lateral electrodes (F3/4, FC3/4, C3/4, CP3/4, and P3/4). These electrodes were based on previous reports of lexicality and phonological effects in Chinese (Hsu et al., 2009; Lee et al., 2007; Yum, Law et al., 2014) and the analysis time windows were set using the peak latencies derived from the mean amplitude for all trials at the selected electrode locations. The main experimental variables were regularity (regular vs. irregular), consistency (consistent vs. inconsistent), and task (LD vs. DN). Topographic variables – hemispheres and electrode locations – were included to examine the scalp distribution of the effects, so effects of these variables were only reported when they interacted significantly with experimental variables. To correct for the violations of sphericity, the Greenhouse-Geisser adjustment was applied. For all *post-hoc* multiple comparisons, the significance thresholds were corrected with the Bonferroni adjustment.

Results

Behavioral results

Mean accuracy and RT are presented in Table 3. In the delayed naming (DN) task, regular characters were named significantly more accurately than irregular characters ($F_1(1,17) = 61.95$, $p < .001$, $\eta\rho^2 = .785$; $F_2(1,156) = 10.23$, $p = .002$, $\eta\rho^2 = .062$), but consistency did not have an effect on naming accuracy and no regularity by consistency interaction was observed (all F's < 2.8, *ns*). In lexical decision (LD), neither regularity, consistency, nor their interaction showed significant effects on response accuracy (all F's < 2.8, *ns*). RTs in LD were significantly faster in inconsistent characters than consistent characters in the subject analysis only ($F_1(1,17) = 5.37$, $p = .033$, $\eta\rho^2 = .240$; $F_2(1,156) = 2.74$, $p = .100$). No difference was seen in RTs between regular and irregular characters ($F_1(1,17) = 1.86$, *ns*; $F_2(1,156) = 0.14$, *ns*). There was a trend for an interaction of regularity and consistency ($F_1(1,17) = 3.79$, $p = .068$; $F_2(1, 156) = 2.19$, *ns*), where a consistency effect was seen in irregular characters only. The lexicality contrast in LD showed that real characters were responded to more accurately than pseudo-characters in the item analysis but not the subject analysis ($t_1(17) = 0.92$, *ns*; $t_2(318) = 2.54$, $p = .012$, $d = 0.28$). Real characters were responded to significantly more quickly than pseudo-characters ($t_1(17) = 3.10$, $p = .007$, $d = 0.50$; $t_2(318) = 9.88$, $p < .001$, $d = 1.10$).

ERP results

Overall, 19 % of trials in DN and 16 % in LD were rejected due to incorrect responses or other artifacts. The grand average waveforms for the regularity and consistency contrasts at N170, P200, N400, and LPC at representative electrodes were plotted in Figs. 1, 2, 3, and 4. Visual inspection of the waveforms confirmed that there was a negative-going component at posterior sites peaking around 150 ms (N170), followed by a positive-going component maximal at fronto-central sites around 230 ms (P200). A broadly distributed negative deflection peaked around 306 ms (N400) and was followed by a sustained positivity (LPC).

N170 (110–190 ms)

There was a significant main effect of task with DN being more negative than LD ($F(1,17) = 5.70$, $p = .029$, $\eta\rho^2 = .251$), and task also interacted with hemisphere and electrode location (Task × Hemisphere: $F(1,17) = 6.57$, $p = .020$, $\eta\rho^2 = .279$; Task × Electrode: $F(1,17) = 4.78$, $p = .043$, $\eta\rho^2 = .220$). Pairwise comparisons indicated that DN was more negative than LD at right hemisphere electrodes ($p = .003$) and at PO7/8 ($p = .009$). A main effect of regularity was found ($F(1,17) = 4.60$, $p = .047$, $\eta\rho^2 = .213$), with regular characters eliciting a greater negativity than irregular characters (Fig. 1), but no main or interaction effects of consistency were observed in this time window (*p*s > .1).

P200 (190–270 ms)

Analysis revealed a main effect of Task ($F(1,17) = 17.23$, $p = .001$, $\eta\rho^2 = .504$), where DN was more positive than LD. Task interacted with hemisphere ($F(1,17) = 7.54$, $p = .014$, $\eta\rho^2 = .307$) such that the task effect was stronger at the left

Table 3 Behavioral results in Delayed Naming (DN) and Lexical Decision (LD) tasks

	Consistent		Inconsistent		All real characters	Pseudo-characters
	Regular	Irregular	Regular	Irregular		
DN accuracy	88.2 % (9.7)	77.4 % (10.8)	88.2 % (7.1)	81.3 % (8.0)	83.8 % (7.8)	n/a
LD accuracy	87.1 % (9.4)	83.6 % (14.4)	87.1 % (8.3)	87.4 % (10.0)	86.3 % (9.6)	82.3 % (10.7)
LD RT	598 ms (100)	612 ms (116)	594 ms (96)	589 ms (87)	598 ms (99)	658 ms (136)

Values are means with standard deviations in parentheses

RT response time

hemisphere electrodes (p < .001) than the right (p = .002), although the effects were in the same direction. No main effects of regularity or consistency were observed (ps > .1). Regularity and consistency produced a significant interaction ($F(1,17) = 6.19$, p = .024, $\eta\rho^2$ = .267). Pairwise comparison revealed that the regularity contrast was not significant in consistent characters (p > .1), but regular-inconsistent characters were more positive than irregular-inconsistent characters (p = .047; Fig. 2). In regular characters, inconsistent characters were marginally more positive than consistent characters (p = .063), but the consistency contrast was not significant in irregular characters (p > .1). Regularity also interacted with task and hemisphere ($F(1,17) = 8.65$, p = .009); pairwise comparison yielded a trend in DN for a right-lateralized effect of regular characters being more positive than irregular characters (p = .059). In LD, neither hemisphere showed an effect of regularity (ps > .1).

N400 (270–450 ms)

Task did not show any significant effect in this epoch (ps > .1). Main effects of regularity or consistency were not observed (ps > .1), but the two factors again produced a significant interaction (midline: $F(1,17) = 9.30$, p = .007, $\eta\rho^2$ = .354; lateral: $F(1,17) = 13.37$, p = .002, $\eta\rho^2$ = .440). Pairwise comparisons revealed that within consistent characters, regular characters elicited larger N400 than irregular characters (midline: p = .021; lateral: p = .006). Within inconsistent characters, irregular characters were more negative than regular characters at lateral sites and showed the same trend at midline (midline: p = .083; lateral: p = .034). In regular characters, consistent characters produced marginally greater N400 amplitudes than inconsistent characters in the lateral analysis only (midline: p > .1; lateral: p = .061). In irregular characters, inconsistent characters were significantly more

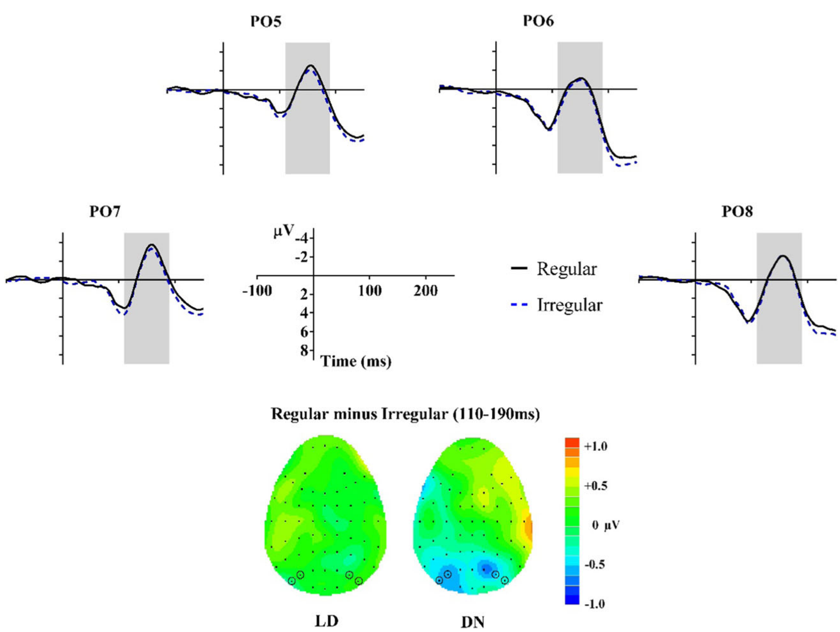

Fig. 1 Grand average waveforms and topographic plots of the N170 regularity effect. The analysis window (110–190 ms) was shaded in grey in the waveforms. The topographic plots were calculated by subtracting irregular characters from regular characters in each task; analysis sites were marked in black circles

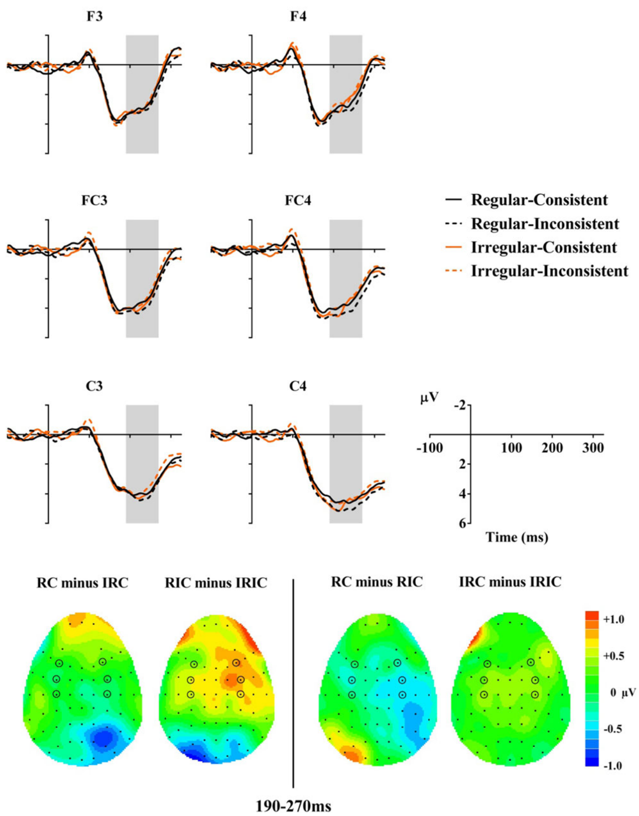

Fig. 2 Grand average waveforms and topographic plots of P200 effects collapsed across tasks. The analysis window (190–270 ms) was shaded in grey in the waveforms. Topographic plots showed the regularity contrasts in inconsistent and consistent characters (left plots) and consistency contrast in regular and irregular characters respectively (right plots). Analysis electrodes were marked in black circles

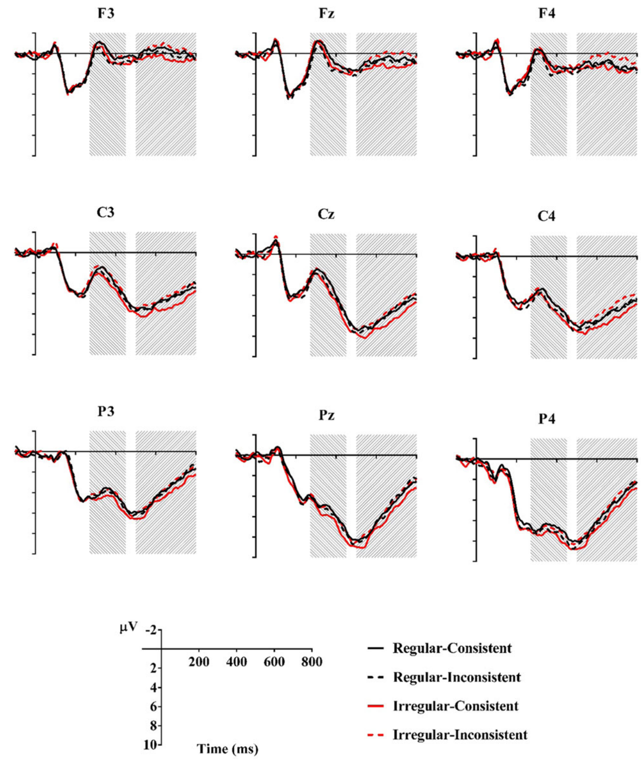

Fig. 3 Grand average waveforms of the N400 and LPC effects collapsed across tasks. The analysis windows (270–450 ms and 500–800 ms) were shaded in the waveforms

negative than consistent characters (midline: $p = .033$; lateral: $p = .021$; Fig. 3).

A main effect of lexicality in LD was observed at the N400 component, where pseudo-characters were more negative than real characters ($F(1,17) = 37.17$, $p < .001$, $\eta\rho^2 = .686$). Lexicality also interacted with electrode locations ($F(4,68) = 9.03$, $p = .001$, $\eta\rho^2 = .347$), but pairwise comparisons indicated that the effect was significant at all electrodes (all $ps < .05$).

LPC (500–800 ms)

A main effect of task indicated that LD was more positive than DN (midline: $F(1,17) = 17.00$, $p = .001$, $\eta\rho^2 = .500$; lateral: $F(1,17) = 9.23$, $p = .007$, $\eta\rho^2 = .352$). No main effects of regularity or consistency were significant at the LPC ($ps > .1$). Regularity continued to interact with Consistency (midline: $F(1,17) = 10.08$, $p = .006$, $\eta\rho^2 = .372$; lateral: $F(1,17) = 12.22$, $p = .003$, $\eta\rho^2 = .418$; Fig. 3). Pairwise comparisons indicated that within consistent characters, irregular characters were more positive than regular characters (midline: $p = .020$; lateral: $p = .016$). Within inconsistent characters, regular characters were marginally more positive than irregular characters at lateral sites but not at midline (midline: $p > .1$; lateral: $p = .091$). In regular characters, consistent characters were not different from inconsistent characters (both $ps > .1$). In irregular characters, consistent characters were significantly more positive than inconsistent characters (midline: $p = .019$; lateral: $p = .005$). This interaction was moderated by a significant five-way interaction of Task × Regularity × Consistency × Hemisphere × Electrodes in the lateral analysis ($F(4,68) = 3.03$, $p = .034$, $\eta\rho^2 = .151$).

Follow-up analyses were then performed within each task at the lateral sites. In DN, no effects were significant except for a trend for the Regularity × Consistency interaction ($F(1, 17) = 3.30$, $p = .087$, $\eta\rho^2 = .163$). In LD, no main effects were found but the interaction of regularity and consistency was significant ($F(1,17) = 8.36$, $p = .010$, $\eta\rho^2 = .330$). Pairwise comparisons revealed significantly more positive amplitudes for consistent characters relative to inconsistent characters in irregular characters ($p = .028$) but not regular characters ($p > .1$). The regularity contrast did not produce any effect ($ps > .1$). A four-way interaction of Regularity × Consistency × Hemisphere × Electrode was also found ($F(4,68) = 6.14$, $p = .001$, $\eta\rho^2 = .265$). Pairwise comparisons showed more positive LPC for irregular-consistent than regular-consistent characters at P4, and more positive amplitudes for irregular-consistent characters than irregular-inconsistent characters at FC4, C4, and CP4 ($ps < .05$).

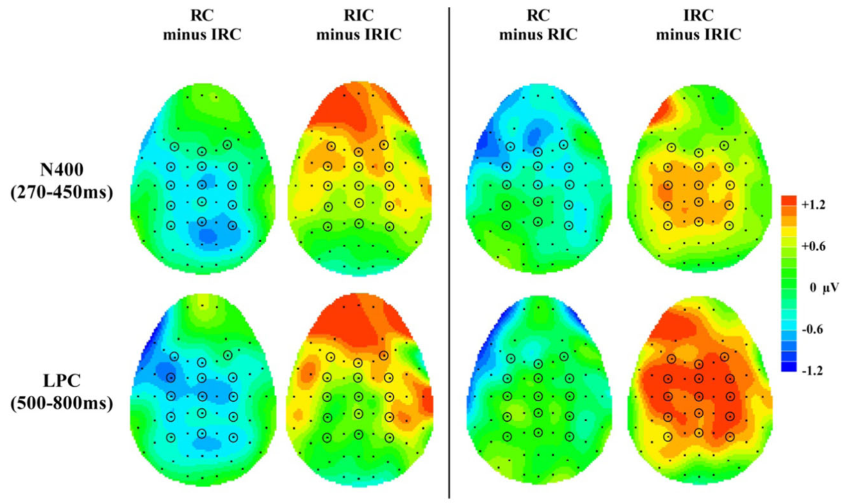

Fig. 4 Topographic difference plots for the N400 (top row) and LPC (bottom row) effects. Analysis electrodes were marked in black circles

Discussion

The behavioral results showed that real characters were responded to more quickly than pseudo-characters in lexical decision, similar to Wang et al. (2003). Regular characters were named significantly more accurately than irregular characters, although no reliable effect either in latency or accuracy was noted in LD. Null effects were found for consistency in all of the behavioral measures. The presence of sensitivity to regularity but absence to consistency are *apparently* compatible with studies of literacy development in Chinese in that children as early as Grade 1 are aware of the pronunciation of the phonetic radical of a phonogram, whereas awareness of phonological information of orthographic neighbors of the phonogram is not firmly developed at Grade 4, the reading level of our L2 Chinese participants (Chen et al., 2003; Shu et al., 2000). The ERP results, however, revealed a much richer picture of sublexical phonological access in character processing of L2 Chinese learners that reflected both regularity and consistency effects. This contrast between relatively few reliable phonological effects from behavioral measures and observations of the same effects across ERP components was also found in Yum, Law et al. (2014).

Regular characters were shown to elicit a greater N170 than irregular characters. Overall brain activities in this time window seem to be right-side dominated and driven by delayed naming. A tendency of similar pattern was also noted in P200, where regular characters elicited more positive responses than irregular characters at right hemisphere electrodes. As no source analysis was carried out, we will not consider the issue of lateralization any further. The pattern of regularity effect was evident among inconsistent characters, i.e., regular-inconsistent characters showed more positive P200 than irregular-inconsistent characters. Significant interaction effects between regularity and consistency were likewise observed in N400 and LPC. In both time windows, a contrast in regularity was obtained among consistent and inconsistent characters, and a difference in consistency was seen among irregular characters. For the regularity effect, regular-consistent characters had more negative N400 and less positive LPC than irregular-consistent characters. The regularity effect among inconsistent characters appeared to continue from the P200 regularity effect, with regular characters eliciting more positive waves in N400 and LPC, albeit only marginally significant in the LPC epoch. For the consistency contrast, inconsistent-irregular phonograms exhibited more negative N400 and less positive LPC than consistent-irregular characters. As mentioned before, stimuli in DN elicited larger amplitudes than in LD in N170 and P200. However in the LPC window, a larger positivity was seen in LD than in DN and the phonological effects were also stronger in LD compared to DN. Finally, pseudo-characters elicited more negative N400 than real characters in lexicality judgment, as commonly seen in previous studies (e.g., Bentin, McCarthy, & Wood, 1985; Holcomb, 1993; Nobre & McCarthy, 1994).

The overall pattern of ERP results demonstrated similarities and differences to previous studies of regularity and consistency effects in L1 adult Chinese readers, as well as novel findings compared with those of beginning L2 Chinese learners. The most notable observations are the early occurrence of regularity effects with regular phonograms showing more negative N170 than irregular characters and the relative time courses of the two effects, i.e., regularity preceding consistency, similar to the results in Yum, Law et al. (2014). As suggested in Yum, Law et al., the N170 regularity effect might be explained by the activation of the phonological form of the phonetic radical interfering with whole character phonological access in irregular characters. The two phonological effects have different time courses because when presented with a phonogram, the reader would first analyze the character into radical components and access the corresponding phonological forms. The phonetic radical would then spread activation to all phonograms containing it; the activated phonograms would subsequently access their phonological representations, which compete with one another. More negative N400 for regular than irregular phonograms was reported in Lee et al. (2006) and Yum, Law et al. (2014), and taken as a reflection of greater processing demand when different word meanings are mapped onto the same phonological form. Greater N400 for inconsistent than consistent characters is, however, incompatible with the pattern in Lee et al. (2007) and Hsu et al. (2009). As phonetic radicals of low consistency tend to be associated with a greater number of alternative syllables compared with those of high consistency (see Table 2), it has been proposed that more negative N400 to inconsistent characters is due to a higher number of activated phonological candidates at this stage resulting in greater overall activation level. Although the consistency contrast was only found among irregular characters in the current study, in both N400 and LPC, the pattern can be considered conforming to the behavioral results in Lee et al. (2005). The similarities between the present findings from L2 Chinese learners and those of previous work on L1 Chinese readers show that for relatively experienced non-native readers of Chinese, the effects of regularity and consistency have independent underlying mechanisms, complex characters are first analyzed into radicals which access phonological information in a highly efficient manner, and that the influence of orthographic neighbors becomes evident shortly after.

Despite the similarities, it is noted that the polarity of regularity effects in this study was different from that in Yum, Law et al. (2014). We want to draw attention to some important differences between the two studies: (i) the regularity effect was restricted to inconsistent characters here but the two ortho-phonological factors were not factorially manipulated in the previous study; (ii) the regularity effect was obtained from characters with an average consistency ratings of 0.21–0.22 in the present study and 0.45–0.50 in Yum, Law et al. It is thus likely that regularity effects are not uniformly related to the degree of consistency of the phonetic radical, which may change the dynamic of interference during phonological processing as a consequence. Previous priming studies in Chinese character reading have found that when orthography and phonology are manipulated independently, the P200 is enhanced by homophone priming (Kong, Zhang, Kang, Du, Zhang, et al., 2010; Zhang, Zhang, & Kong, 2009). The P200 enhancement for homophones was interpreted as facilitation in phonological processing (Kong et al., 2010); we speculate that in the current results regular characters elicited more positive P200 than irregular characters among inconsistent characters due to facilitated phonological access, i.e., the phonetic radical in regular characters primed lexical-level phonology. It follows then that the smaller N400 for regular-inconsistent compared to irregular-inconsistent characters might be explained by the pre-activation of semantic representations by the phonological forms, since reduced N400 is generally interpreted as easier semantic access. The patterns in P200 and N400 were only observed in low consistency characters possibly because of a trade-off in using regularity versus consistency information. The high number of phonological competitors (i.e., orthographic neighbors and alternative syllables) in inconsistent characters hinders a single phonological or semantic form from reaching threshold. The difficulty in using neighborhood information might dispose the L2 readers to rely on available information from the phonetic radical. Thus the facilitation from the phonetic radical in regular characters is captured in inconsistent characters only.

Whereas effects of regularity and consistency in L1 Chinese reading have been consistently found in N400 and early components including N170 and P200 (Hsu et al., 2009; Lee et al., 2006, 2007; Yum, Law et al., 2014), such effects have not been reported for later time windows, e.g., LPC. On the contrary, phonological effects on word reading in English have reported activities at late components that reflect post-lexical analyses, e.g., Fischer-Baum et al. (2014). Our findings of L2 Chinese readers show that while regularity effects emerged as early as N170 and consistency effects in N400, they persisted into the LPC time window. Importantly, we analyzed the L1 adult Chinese data in Yum, Law et al. from the same channels and time window and did not detect the presence of any phonological effects.

The LPC has been associated with different cognitive functions, such as conflict resolution, predictability, and memory retrieval, particularly in processing of sentences requiring reanalysis. More positive LPC generally indicates greater processing effort. We attribute greater positivity in LPC to more interference from phonological competitors for irregular compared with regular characters, and high compared to low consistency characters. The situation with regularity is obvious. For consistency, Yum, Law et al. (2014) have previously proposed that fewer phonological competitors would actually induce stronger inhibition among one another than when there are more competitors. Since consistent characters have fewer phonological alternatives than inconsistent phonograms, this may result in greater competition and mutual interference. In both contrasts, greater positivity was obtained in a condition where regularity and consistency provided incongruent information (i.e., irregular-consistent) compared to conditions where regularity and consistency were congruent (i.e., regular-consistent and irregular-inconsistent). Thus, the LPC might also reflect post-lexical evaluation of information mismatch between the two measures of sublexical orthography-to-phonology mapping. At present, it is hard to determine whether the lingering phonological effects in the LPC time window and later emergence of consistency effect in N400 in L2 Chinese learners, compared with its occurrence in P200 among L1 Chinese adults (Yum, Law et al., 2014), represent slower processing of orthographic neighbors because of their comparatively lower reading skills, or influence from their experience in reading an alphabetic script as L1.

The current design of employing lexical decision and delayed naming was to examine the extent to which phonological effects were subject to task demands, and we found a major difference between L1 and L2 Chinese readers. When L1 Chinese participants were asked to name characters or judge the lexicality of characters varying in regularity and consistency, effects of these variables reflected in ERPs were found only in delayed naming. In contrast, such an interaction between task and experimental conditions was not obtained in L2 Chinese learners until the LPC time window. It is worth noting that regularity effects in a lexical decision task have been observed in 9-year-old native Chinese readers, most of whom just finished Grade 4 (Su, Lau, & Law, 2013). The presence of phonological effects in LD performed by L1 Chinese developing readers and L2 Chinese learners can be interpreted as automatic extraction of phonological information during character recognition, whereas the absence of these effects in LD among L1 adult readers can be indicative of high reading skills and very efficient visual/orthographic analysis of characters, such that the lexicality status of a character can be judged solely on its orthographic form. Although neither phonological effect interacted with task until post-lexical access in the LPC, it is worth noting that brain activities were stronger in DN than in LD during the N170 and P200 windows, but stronger for LD than for DN in LPC. We speculate that the task effects have different underlying processes, that is, extraction of phonological information for naming versus perhaps a general reappraisal process.

The alert reader may notice that the order of task administration was LD before DN for all participants, and question whether there would be long-term priming in DN from LD. We suggest that the overall pattern of findings is unlikely to be influenced by the fixed task order based on two observations. First, there was no support from interaction effects between phonological effects and task. If priming was a factor, one would expect stronger effects in DN than LD across all ERP components, but this was not the case. Second, the same set of target stimuli was presented in both tasks. If priming played a role, it should be comparable for all stimulus types. In other words, the reason for suspecting differential priming as a function of stimulus type is not strong.

Finally, although the L2 Chinese learners with an intermediate level of reading proficiency in the present study demonstrated near-native neural responses reflecting sublexical phonological access, we are careful not to immediately generalize the results to all L2 Chinese learners. We are keenly aware of the fact that they may be quite different from L2 learners one normally encounters in a classroom. Our participants are fluent in the spoken language and they live in an environment that allows extensive exposure to the script. It is not unlikely that their highly efficient phonological access at the lexical and sublexical levels is due to the combination of both factors. Future studies in this direction should involve L2 learners of different levels of proficiency in the oral and written languages, as well as extents of exposure to the orthography in their daily life.

Conclusions

Our present observations based on neural correlates of sublexical phonological access in L2 Chinese learners of L1 alphabetic scripts during Chinese character processing have yielded a rich picture delineating the underlying mechanisms across stages. The ERP results suggest that the overall pattern of brain activities exhibited by non-native Chinese readers resembles that of L1 Chinese in terms of the distinctive time courses and nature of regularity and consistency effects. L2 Chinese readers who have achieved a reading level of Grade 4 can orthographically and phonologically process phonograms as efficiently as native Chinese readers. Although orthographic neighbors clearly participate in character processing, the timing of their impact seems to be somewhat delayed compared with L1 Chinese readers. The early appearance of regularity effects and the occurrence of both phonological effects in LPC suggest accommodation as well as assimilation of reading processes in learning to read a typologically distinct orthographic system as a second language. The current findings complement previous reports of beginning L2 Chinese learners, and highlight the importance that a full understanding of bilingual literacy development of different orthographic systems must depend on examination of learners representing a wide range of competence.

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