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N170 reflects visual familiarity and automatic sublexical phonological access in L2 written word processing

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Abstract

The literature has mixed reports on whether the N170, an early visual ERP response to words, signifies orthographic and/or phonological processing, and whether these effects are moderated by script and language expertise. In this study, native Chinese readers, Japanese–Chinese, and Korean–Chinese bilingual readers performed a one-back repetition detection task with single Chinese characters that differed in phonological regularity status. Results using linear mixed effects models showed that Korean–Chinese readers had bilateral N170 response, while native Chinese and Japanese–Chinese groups had left-lateralized N170, with stronger left lateralization in native Chinese than Japanese–Chinese readers. Additionally, across groups, irregular characters had bilateral increase in N170 amplitudes compared to regular characters. These results suggested that visual familiarity to a script rather than orthography-phonology mapping determined the left lateralization of the N170 response, while there was automatic access to sublexical phonology in the N170 time window in native and non-native readers alike.

Introduction

In event-related potential (ERP) studies of orthographic processing, the N170 component – usually found to peak between 160–200 ms post-stimulus onset and having a typical distribution of occipital-temporal negativity coupled with frontal-central positivity – is a robust index of one's sensitivity to print (see Maurer & McCandliss, 2007 for review). The amplitude of N170 is stronger in response to words, pseudowords, and letter strings in contrast with non-linguistic visual forms (e.g., Nobre, Allison & McCarthy, 1994; see Xue, Maurer, Weng & Zhao, 2019 for a brief review), and left lateralized N170 is indicative of reading expertise in young and adult readers (e.g., Maurer, Brandeis & McCandliss, 2005; Maurer, Zevin & McCandliss, 2008; Rossion, Joyce, Cottrell & Tarr, 2003; Tong, Maurer, Chung & McBride, 2016). The left lateralization of the word N170 is thought to originate from the left occipital-temporal cortex named the visual word form area (VWFA; Cohen & Dehaene, 2004).

The roles of writing system, visual expertise, and phonological mapping

While early findings of the reading-related N170 focused on alphabetic scripts, subsequent investigations reported the component in other writing systems, including non-alphabetic languages such as Japanese, Korean, and Chinese (Xue, Jiang, Chen & Dong, 2008; Zhao et al., 2012). Based on the observations that Chinese character reading requires deep visuospatial analysis and shares visual features with pictured objects, which is right-lateralized, some researchers suggested that N170 may be more bilaterally distributed in a logographic script such as Chinese or Japanese kanji (Maurer et al., 2008; Yum, Holcomb & Grainger, 2011). A non-exhaustive survey of the current N170 reports in Chinese with adult readers showed mixed results with regards to hemisphere laterality. Some studies indeed found a right-lateralized or bilateral topography. Most of them involved tasks requiring phonological access such as naming (Hsu, Tsai, Lee & Tzeng, 2009; Lee et al., 2007; Liu & Perfetti, 2003; Wang & Maurer, 2017; Yum et al., 2011), while some employed lexical decision (Su, Mak, Cheung & Law, 2012), repetition detection of single Chinese characters, Roman letters, Chinese character strings, and letter strings (Wang & Maurer, 2017; Wong et al., 2005), or even passive viewing (Xue et al., 2008). There are also studies that found a left-lateralized topography. Interestingly, the great majority, if not all, of these reports were based on content-irrelevant tasks such as color-matching (Cao et al., 2011; Lin et al., 2011; Xue et al., 2019; Zhao et al., 2012), size judgment (Lu et al., 2011), and repetition detection (Maurer et al., 2008; Qin, Maurits & Maassen, 2016). Taken together, these results suggested that the N170 effect can be found across different writing systems, and its lateralization may not be a distinct characteristic of a particular writing system as previously thought.

Although numerous studies have obtained distinctive N170 responses to written linguistic vs. non-linguistic materials, many of them have also noted a stronger left-lateralized N170 to real and pseudo words compared with consonant strings in alphabetic scripts (see Xue et al., 2019 for review). One account for these findings is based on visual familiarity. As such, Xue et al. (2019) presented Chinese characters in normal print form, characters in cursive form, and meaningless stroke combinations to skilled Chinese readers in a color-matching task. It was found that participants could correctly identify the cursive form characters in an offline task, but only showed left lateralization of the N170 to regularly printed characters. These results have led to the conclusion that visual familiarity is a main driver of the increased and left-lateralized N170 effect.

Besides expert sensitivity to print, some researchers have hypothesized that the word N170 may also reflect early mapping between orthography and phonology. This phonological recoding hypothesis was raised for the print tuning effects among alphabetic language learners (Maurer et al., 2005). Yoncheva, Wise and McCandliss (2015) reported an artificial word learning study in which training in grapheme-phoneme mapping, but not whole word mapping, led to left lateralization of the N170 in a forced-choice reading verification task matching auditory word and visual word. Some studies have linked the lateralization of word recognition to the same hemisphere as language production, providing argument for the phonological hypothesis (Cai, Lavidor, Brysbaert, Paulignan & Nazir, 2008).

The current literature has revealed inconsistent findings on whether sublexical phonology may have already come into play at the N170 component. In English word reading, the phonological regularity effect can be detected in the late positive complex (LPC) occurring after 600 ms post-stimulus onset (Fischer-Baum, Dickson & Federmeier, 2014). On the contrary in Chinese, phonological regularity reflecting congruity between the whole character and the phonetic radical is a robust effect of sublexical phonology in behavioural measures (Lee, Tsai, Su, Tzeng & Hung, 2005). The effect has been reported in the form of larger N170 to regular characters, compared with irregular ones in delayed naming but not lexical decision (Yum, Law, Su, Lau & Mo, 2014a). However, more recently, Yum and Law (2019) employed a large set of 500 Chinese characters in a delayed naming task, in which 64% were regular and irregular characters following the distribution of Chinese textbooks, to explore the effects of regularity, lexical frequency and age-of-acquisition (AoA) using mixed-effects modelling. While no main effect of regularity was found, interactions between Regularity and AoA and that between Regularity and Frequency were obtained in the N400 and LPC time windows, respectively.

Non-native readers' N170 response in different writing systems

The reading-related N170 has been examined not only among native readers but also non-native readers to understand how the similarities between first language (L1) and second language (L2) scripts may influence processing of L2 words. Studies of readers of alphabetic and logographic writing systems using different tasks have so far yielded discrepant findings, as reviewed below.

Employing a binary semantic decision task in L1 Korean–L2 Chinese and English learners, Kim, Yoon and Park (2004) found left-lateralized N170 response (referred to as N200 in the paper) to English and Korean words, but bilateral posterior activation to Chinese words and pictures, highlighting the influence of orthography-phonology mapping, as both Korean Hangul and English are alphabetic scripts. Maurer et al. (2008) subsequently observed left-lateralized N170 response to English words among L1 Japanese–L2 English learners in a repetition detection task, suggesting that the orthographic characteristics of a native script do not transfer to or affect the left lateralization of the early component in L2. The result appears to be reinforced by Yum, Midgley, Holcomb and Grainger (2014b), in which a training study was conducted with native English readers who were initially naïve to Chinese scripts. Learners were exposed to 200 Chinese words in ten laboratory sessions and they were tested on word meaning but not pronunciation. A left-lateralized increase in N170 was found for fast learners, interpreted as reflecting development of orthographic sensitivity. More recently, to assess L2 Chinese readers' awareness of orthographic well-formedness of characters, Yum, Law, Lee and Shum (2018) presented characters violating orthographic rules to non-native Chinese learners of L1 alphabetic scripts in a repetition detection task. The participants exhibited bilateral P100 and N170 responses, but the radical position contrast showed a right-lateralized P100 effect followed by left-lateralized N170 effect, while L1 Chinese readers showed the effect at left-hemisphere electrodes in the P100 time window. In another study that examined phonological effects (Yum et al., 2016), non-native Chinese learners of a similar language background to those in Yum et al. (2018) participated in delayed naming and lexical decision tasks. It was found that regular characters elicited stronger N170 than irregular characters, and the overall brain activities were right-side dominated and driven by delayed naming.

In sum, early neural responses can be seen among non-native readers reflecting visual/orthographic sensitivity and phonological effects in naming tasks that explicitly require access to phonology, apparently regardless of similarity in linguistic features between native and non-native scripts. However, the laterality of the response seems to vary across studies, perhaps related to task conditions.

Current study

In this study, we examined the N170 responses to single Chinese characters in Japanese–Chinese and Korean–Chinese bilinguals, relative to native Chinese readers. The differences among these three typologically different writing systems offer a unique opportunity to examine how visual/orthographic properties and orthography-phonology mapping may impact the N170 of a non-native script. Details of the three writing systems are provided below. A one-back repetition detection task (e.g., Maurer et al., 2008) was chosen because it required visual word form identification, which was a basis for character reading. Moreover, activation of phonological information is non-obligatory in such a task; if phonological effects are seen, it would suggest early and automatic retrieval of phonological information at the N170 time window. As far as we know, the manipulation of phonological regularity in repetition detection has not been done previously. A large set of stimuli of over 400 characters was used in a mixed effects model to have sufficient power to detect group and condition differences and to include relevant orthographic variables as

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covariates. The phonological regularity status and lexical frequency of the characters were naturally distributed, which allowed a more thorough and generalizable analysis of Chinese character processing than previous investigations.

The results of the study allow us to address the following questions:

- Are phonological effects detectable at the N170 in a form-based repetition detection task to reflect automaticity of early phonological access in native and non-native scripts?
- If so, are phonological effects affected by the readers' native script?
- Do orthographic or phonological factors affect the lateralization of the N170?

Characteristics of Chinese, Japanese, Korean writing systems

A core difference among existing writing systems is the degree of sublexical phonological coding. Alphabetic languages have grapheme-phoneme conversion rules, and phonemic-level sublexical phonological information is integral to lexical access in alphabetic systems (Grainger & Holcomb, 2009). Syllabic systems such as Japanese kana lack such phonemic level conversion but grapheme-syllable mapping also promotes phonological recoding (e.g., Okano et al., 2013). In contrast, in morphosyllabic systems like Chinese, access from orthography to semantics is relatively early and direct (e.g., Zhou & Marslen-Wilson, 2000), whereas orthography to phonology mapping is opaque. However, there is coarse-grained sublexical phonological information that can be retrieved in many Chinese characters.

The existence of sublexical units that independently carry phonological and semantic representations is a distinct feature of the Chinese orthography. More than 80% of all Chinese characters are phonograms with a phonetic radical, which may provide sublexical clues to the character's pronunciation. Phonological regularity is defined by the correspondence of the pronunciation of the phonetic radical and the whole character (Shu, Chen, Anderson, Wu & Xuan, 2003). Regular characters shared the same onset and rime with their phonetic radicals, regardless of tone. For instance, the regular character 清 /qīng/ has a phonetic radical 青 /qīng/ on the right (phonetic transcriptions are given in Hanyu pinyin). Irregular characters have different onset or rime compared to their phonetic radicals, but may have same or different tones, e.g., 猜 /cāi/ has different onset and rime compared to its phonetic radical 青 /qīng/. Some phonograms contain bound phonetic radicals, which do not have individual pronunciation or meaning in modern Chinese: for instance, 峰 /fēng/ with the phonetic radical 夆. Around 10% of Chinese characters are simple characters that cannot be subdivided into radicals, e.g., 片 /piān/ and that contain no sublexical information. Other characters may be ambiguous in regularity because either the character or the phonetic radical has more than one pronunciation.

The Japanese writing system uses a mixture of three scripts. The two kana scripts, Hiragana and Katakana, are syllabaries in which one sign represents one syllable in a highly regular manner. The Japanese kanji script is highly similar to Chinese characters in terms of visual form, and many characters are cognates with Chinese characters with similar meanings. However, on the phonological level, there is divergence between Japanese and Chinese reading. Japanese kanji has a dual-pronunciation system, with *kunyomi* 'native-Japanese pronunciations' and *onyomi* 'Sino-Japanese pronunciations' (Joyce & Masuda, 2018). Although the prevalence of regularity in the *onyomi* reading of kanji characters is around the same as in Chinese characters (~32%, as cited in Fushimi, Ijuin, Patterson & Tatsumi, 1999), sublexical phonological information from phonetic radical is much less reliable than in Chinese. The main reason is that the typical kanji character has one-to-many orthography-to-phonology mappings, meaning that both the phonetic radical and the character may carry several pronunciations. Thus, even when the character is fully regular in *onyomi* reading, only one reading of the phonetic radical will provide clue for one of several legitimate readings of the whole character. This inherent ambiguity in kanji phonology has been noted by several researchers, who argued that the smallest unit of Japanese kanji phonology should occur at the character-level rather than the sub-character level (Fushimi et al., 1999; Mori, 1998). Additionally, while *onyomi* are derived from Chinese pronunciations, their correspondence with contemporary Mandarin pronunciation is low as lexical borrowing and phonological change occurred over a span of hundreds of years.

Korean *hangul* characters are block-like with several internal structures (top-bottom, left-right, etc). The ensuing visual analysis for sublexical orthographic information may be somewhat similar to Chinese characters. However, Korean writing is an alphabetic syllabary, in that separate characters correspond to syllables, and each character is made up of at least two sub-character phonemic "letters." The mapping of these letters and phonemes is transparent and regular, so there is one-to-one mapping of a written character to a syllable and sublexical phonological support is strong and reliable. Previously, Wang, Koda and Perfetti (2003) found that native speakers of Korean misclassified homophones of English targets (*stare* instead of *stair*) more often than visual controls (e.g., *stars*), whereas native speakers of Chinese did not show this pattern. This points to a more phonological processing approach in Korean speakers.

In short, in terms of visual similarity, Japanese kanji is highly similar to Chinese[1], whereas Korean Hangul is superficially so. If visual familiarity is a main driver of increased left-lateralized N170 as argued in Xue et al. (2019), then the pattern of neural activation of L1 Japanese readers is expected to resemble that of L1 Chinese, compared with L1 Korean. Additionally, if early automatic phonological access is reflected in N170 which may or may not be lateralized, and if there is transfer of L1 to L2 processing, effects of sublexical phonological access when viewing Chinese characters may be expected of Korean–Chinese but not Japanese–Chinese readers, on the basis that kanji and kana promote an addressed phonology approach, while Hangul contains sublexical phonology as in other alphabetic scripts.

Method

Participants

Three groups of participants who were native speakers of different languages participated in this study – (i) 22 native Mandarin speakers (18 females; mean age: 23.2, SD: 4.4) participated as native readers of the simplified Chinese script; (ii) 22 native Korean speakers (19 females; mean age: 20.6, SD: 2.5); and (iii) 18 native Japanese speakers (10 females; mean age: 28.2, SD: 9.8) participated as non-native readers of simplified Chinese. However, data from three Japanese participants were excluded due to repetition detection accuracy below 70% and low

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Table 1. Demographics and Language Background of the Three Participant Groups

	Chinese	Japanese	Korean	*p*
Gender (M:F)	4:18	5:10	3:19	
Age (in years)	23.2 (4.4)	29.7 (10.0)	20.6 (2.5)	<.001
Handedness[a]	79.2 (15.6)	74.8 (17.9)	80.2 (27.8)	.740
Accuracy in Chinese screening test (out of 75)	N.A.	66.8 (7.9)	61.3 (10.1)	.086
Self-rated Chinese reading ability (out of 5)[b]	N.A.	3.9 (1.0)	3.6 (1.1)	.404
Age of Acquisition of Chinese	N.A.	14.6 (9.7)	10.9 (3.1)	.102

Notes. N.A. = Non-applicable.
[a]Measured by the Edinburgh Handedness Inventory (Oldfield, 1971); participants were considered right-handed if they scored from 40 to 100. [b] Larger value indicated higher self-rated ability.

signal-to-noise ratio, resulting in 15 usable datasets in this group. A character reading task was used for screening to ensure that the non-native participants were able to read simplified Chinese at the expected intermediate-advanced level. Participants had normal vision and hearing, a healthy neurological profile, and no history of reading or learning difficulties. All participants were right-handed except for one ambidextrous Korean speaker. A language background questionnaire was administered to collect information on the non-native Chinese readers' age of acquisition and self-rated Chinese proficiency. Demographics, language background, and performance on screening test were provided in Table 1. Written informed consent was obtained from all participants at the beginning of the experimental sessions. The study was conducted in accordance with the Declaration of Helsinki with approval of the University of Hong Kong Human Research Ethics Committee for Non-Clinical Faculties (Ref. # EA840114). Participants received cash upon completion of the experimental tasks as compensation for their time.

Stimuli

Experimental stimuli were selected from the Hanyu Shuiping Kaoshi (HSK) vocabulary lists. The HSK is a standardized test of Chinese ability with six levels– level 1 is the beginner level, while level 6 is highest.

Screening task

The screening task consisted of 75 Chinese characters which were at Level 5 of the HSK and did not appear in the experiment. Level 5 corresponded to an intermediate-advanced Chinese level with an estimated vocabulary of 1685 different characters in the simplified script, commonly used in mainland China and Singapore. Participants who correctly read aloud at least 50 items out of the 75 were invited to continue with the experiment.

Repetition detection task

For the repetition detection task, we selected 416 single characters at HSK Levels 1 through 5 (see Appendix A for the complete list of the stimuli). With reference to the distribution of phonological regularity in school Chinese (Shu et al., 2003), regular and irregular characters each made up around 32% of stimuli. There were 132 regular characters and 134 irregular characters in the stimuli list, and their phonetic radicals were characters learned within HSK levels 1 to 5 as well. To minimize repetition or neighborhood effects within the experiment, each phonetic radical appeared at most twice in different characters. There were 74 characters with only lexical-level, but no sublexical-level phonological representations, i.e., simple characters or compound characters without standalone radicals. All regular and irregular characters, their associated phonetic radicals, and the lexical-only characters have a single legitimate pronunciation. The remaining 76 characters were phonologically ambiguous because the character or the phonetic radical had multiple pronunciations.

Regarding character structures, there were 231 characters with left-right structure (e.g., 林), 115 characters had top-bottom structure (e.g., 杏), and 70 characters with semi-enclosed (e.g., 床) or simple (e.g., 木) structures. For details of the psycholinguistic properties of the stimuli, please refer to Table 2. As can be seen, the lexical-only and ambiguous characters tended to be more frequent, acquired earlier, and contained fewer strokes than regular and irregular characters. Meanwhile, the regular and irregular characters in the stimuli were closely matched in their psycholinguistic properties. Only L2 homophone density was significantly larger for Regular than Irregular characters (p = .003), because regular characters were homophonous with their phonetic radicals by definition.

Of the 416 single Chinese characters, 215 (51.7%) have visually identical kanji cognates appearing in *joyo kanji,* an official list of 2136 kanji in common use. The cognates are distributed evenly among regular and irregular characters – 60 out of 132 regular characters (45.5%) and 61 over 134 irregular characters (45.5%), while in higher proportion for ambiguous characters (43 out of 76; 56.6%) and characters with lexical-only phonology (51 over 74; 68.9%). For the regularity status of the kanji cognates, 51 of 60 regular and 51 of 61 irregular characters had phonetic radicals that appeared in the *joyo kanji*. Of these, 39 of the regular Chinese characters were also regular in Kanji, i.e., with identical pronunciations between the On readings of the phonetic radical and the whole character. Meanwhile, 17 of the irregular Chinese characters were regular in Kanji. For the ambiguous characters, there were 21 characters with identifiable phonetic radicals among the 43 kanji cognates, and 5 were regular.

Procedure

In an electrically and acoustically shielded room, participants completed a go/no-go 1-back repetition detection task with response hand counter-balanced across participants. Participants were asked to make a button-press response when identical stimulus was presented consecutively and not to make a response if the stimulus was not repeated. Among the stimuli, 64 characters (13.3%) were repeated as targets (20 regular characters, 22 irregular characters, 11 lexical-only characters, and 11 ambiguous characters). On each trial, a white fixation cross on a black background

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Table 2. Psycholinguistic Properties of Stimuli Separated by Sublexical Phonological Status

	Regular (n = 132)	Irregular (n = 134)	Lexical-only (n = 74)	Ambiguous (n = 76)	Range of all items (n = 416)
	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Min – Max
Lexical frequency[a]	3.64 (0.59)	3.65 (0.56)	4.20 (0.64)	3.90 (0.62)	1.96–6.07
HSK level	3.86 (1.30)	3.85 (1.25)	2.91 (1.39)	3.39 (1.36)	1–5
No. of strokes	9.53 (2.81)	9.33 (2.45)	6.00 (2.16)	9.71 (3.03)	2–21
Concreteness[b]	4.97 (1.01)	5.09 (0.93)	4.90 (1.07)	4.91 (1.01)	2.63–7
L1 HD[c]	38.49 (39.23)	31.28 (27.77)	32.16 (28.56)	29.76 (25.67)	1–205
L2 HD[d]	4.02 (2.77)	3.06 (2.55)	2.97 (2.72)	2.82 (2.49)	1–15
HSK level of PR	3.39 (1.31)	3.28 (1.50)	N.A.	N.A.	1–5
Family size of PR[e]	2.61 (1.62)	2.41 (1.63)	N.A.	N.A.	1–3
No. of strokes of PR	5.86 (2.25)	5.92 (2.20)	N.A.	N.A.	1–9
Character structure	92 L-R; 27 T-B; 13 Oth	91 L-R; 28 T-B; 15 Oth	41 L-R; 28 T-B; 7 Oth	7 L-R; 32 T-B; 35 Oth	

Notes. HD = homophone density. PR = Phonetic Radical. N.A. = Non-applicable. L-R = left-right. T-B = top-bottom. Oth = others (simple and semi-enclosed).
[a]Log-transformed lexical frequency of single characters appearing in film subtitles, taken from the SUBTLEX-CH database (Cai & Brysbaert, 2010). [b] Ratings of concreteness were taken from the database constructed by Liu, Shu, and Li (2007); greater values indicated more concrete characters. [c] L1 homophone density values were taken from the database by Liu et al. (2007); the values showed the number of characters with the same syllabic level pronunciation (onset, rime, and tone) in all Chinese characters. [d] L2 homophone density was calculated from the HSK vocabulary list levels 1 to 5, and showed the number of characters with the same syllabic level pronunciation (onset, rime, and tone) within the vocabulary lists. [e] Family size of a phonetic radical referred to the number of phonograms that contain the phonetic radical.

was presented for 500 ms, followed by a variable blank screen of 900–1100 ms. Then a Chinese character in white on a black background was presented for 1000 ms and a variable blank screen of the inter-trial interval (ITI) of 900–1100 ms was shown before the next trial. The Chinese characters were presented in FangSong font with 40 font size in bold, and subtended visual angles of around 3 degrees vertically and horizontally. Presentation of stimuli and recording of behavioral data were done by the EPrime 2.0 (Psychological Software Inc.). There were 11 practice trials before the actual experiment and the stimuli were presented over four blocks. Instructions were given before each block to remind the participants to give a response to the repeated item. Each block lasted 7–8 minutes, and breaks without time limit were allowed between blocks.

ERP recording and processing

Electroencephalogram (EEG) was recorded using SynAmps2 Neuroscan system with a 64-channel Ag/AgCl electrode cap and digitally sampled at 1000 Hz with a bandpass filter of 0.05 to 200 Hz and subsequently down-sampled to 500 Hz before data analysis was carried out. During recording, the vertex was used as reference and the ground was anterior to Fz. Eye blinks and horizontal eye movements were monitored by electrodes placed above and below the left eye and at the outer canthus of each eye. The impedance of all electrodes was kept below 5 kΩ during recording. ERP data were filtered offline using NeuroScan4.5 software with a zero phase-shift bandpass filter of 0.05 to 30 Hz with 12 dB/Oct slopes. Data affected by eye blinks were corrected using the ocular artefact reduction procedure implemented in Scan4.5, with individually modeled blinks computed from at least 100 blink artefacts. Epochs of 200 ms pre-stimulus onset to 1000 ms post-stimulus onset were then extracted, baselined to the pre-stimulus interval, and re-referenced to a whole-head average reference. Only non-response trials were used in statistical analyses, and trials with errors (false positive) or amplitudes exceeding ±100 μV in any channel were rejected.

Data analysis

Behavioral accuracy for repetition detection was summated and compared across participant groups to ensure task engagement. ERP data's epoch for analyses was selected based on the mean global field power (MGFP) of all participants' data in all groups and conditions. The grand average ERPs revealed the N170 peak in occipital regions at around 168 ms. The dependent variables were the mean amplitude and peak latency of the N170 (140–200 ms) averaged over the left parietal-occipital electrodes PO7, PO5, P7, P5, O1 and the corresponding electrodes on the right PO8, PO6, P8, P6, O2. After rejecting artefacts and false alarms, 91.0% of all critical trials were retained. Examination of the Q-Q plot of the N170 data revealed that the values were not normally distributed at both tail ends. Since this violated the normality assumption of regression models, extreme values that exceeded three standard deviations from the overall mean were trimmed (0.97%). Remaining data were normally distributed and were submitted to linear mixed-effects regression analyses using restricted maximum likelihood (REML) estimation.

In the models, the N170 responses of the two trilingual groups were compared with those of the native Chinese group. Fixed factors included: (i) Participant Group, (ii) Laterality, (iii) Regularity, (iv) Character Structure, (v) Number of Strokes, (vi) Lexical

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Frequency, and (vii) Age of Participants. Factors (i) to (iii) and their interactions were tested as the main fixed effects and factors (iv)-(vii) served as control variables. The Regularity factor was compared using Helmert contrasts – lexical-only characters were first compared to the mean of all other levels (single representation contrast); ambiguous characters were compared to the mean of Regular and Irregular characters (ambiguity contrast); finally, Regular and Irregular characters were contrasted (regularity contrast). Continuous fixed factors (i.e., number of strokes, lexical frequency, and age) were standardized to *z*-scores to reduce multicollinearity. Number of strokes and lexical frequency were significantly correlated ($r = -.26$, $p < .001$) while age was not correlated with either variable. The F-statistics from omnibus Type III ANOVAs were reported, and, for significant interactions, post-hoc pairwise comparisons were reported with Bonferroni corrections.

The random effects structure was determined by model comparisons using likelihood ratio tests. First, random intercepts for subjects and items were tested, then random slopes for significant fixed factors of interest were forward-fitted. A more complex random structure was adopted only if model comparison suggested a significant improvement (Baayen et al., 2008). In the mean amplitude model, there were significant random slopes of Regularity by Participant ($p < .001$), Number of Strokes by Participant ($p < .001$), and Group by Item ($p < .001$), while the model did not converge when Laterality, Character Structure, or Age were fitted as random slopes. In the peak latency model, significant random slope of Laterality by Participant was found ($p < .001$), where the model did not converge when other fixed factors were fitted as random slopes.

Results

Behavioral response

Behavioral accuracies were comparable across groups. Out of 64 repeated items, the mean hits (SDs) were 61.7 (5.3) for L1 Chinese participants, 58.9 (8.0) for Korean participants, and 60.9 (8.1) for Japanese participants. For false alarms, it was 0.2 (0.5) for Chinese participants, 0.9 (1.8) for Korean participants, and 0.8 (1.3) for Japanese participants. One-way ANOVAs revealed no significant group difference for either hits ($F_{(2,\ 56)} = 2.15$, $p = .127$) or false alarms ($F_{(2,\ 56)} = 1.84$, $p = .168$).

N170 amplitude

The grand average waveforms for representative electrodes and topoplots during 140–200 ms are shown in Figure 1 and Figure 2, respectively. Observed mean amplitudes in the N170 time windows of the three groups by regularity and laterality are given in Table 3.

The main effect of Regularity was significant ($F_{(2,\ 125)} = 3.42$, $p = .020$) – the single representation contrast and ambiguity contrast were not significant, while the regularity effect indicated more negative N170 to irregular phonograms than regular phonograms (see Table 4 for parameter estimates). The Regularity effect did not interact with Group (Regularity x Group: $F_{(6,\ 73)} = 0.65$, $p = .694$) or Laterality (Regularity x Laterality: $F_{(3,\ 43738)} = 0.18$, $p = .913$). The main effect of Group was not significant ($F_{(2,\ 56)} = 2.07$, $p = .136$), indicating no overall difference in N170 amplitudes in native Chinese, Japanese, and Korean participants. Overall, participants showed a left-lateralized N170, as shown by a significant main effect of Laterality ($F_{(1,\ 43736)} = 186.54$, $p < .001$). Moreover, this lateralization pattern was moderated by Group (Group x Laterality: $F_{(2,\ 43737)} = 64.62$, $p < .001$) (see Figure 2 and Table 4). Native Chinese readers showed stronger left-lateralization of the N170 than both Japanese and Koreans groups. Post-hoc pairwise comparisons showed significant left-lateralization for the native Chinese and Japanese groups (both $ps < .001$), but not the Korean group ($p = 1.00$). The native Chinese group had more negative N170 amplitudes than the Korean group over left electrodes ($p = .023$). The three-way interaction of Regularity x Group x Laterality was not significant ($F_{(6,\ 43738)} = 0.25$, $p = .960$).

Among the control variables, age of the participants significantly predicted N170 amplitudes, with older participants showing greater negativity ($F_{(1,\ 55)} = 18.46$, $p < .001$). The effect of Character Structure was also significant ($F_{(2,\ 408)} = 4.49$, $p = .012$), with top-bottom structure showing greater N170 compared to the left-right and other structures. Other effects did not reach statistical significance.

N170 peak latency

The main effect of Regularity was not significant ($F_{(3,\ 418)} = 0.43$, $p = .729$), nor was the effect of Group ($F_{(2,\ 56)} = 0.07$, $p = .932$) or Laterality ($F_{(1,\ 56)} = 2.43$, $p = .125$). The two-way interactions of Regularity x Group ($F_{(6,\ 44781)} = 1.82$, $p = .090$), Regularity x Laterality ($F_{(3,\ 44737)} = 0.55$, $p = .582$), and Group x Laterality ($F_{(2,\ 56)} = 0.55$, $p = .582$) did not reach statistical significance. The Regularity x Group x Laterality interaction also was not significant ($F_{(6,\ 44737)} = 1.46$, $p = .188$). Age of the participants significantly predicted N170 latency, with older participants showing earlier N170 peak ($F_{(1,\ 55)} = 7.92$, $p = .007$). No other effects showed reliable difference.

Effect correlations with offline measures

To further explore the relevant factors for the observed effects, we ran Pearson's correlations between the magnitude of the regularity effect (amplitudes of regular minus irregular characters) and degree of lateralization (activation of left electrodes minus right electrodes) with several offline measures. Across the three groups, the regularity effect was unrelated to repetition detection accuracy ($r = .06$, $p = .668$) or age ($r = -.02$, $p = .901$). For the two groups of non-native readers, the regularity effect was uncorrelated with age of acquisition of Chinese ($r = -.23$, $p = .168$), but significantly and negatively correlated with the screening task score ($r = -.42$, $p = .010$; see Figure 3). Post-hoc correlations for the regularity effect and the screening score separated by group showed that the relationship was driven by the Korean group ($r = -.46$, $p = .033$), not the Japanese group ($r = -.18$, $p = .510$). The lateralization of the N170 was unrelated to behavioral response accuracy of the task ($r = -.10$, $p = .435$) or age ($r = -.12$, $p = .381$) for all participants. For non-native readers only, N170 lateralization was also not correlated with screening task performance ($r = .11$, $p = .514$), nor age of acquisition of Chinese ($r = -.12$, $p = .482$).

Discussion

The main purpose of this study was to examine the N170 responses in native Chinese, Japanese–Chinese, and Korean–Chinese readers when processing single Chinese characters in a repetition detection task. The results revealed several key points

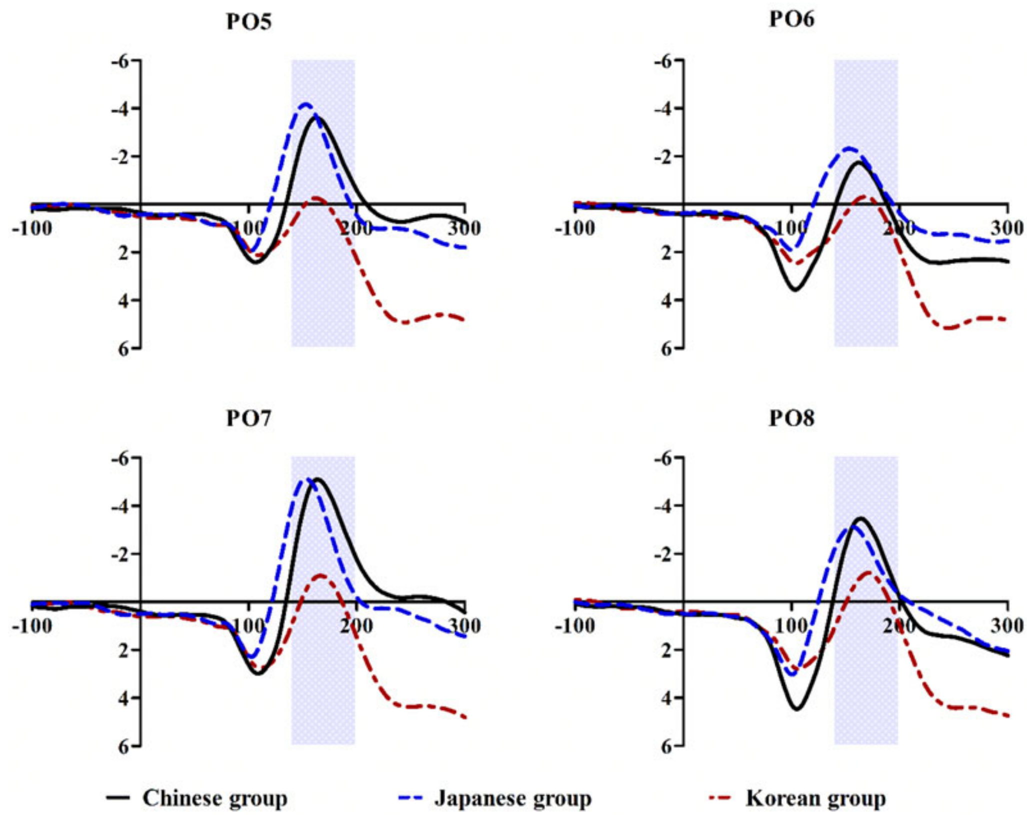

Fig. 1. Grand average waveforms of the three groups at representative electrodes (PO5 & PO7 in the left hemisphere and PO6 & PO8 in the right hemisphere). The shaded areas marked the 140–200 ms time window.

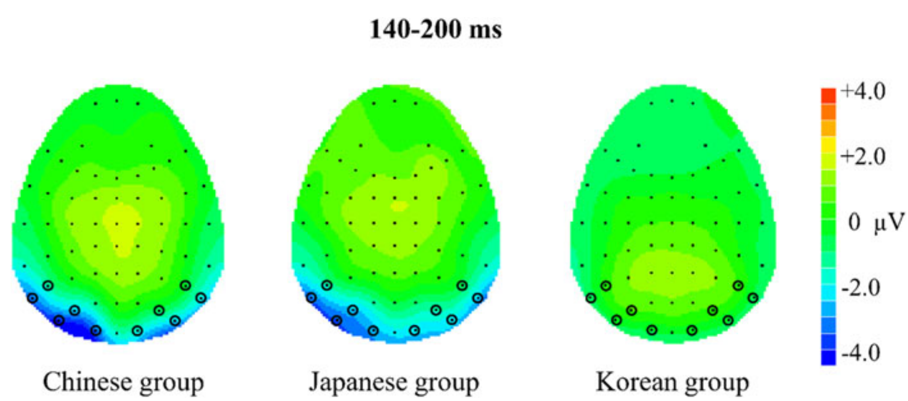

Fig. 2. Topoplots of the three groups using average values in 140–200 ms post-stimulus onset. The posterior electrodes used in the analysis were marked with circles.

with regards to the mechanisms of single word visual processing and how properties of the native language writing systems would moderate these processes in a non-native script.

The first research question investigated whether phonological effects could be found at the N170 component even though phonology is task-irrelevant. Since this study used a large number of stimuli items with a representative composition of Chinese characters with different phonological status, it was possible to simultaneously examine three contrasts of phonological effects that differed in the levels of phonological activation. First, the single representation contrast compared characters that only had one phonological form, e.g., unambiguous characters with no sublexical unit, and characters that have multiple phonological representations at sublexical or lexical levels. Second, the ambiguity contrast compared characters with ambiguous phonological forms on either lexical or sublexical levels (within-level competition) with regular and irregular phonograms that had one lexical and one sublexical level phonological forms (no within-level competition). Third, the regularity contrast compared irregular phonograms (cross-level competition) and regular phonograms (no cross-level competition). Results showed neither an effect of number of phonological representations, nor that of within-level phonological competition in ambiguous character processing in any group. Only the regularity effect was observed, indicating that at the N170 time window, cross-level activations of phonological forms were being processed. The presence of sublexical phonological effect in a visual task can be taken to support that Chinese character processing promotes early and automatic access

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Table 3. Observed mean values (SDs) of the N170 by participant group, regularity status, and laterality

	Chinese		Japanese		Korean		All groups	
	Left	Right	Left	Right	Left	Right	Left	Right
Regular	−2.66 (5.61)	−1.28 (5.60)	−2.62 (5.42)	−1.86 (5.34)	−0.08 (6.09)	−0.10 (6.50)	−1.73 (5.87)	−1.00 (5.92)
Irregular	−2.88 (5.58)	−1.43 (5.59)	−2.80 (5.36)	−2.16 (5.29)	−0.47 (5.97)	−0.49 (6.47)	−1.99 (5.78)	−1.27 (5.89)
Lexical-only	−2.51 (5.71)	−1.15 (5.70)	−2.63 (5.33)	−1.68 (5.24)	−0.39 (6.20)	−0.31 (6.69)	−1.77 (5.89)	−0.98 (5.99)
Ambiguous	−2.65 (5.60)	−1.31 (5.59)	−2.78 (5.36)	−1.91 (5.18)	−0.58 (6.12)	−0.53 (6.52)	−1.94 (5.82)	−1.18 (5.87)
All stimuli	−2.70 (5.61)	−1.31 (5.61)	−2.71 (5.37)	−1.94 (5.28)	−0.35 (6.08)	−0.34 (6.53)	−1.86 (5.84)	−1.12 (5.91)

to phonology (Perfetti, Liu & Tan, 2005). Nonetheless, it is arguable that although phonological or lexical access was not required for this task, since all our stimuli were real characters and can be pronounced, covert naming may facilitate visual memory for task completion.

Based on the characteristics of Japanese and Korean languages, one may predict native Japanese readers to be more sensitive to ambiguous phonological forms or used to assembled phonology, while native Korean readers may adopt a more sublexical processing style. Results revealed that native language did not moderate any phonological effects – at the N170 time window, Japanese–Chinese and Korean–Chinese readers showed the same pattern of phonological processing as native readers when viewing Chinese characters. Contrary to Wang et al. (2003), orthography-phonology mapping of the L1 did not seem to transfer to L2 reading, at least at intermediate/advanced level of L2 Chinese. Since phonological regularity of the phonetic radical is a unique construct in Chinese not found in alphabetic or syllabic languages, the two L2 groups showed a pattern of accommodation in viewing these characters. The robust effect of phonological regularity at the N170 across different groups underlined the integral nature of radical processing in Chinese character reading, as demonstrated in a number of previous ERP studies (Lee et al., 2007; Yum et al., 2014a; 2016).

The timing as well as bilateral distribution of the regularity effect was compatible with previous reports in lexical decision and delayed naming tasks in L1 and L2 Chinese readers (Yum et al., 2014a; 2016), while a subsequent report did not find regularity effect at the N170 in a delayed naming task for native Chinese readers (Yum & Law, 2019). In the previous studies, greater N170 in regular characters relative to irregular characters was taken to reflect stronger activation of the phonological form of the character since there would be no interference. However, the present study revealed a reverse pattern where irregular characters had more negative N170 amplitudes than regular characters. The regularity effect was correlated with reading proficiency of the Korean–Chinese participants, with stronger regularity effect in less proficient participants. This suggested that less proficient readers experienced more interference from irregular characters' phonetic radical, with moderating effect from one's native writing system. Additionally, there were at least three important differences between the previous studies and the current one. First, although phonological consistency was shown to interact with phonological regularity in Yum et al. (2016), it was not considered in this study. This was mainly because it was difficult to accurately assess phonological neighbourhood in L2 readers. However, consistency effects were shown to begin at the P200 component, after the N170 effects. Second, unlike a naming task, a repetition detection task does not require rapid generation of a phonological output. The task may be completed just as well while maintaining several possible phonological forms and not resolving them. Wang and Maurer (2017) showed that task demands may indeed exert top-down influence in the print tuning effect at the N170. Third, previous investigations relied on a factorial design and stringent stimuli selection to contrast phonological regularity, while we used linear mixed effects modelling to statistically control for relevant covariates (e.g., number of strokes, character structure, lexical frequency). Since we used a much greater number of stimuli and included random effects relating to participants and stimuli in the model, the results should be reliable. Examination of the observed mean values of the amplitudes (Table 3) indicated that both irregular and ambiguous characters

Table 4. Parameter estimates of significant fixed effects.

Model formula: N170 amplitude ~ Group * Regularity * Laterality + Age + Stroke + Structure + Frequency + (1 + Regularity + Stroke | Participant) + (1 + Group | Item)

			95% *CI*			
Effects	*β*	*SE*	Lower	Upper	*t*	*p*
Regularity: Irregular - Regular	−0.27	0.10	−0.47	−0.08	−2.73	.007
Laterality: Right - Left	0.73	0.05	0.63	0.84	13.66	< .001
Age	−1.16	0.27	−1.69	−0.62	−4.26	< .001
Structure:						
Top-bottom − Left-right	−0.22	0.09	−0.40	−0.04	−2.42	.046
Other − Left-right	0.09	0.12	−0.13	0.32	0.79	1.000
Other − Top-bottom	0.31	0.12	0.11	0.57	2.62	.026
Group x Laterality:						
(JP − CH) x (Right − Left)	−0.59	0.13	−0.85	−0.32	−4.35	< .001
(KR − CH) x (Right − Left)	−1.38	0.12	−1.62	−1.14	−11.35	< .001

Notes. CH = Chinese group; JP = Japanese group; KR = Korean group. Effects of categorical predictors were relative to the reference levels placed after minus signs. Since continuous predictors have been standardized, effects indicated change in amplitude per increase in 1 SD.

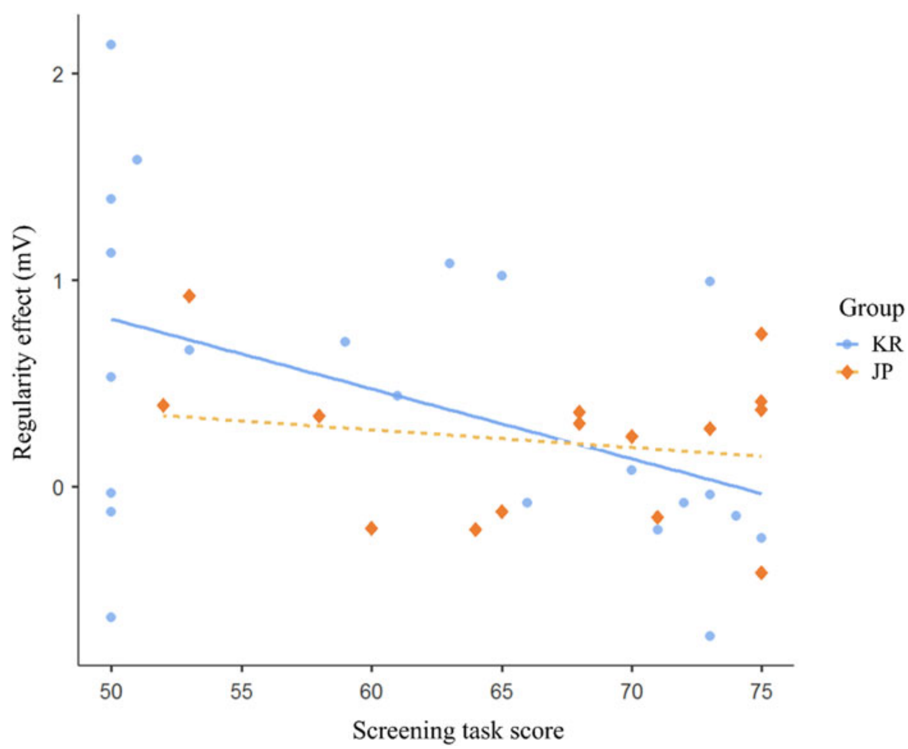

Fig. 3. Scatterplot of the regularity effect (amplitudes of regular minus irregular characters) against screening task score for the non-native Chinese reader groups. Data from the Korean group (KR) are in blue dots and solid line, while data from the Japanese group (JP) are in orange diamonds and dotted line.

tended to elicit more negative N170 than regular characters and lexical-only characters. Thus, one interpretation may be that increased N170 reflected the summed activation of phonological alternatives prior to lexical access, and response resolution as required in delayed naming was reflected in later components, e.g., N400.

Our findings also indicated that one's native writing system influenced the lateralization of the N170, as left lateralization of the component was observed in the Chinese and Japanese groups, but bilateral distribution was found for the Korean group. Although both Chinese and Japanese groups showed left lateralization, the degree of left lateralization was higher in the native Chinese group (see Table 4). These results replicated past findings of left lateralization of N170 in a repetition detection task for skilled readers (Maurer et al., 2008; Qin et al. 2016), and bilateral N170 response to Chinese characters in L2 Chinese readers with alphabetic L1 (Yum et al., 2018). This pattern of results may relate to the participants' visual experience with Chinese characters –

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interpreted as a basic level of visual familiarity that depended on amount of script exposure rather than access to phonological or lexical representations. For example, Maurer et al. (2008) showed that familiar Katakana words and unfamiliar Katakana words that spelled out kanji words elicited similar left-lateralized N170 responses. Correspondingly, Xue et al. (2019) reported that left-lateralized N170 was only elicited by characters in normal print font, not by the same characters written in visually unfamiliar cursive form. Since Japanese kanji have highly similar structures and constituents compared to Chinese characters, in terms of accumulated visual experience, native Japanese readers may be almost comparable to native Chinese readers. In contrast, although the Korean–Chinese participants were of at least intermediate L2 Chinese proficiency, their visual familiarity with the Chinese script was assumed to be much lower. Our results are thus in line with the visual familiarity account of N170 lateralization. The additional findings that the extent of lateralization was not related to proficiency or AoA among the non-native readers seemed to support this interpretation. While accumulating evidence pointed to a visual expertise account for the left lateralization of the N170 component, there remained some controversy about whether phonological effects may also drive the development of left-lateralized N170 component. The current result of regularity effect was observed at both hemispheres in all three groups and thus went against the phonological mapping account of left lateralized N170.

Limitations and conclusions

The current study examined the N170 responses to Chinese characters in Japanese–Chinese and Korean–Chinese readers in a cross-group design. This ensured that participants viewed the same items so group differences were not driven by visual properties of the stimuli. It would be interesting to directly compare the visual familiarity and phonological regularity effects in L1 and L2 scripts (i.e., compare Japanese and Chinese or Korean and Chinese script processing) within the same participants. In addition, the phonological regularity effect appeared to be modulated by task or L2 proficiency: future studies could investigate these factors in a more systematic manner.

In sum, the N170 reflected both orthographic and phonological activations in native and non-native Chinese readers. Sublexical phonological regularity effect was found in native Chinese, Japanese–Chinese, and Korean–Chinese groups with no difference among the three participant groups. This is the first demonstration of involvement of sublexical phonology in an implicit repetition detection task, and it is taken to reflect early automatic phonological activation in Chinese character reading. Meanwhile, the lateralization of the N170 component appeared to reflect visual familiarity to the script, but not phonological processing.

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Notes

[1] Japanese kanji and simplified Chinese are distinct orthographies, with different levels of visual complexity and different numbers of graphemes (Chang, Plaut & Perfetti, 2016). We merely note that there are similarities across the two scripts that may generalize in L2 visual word processing.

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