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Neuroimaging evidence for sensitivity to orthography-to-phonology conversion in native readers and foreign learners of Chinese

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ABSTRACT

Through recent neuroimaging research into brain mechanisms of proficient reading and literacy acquisition in different languages, a common neural network supporting reading has been identified in native readers across various writing systems. However, whether the same or different brain regions are involved in learning to read a foreign language is largely unexplored. To investigate (1) neural correlates of literacy acquisition of Chinese in adults whose learning of this logographic language was relatively late, and (2) to examine which cognitive factors might be predictors of literacy acquisition that would modulate the computation demands on reading-related brain regions, native and non-native Chinese readers were recruited to participate in pronunciation and color verification tasks using Chinese pseudo-phonograms in fMRI while their sensitivity to extracting systematic regularity in nonverbal materials, as well as their IQ and working memory, was measured in a visual statistical learning (VSL) task. The results indicated that native participants activated a left lateralized reading network that is consistent with previous research on orthography-to-phonology conversion (OPC) of Chinese, while a similar but extensive network that also includes regions in the right hemisphere was engaged in the non-natives. Within this network, left inferior frontal sites were found to be crucial to the mapping of Chinese pseudo characters to potential sounds especially in non-natives. More important, only the VSL scores of native and non-native participants, but not their general cognitive abilities, were negatively correlated with the brain activities in the left inferior parietal and left inferior frontal regions, respectively, suggesting that the fundamental capacity of SL supports literacy acquisition through modulating computation demands on the brain regions associated with OPC processing, which is critical to Chinese character recognition.

1. Introduction

Learning to read is to connect specific visual forms to corresponding sounds and meanings. Numerous studies on alphabetic languages have already demonstrated a cortical network supporting fluent reading, including two posterior systems (i.e., the occipitotemporal and temporoparietal regions) and one anterior system (i.e., the inferior frontal gyrus) (Pugh, Shaywitz, Shaywitz, &

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Constable, 1996; Pugh et al., 2001). Neuroimaging evidence from multiple languages has shown that during reading the occipital and fronto-temporal systems play pivotal roles in orthographic and semantic processes, respectively (e.g., Bolger, Perfetti, & Schneider, 2005), while the temporoparietal regions are critical to phonological processing (Temple, 2002). Recent findings from native readers of four drastically different writing systems (i.e., Chinese, Hebrew, English, and Spanish) have also shown that the reading networks underlying orthographies with different "depths", in terms of how phonology is represented in written words, are largely overlapping (Rueckl et al., 2015). Despite these advances in research on reading, it yet remains unclear whether people rely on the same brain regions that are involved in their native languages to acquire a novel writing system, and whether cognitive predictors of literacy acquisition would modulate the computation demands on reading-related brain regions.

Initial attempts in studying brain mechanisms in Chinese-English bilinguals demonstrated that orthographic processing of the first (L1) and second languages (L2) recruit both similar and distinct brain regions (Ding et al., 2003). This study revealed a higher right lateralized activity in L2 (i.e., English) than in L1 (i.e., Chinese) as a major distinction between the brain activity patterns in the two languages. Another study also reported that Chinese-English bilinguals recruit brain regions typical of the Chinese reading network such as posterior parietal and middle frontal regions to read English, leading to the conjecture that native language influences the second language network (Tan et al., 2003). Later, the strategies of "assimilation" and "accommodation" were put forward to explain L2 acquisition at the neural level (Perfetti et al., 2007). According to the "assimilative" strategy, the brain reused the L1 network to learn to read L2, whereas in "accommodation" the brain was believed to recruit new regions to carry out functions unique to the L2 learnt.

In the literature of language acquisition, a powerful mechanism for detecting statistical regularity among items, namely, statistical learning (SL), plays a central role in learning natural languages. SL is a form of implicit learning (Perruchet & Pacton, 2006) that has been defined as the sensitivity to association among items with variable associations, which is necessary for humans to extract regularities and patterns from the environment to increase the chance of survival. It has been established to exist in humans via non-linguistic as well as linguistic materials (Newport & Aslin, 2004; Saffran, Aslin, & Newport, 1996). Recent studies have also suggested that SL may not be a unitary mechanism for different kinds of input. For example, SL of transitional probabilities among materials in different modalities (auditory versus visual) and in different formats (sequential versus spatial) has been shown to be domain-specific (Frost, Armstrong, Siegelman, & Christiansen, 2015).

The contribution of SL to acquisition of spoken language has been investigated via artificial language extensively. In a landmark study, Saffran et al. (1996) showed that eight-month-old infants have the ability to detect the co-occurrence of syllables embedded in a pseudo speech stream. Specifically, when eight-month-old infants were exposed to a two-minute concatenated stream of pseudo speech, their looking time exhibited that they learned to distinguish novel items from familiar ones. Aslin, Saffran, and Newport (1998) further demonstrated that infants are sensitive to the transitional probability among syllables but not to the frequency of the syllable sequence. Estes and colleagues (Estes, Evans, Alibali, & Saffran, 2007) also showed that17-month-old infants were able to map meanings to words based on SL.

Because there are abundant statistical cues to the structure of natural language, it seems reasonable that SL underlies the acquisition of both spoken and written language. However, most of the previous literature has employed artificial materials, while little empirical evidence from acquisition of natural language is reported to support this claim. One exception was a study by Evans, Saffran, and Robe-Torres (2009), in which English-speaking children with specific language impairment were found to perform more poorly than normal children on SL tasks. More important, SL performance was positively correlated with performance on standardized tests of vocabulary in both normal children and children with specific language impairment, and this correlation was not mediated by IQ. As for the link between SL and literacy acquisition, although it has been reported that children and adolescents with developmental dyslexia were impaired on implicit learning tasks (Vicari et al., 2005), such association was not found in another study (Rüsseler, Gerth, & Münte, 2006). A recent paper (Arciuli & Simpson, 2012) directly examined whether the variability of SL in a typical task of visual implicit learning (i.e., the embedded triplet test) was related to reading performance of English in healthy children and adults. The results provided strong support for the critical contribution of SL to literacy acquisition which could not be accounted for by age.

While previous research has focused on investigating the relationship between SL and first language (L1) acquisition, its role in second language (L2) literacy acquisition was first studied in a recent pioneering study on native English speakers learning Hebrew performing ASL and VSL tasks. Specifically, the SL ability of young adults, measured by a VSL task in which nonlinguistic visual shapes were employed, was observed to reliably predict their improvement on Hebrew proficiency tests one semester later (Frost, Siegelman, Narkiss, & Afek, 2013). That is, individuals with high sensitivity to regularity embedded in nonlinguistic visual shapes also exhibited great improvement particularly in the tests measuring participants' orthographic knowledge of Semitic languages (e.g., morphological priming). Given that there are systematic correlations between written words and the meanings they refer to, the observed relationship between VSL and L2 literacy acquisition is not unexpected.

Alphabetic (such as English) and non-alphabetic (such as Chinese) languages differ from each other fundamentally in their orthographic forms, but there are systematic correlations among orthography, phonology, and semantics in both types of languages. An alphabetic word consists of a sequence of letters that represent graphemes corresponding to phonemes. Unlike the linear structure of an alphabetic word, a Chinese character corresponding to a syllable consists of the combination of strokes that represent radicals to form a square structure. The majority (∼70%) of Chinese characters have a horizontal structure with a semantic radical on the left side and a phonetic radical on the right side. For example, the Chinese character "清" contains the semantic radical "氵" and the phonetic radical "青". According to Academia Sinica Balanced Corpus (Chen, Huang, Chang, & Hsu, 1996), there are about 700 phonetic radicals and 200 semantic radicals, which provide coarse cues for the pronunciation and the meaning of a character, respectively. That is, the correspondence between character forms and sounds is semi-regular and semi-consistent. Specifically, only 47% of common Chinese characters have identical pronunciation (regardless of the tone) as their phonetic radical (i.e., phonologically regular, as the character "材" and its phonetic radical "才" have the same pronunciation "cai2"). On the other hand, only 34% of the characters have the same pronunciation as their orthographic neighbors who share the same phonetic radical (i.e., phonologically consistent) (Hsiao & Shillcock, 2006).

Although the characteristics of the Chinese writing system render the retrieval of phonology from orthography less reliable and the access of meaning via phonology more ambiguous than alphabetic languages, the sublexical mapping between phonetic radicals and character pronunciations still provide useful cues for readers to recognize characters, as evident by abundant previous studies (e.g., Lee, Tsai, Su, Tzeng, & Hung, 2005; Liu, Shu, & Li, 2007). These findings are consistent with the results of a survey by (Chung & Leung, 2008), which showed that 66% of the 2570 simplified characters and 59% of 3844 traditional characters used in Hong Kong were semi-regular as their pronunciations shared the same syllable with or without the same tone as their phonetic radicals. Recent findings in an MEG study from our laboratory (Hung, Hung, Tzeng, & Wu, 2014) have shown that native readers of Chinese are sensitive to the repetition of phonetic radicals in as soon as 100 ms after the presentation of the second character of two successfully presented character pair. On the other hand, no early MEG components were sensitive to the repetition of semantic radicals. In another recent report, we also showed that the repetition of phonetic radicals in the list items in a short-term memory task hindered native speakers' retention of Chinese characters (Lin, Chen, Lai, & Wu, 2015).

Given the semi-regular relationship between Chinese orthography and phonology, it may not be surprising to find that VSL performance is associated with literacy acquisition of Chinese as a L2. Indeed, research from our lab (Wu, Shih, Hsuan, Yu, Hung, submitted) has shown that in a cross-sectional design, individual difference of young adults who are foreign learners of Chinese in a VSL task adopted from Frost et al. (2013) was significantly correlated with their vocabulary (character) size after controlling for the effects of Chinese learning time, IQ, and working memory. Moreover, for a subgroup of participants who did not continue to take formal Chinese courses after the first testing session, their VSL scores at the first testing session predicted the improvement of their Chinese vocabulary size significantly at the second testing session at least four months later. The relationship between VSL and learning to read Chinese characters is considered to reflect that sensitivity to statistical probabilities govern the acquisition of consistency of phonetic radicals, which is critical to orthography-to-phonology conversion (OPC) processing.

Consistency of Chinese phonetic radicals reflects the different degrees of regularity in the mapping between written characters encompassing particular phonetic radicals and the corresponding pronunciations of these characters. This characteristic of Chinese orthography has been shown to aid learning of Chinese in native children, and affect character naming accuracy and speed in native children as well as adults (Lee et al., 2004, 2005; Tzeng & Lee, 2012). Previous neuroimaging studies investigated the neural correlates of OPC processing in native Chinese readers by utilizing homophone judgment tasks (Lee et al., 2004; 2005; Tzeng & Lee, 2012). The typical findings from such tasks are that low-consistency characters induce greater activation than high-consistency characters in left inferior and middle frontal gyrus, the left temporoparietal regions (in particular, the left inferior parietal gyrus), the left medial frontal gyrus, the left fusiform gyrus, as well as the anterior cingulate (Booth et al., 2006).

As discussed above, there has been ample evidence demonstrating the neural basis of OPC processing in L1 readers of various languages such as English and Chinese. However, there is a gap in our understanding of (1) the neural network involved in OPC processing in L2 learners acquiring the language – specifically, how similar or different the L2 network is to those in L1 readers, and (2) how cognitive abilities found to be crucial to L2 literacy acquisition, such as VSL, influence these L2 neural networks. The current study aimed at addressing these issues, and additionally, also aimed to dissect if or how VSL mediates L2 learners' sensitivity to OPC rules, which have been shown in past research, to be crucial in determining Chinese reading skills.

2. Materials and methods

2.1. Participants

Twelve L2 learners of Chinese whose native language was an alphabetic one, and 12 native speakers of Chinese participated in the study. Both groups of participant were mainly recruited from student populations of National Taiwan Normal University (NTNU), National Taiwan University (NTU), National Cheng Chi University (NCCU), and National Central University (NCU) in Taiwan. All participants provided their language background information via an online survey, and were naïve to Korean, which was used as stimuli in a control condition of the fMRI paradigm. They all completed a battery of tasks including measurements of their general cognitive abilities (e.g., IQ, working memory), had no family or personal history of neurological diseases, and had normal or corrected-to-normal vision. All participants are right-handed, which was verified via the Edinburgh Inventory (Oldfield, 1971). All participants provided informed consent for both the behavioral tests and the MRI scanning procedure.

Participants in the non-native group all have an alphabetic language background (see Table 1), have been immersed in a Mandarin-speaking environment for at least six months, and most of them have been or are currently enrolled in a Chinese course. Their Chinese proficiency was measured by a standardized test developed to measure Mandarin vocabulary of native Taiwanese children (Lee, 2012). All these L2 learners had a vocabulary (character) size of at least 375 characters, which were equivalent to or greater than estimated minimum of the vocabulary size of native Chinese speakers at Grade 1.

2.2. Visual statistical learning (VSL) task

The VSL task was from Frost et al. (2013), which employed visual stimuli that were originally developed by Turk-Brown et al. (2005). Specifically, 24 relatively complex visual shapes that are difficult to name verbally were prepared and organized into eight triplets. In the first (familiarization) phase of the task, these triplets were randomly selected and continuously presented at a rate of one second per triplet in a 10-min stream. That is, the transitional probabilities (TPs) among members in a triplet were equal to one, while those among members of different triplets were close to zero. Participants were only instructed to attend to the shapes presented sequentially on the screen without being informed of existence of the triplets explicitly. In the second (testing) phase of the task, participants answered 32 two-alternative-forced-choice (2AFC) questions to decide between two triplets of visual shapes. One of these alternatives was a triplet that had appeared repeatedly during the familiarization phase ($TP = 1$), while the other one was a foil triplet composed of three of the same 24 shapes but in a novel sequence not shown

Table 1
Background information of non-native participants.

Sub. Name	Age (Years)	Native language	Months of Learning Chinese[a]	Vocabulary (Character Size)	Block Design	Visual Statistical Learning	Digit Span
FG	28	German	38	979	60	0.60	6
TQ	25	English	16	2291	64	0.69	6
BJ	24	German	5	375	66	0.63	7
ME	22	French	5	375	58	0.56	6
SS	23	Indonesian	60	2479	35	0.50	8
SL	24	French	9	1479	51	0.63	8
RA	24	English	[b]	1000	62	0.91	6
JS	32	English	57	2542	61	0.88	9
ALG	26	French	12	1521	51	0.84	6
RP	28	Spanish	24	938	65	0.97	5
SC	24	English	[b]	1250	60	0.94	6
PB	27	English	12	2417	63	0.94	6

[a] Months of learning Chinese in formal language courses. All the participants have lived and immersed in Mandarin-speaking environments for at least six months.

[b] These participants have never taken any formal Chinese courses; however, they have lived and immersed in Mandarin-speaking environments for years to acquire sufficient knowledge of Chinese orthography to complete the tasks in the present study.

before (TP = 0). The accuracy of this task, which was taken as an index of individuals' ability of visual statistical learning, was recorded as the VSL score. All stimuli in the task were presented on a ThinkPad laptop in a Windows 7 environment. The presentation of the stimuli and the data collection were achieved via Presentation Software (Neurobehavioral Systems, Albany, CA, USA).

2.3. *fMRI experimental paradigm*

To measure OPC processing in the native and non-native readers of Chinese, participants were required to indicate whether a spoken syllable matches the likely pronunciation of a Chinese pseudo-phonogram. In this sound verification task, it is assumed that participants relied on their knowledge of Chinese phonetic radicals to perform OPC processing explicitly. In comparison, participants also performed a color verification task on the same set of stimuli, during which the OPC processing might occur implicitly. In addition, a color verification task on Korean characters, which are meaningless to both groups of participants, was also included as a control baseline. Details of the three tasks are provided below.

2.3.1. *Pronunciation verification of Chinese pseudo-phonograms (PV):*

In the pronunciation verification task, 128 Chinese pseudo-phonograms with novel combinations of legitimate semantic and phonetic radicals were prepared. Each radical only appeared in one pseudo-phonogram in the position that it typically appears in real Chinese characters. For the majority of the pseudo-phonograms (92 out of 128), each of them was paired with the most consistent pronunciation of its phonetic radical (e.g., “木韋”, “wei3”). For the other pseudo-phonograms (36 out of 128), they were paired with a non-dominant but possible pronunciation (e.g., “馬見”,“xian4”). The pairings between the pseudo-phonogram and its potential pronunciation constituted “matched” responses. For “unmatched” responses, all the possible pronunciations in the “matched” responses were shuffled and paired with the pseudo-phonograms that are not associated with the particular pronunciations in any real Chinese characters.

2.3.2. *Color verification of Chinese pseudo-phonograms (CV):*

In this task, the stimuli were the same set of 128 Chinese pseudo-phonograms as those in the pronunciation verification task in red, green, blue, or yellow (i.e., 32 stimuli in each color). For “matched” responses in this task, each stimulus was paired with the spoken Chinese word of its color. For “unmatched” responses, each stimulus was paired with the spoken Chinese word of one of the other three colors.

2.3.3. *Color verification of Korean characters (CV_K):*

In this task, 64 Korean characters, consisting of strokes and formation similar to Chinese characters but unknown to participants, in four colors were also included. For “matched” responses in this task, each stimulus was paired with the spoken Chinese word of its color. For “unmatched” responses, each stimulus was paired with the spoken Chinese word of one of the other three colors.

2.3.4. *Task procedures*

Each participant received 64 trials of each of the three conditions. For each trial, after a jittered fixation period of two, four, or six seconds, a colored stimulus appeared at the center of the screen. One second after the visual presentation of the stimulus, a sound of a Chinese word was played, after which the participants had up to four seconds to make a “matched” or “unmatched” response between the stimulus seen and the sound heard, via a button press on a response pad. In the PV condition, participants determined whether the spoken word is the likely pronunciation of the pseudo-phonogram. In the CV and CV_K conditions, participants determined whether the spoken color word matches the color of the Chinese pseudo-phonogram and the Korean character, respectively (see Fig. 1).

The 64 trials of each of the three conditions were divided into eight mini-blocks in an event-related design, resulting in eight trials

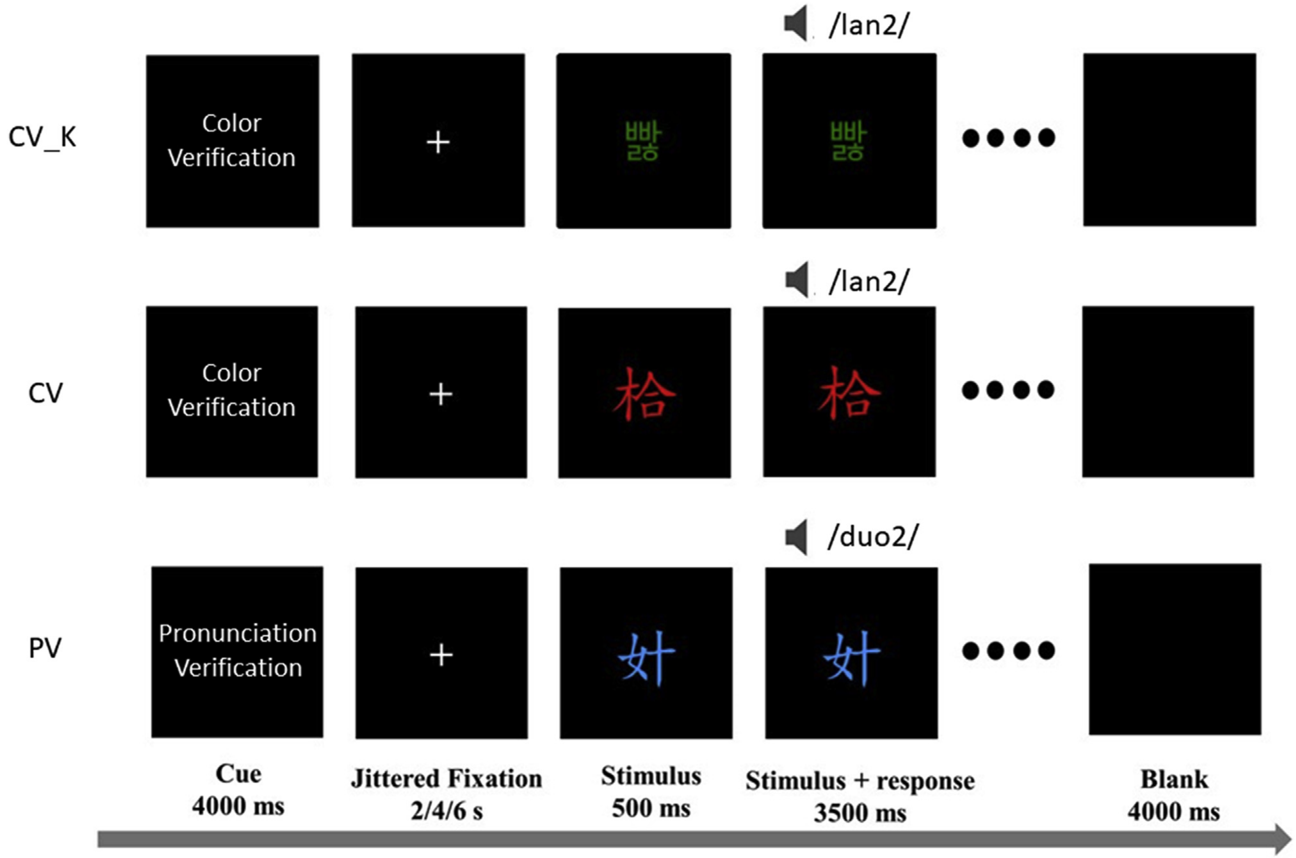

Fig. 1. The design of the fMRI paradigm employed in the pronunciation verification (PV) and color verification (CV) tasks using Chinese pseudo-characters, and the color verification task using Korean characters (CV_K). In Mandarin,/duo2/is a non-color word, and/lan2/refers to the color blue. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

per mini block. At the beginning of each mini-block, there was a written cue for four seconds indicating the task type. At the end of each mini-block, there was a four-second blank. Within each mini-block, there were two stimuli in each of the four colors, with half of the trials requiring a “matched” response, and the other half requiring an “unmatched” response. There were two mini-blocks of each of the three conditions within a run, and the order of the mini-blocks was counter-balanced via a Latin square sequence across all four runs for each participant. Eight practice trials of each condition were provided before the formal fMRI testing.

2.4. Apparatus

All participants performed all the behavioral tests via a ThinkPad individually in a quiet room. The fMRI experiment was conducted in a separate session, at least one week after the behavioral tests, and stimuli presentation and data collection were achieved via Python (Python Software Foundation, Beaverton, OR, USA) with the PsychoPy toolbox on a ThinkPad laptop in a Windows 7 environment. The visual stimuli were projected onto a viewing screen directly above the head of the participant, and the auditory stimuli were played through earphones while inside a 3T Siemens MAGNETOM Skyra MRI scanner. Participants were provided with a response pad with four buttons, and were instructed to make “matched” and “unmatched” responses with their right and left thumbs on the response pad by pressing on the right-most and the left-most buttons, respectively. All participants had their heads stabilized with sponges during scanning, and were cautioned against any head movements throughout the process.

2.5. Image acquisition

All images were acquired using a 3T Siemens MAGNETOM Skyra MRI scanner. Each of the participants underwent AutoAlign provided by the scanner to screen for unusual brain structures that would be difficult to map onto a standard brain template (e.g. having a fifth ventricle, etc.). To achieve equilibrium longitudinal magnetization, three dummy scans were done at the beginning of each run. In all runs, functional gradient-echo echo-planar images (EPIs) were acquired with the following parameters: slice thickness = 3 mm, 36 slices (interleaved with even slices first), time repetition (TR) = 2000 ms, echo time (TE) = 30 ms, flip angle = 77°, field of view (FOV) = 220 mm, matrix size = 64 × 64. Pre-scan normalization was done for each run of the functional images to remove coil heterogeneity. The anatomical scan parameters (T_1-weighted MPRAGE) are as follows: TR = 2530 ms, TE = 3.3 ms, FOV = 260 mm, matrix size = 256 × 256, sagittal plane, slice thickness = 1 mm, 176 slices.

2.6. Data processing

All image preprocessing and statistical analyses were performed using SPM8 (Wellcome Department of Cognitive Neurology, London, UK) via MATLAB R2013a (The Mathworks Inc., Natick, MA, USA). Slice timing correction was applied to EPI data to correct for the difference in signal intensity due to temporal delay between the slices during data acquisition (TR = 2000 ms, time of acquisition (TA) = [TR-(TR/number of slices)] = 1.944, slice order = 2 to 36 then 1 to 35 interleaved). Functional images within each run were realigned to correct for motion artifacts, and the alignment across different runs was corrected by co-registering the mean image of the first run to the T_1-weighted structural image, and then co-registering the mean images in the following runs to the mean image of the first run. Normalization of both structural and functional imaging data was done to fit participant data into the standard Montreal Neurological Institute (MNI) coordinate, specifically the 152 T_1 template (Grabner et al., 2006). Finally, all functional data was spatially smoothed with an 8-mm full-width-half-maximum Gaussian kernel, and all the time-series had a high-pass filter of a cut-off at 128 s to remove low-frequency BOLD signal drifts.

Only the signals from accurate trials were included in the following analyses. In the first level analysis, three main regressors were specified in the design matrix of a general linear model (GLM) to model the BOLD response evoked by the event of stimulus presentation in each trial (the time elapsed between stimulus onset and response) of the three conditions (PV, CV, CV_K) in the two participant groups (native, non-native) separately. The zero- and first-order temporal derivatives of the three regressors as well as the six regressors for rigid body motion correction (translation and rotation around the x-, y-, z-axes) were also included in the GLM. The regressors were convolved with the canonical hemodynamic response function (HRF). The time-series of the fixation task cues were included as part of the baseline as they were not explicitly modeled.

To control for the difference of general brain activation levels across different participants, the signals from pronunciation and color verifications of Chinese pseudo-phonograms were first contrasted with the signals from color verification of Korean characters (PV > CV_K and CV > CV_K) using two separate factorial designs for each group modeling the two conditions. All between-condition (PV versus CV) comparisons were then carried out using within-subject t tests for each participant, and combining them at the second level, within each group. Brodmann areas were determined via MRICron toolbox (http://people.cas.sc.edu/rorden/mricron/index.html) and anatomical labels using AAL toolbox (Tzourio-Mazoyer et al., 2002). T-maps of brain activation were made after activating the option of voxel-wise FDR in SPM8, at voxel-wise FDR $p < .05$, $k > 10$ or a voxel-wise uncorrected $p < .001$, $k > 10$ threshold with a cluster-level FDR correction at $p < .05$, where required and thus, the thresholds are mentioned accordingly.

In the present study, we were particularly interested in the activation of specific brain regions underlying OPC processing demanded by the PV task, and the relationship between VSL abilities and such activation. As a result, six such regions of interest (ROI) that were associated with rhyming judgment on Chinese two-character words, in contrast with semantic judgment on these words and with line judgment, reported in Booth et al. (2006) were chosen. Specifically, the following six regions were selected: the left inferior parietal lobule (LIPL, [-18, −66, 54]), the left inferior frontal gyrus (LIFG, [-36, 27, −9]), the left middle frontal gyrus (LMFG, [-51, 24, 21]), the left medial frontal gyrus (MedFG, [0, 21, 48]), the left fusiform gyrus (LFG, [-42, −60, −21]), and the right fusiform gyrus (RFG, [-27, −90, −6]). These ROIs have covered the neural network of phonological processing of Chinese characters that has been generally reported in the previous literature (cf., a meta-analysis by Wu, Ho, & Chen, 2012), but the exact functions of individual brain areas are still under debate. ROI analyses were conducted through the MarsBaR toolbox (Brett, Anton, Valabregue, & Poline, 2002) by using a 10-mm radius spherical search volume centered at the six coordinates specified above in the environment of SPM8 under MATLAB. Condition-wise responses in these brain regions were also extracted and tested for group differences.

3. Results

3.1. General cognitive abilities and VSL results

The means and standard deviations of general cognitive abilities and VSL for both native and non-native participants, as well as Chinese proficiency measured by vocabulary (character) size for the non-native participants, are presented in Table 2. Although the non-native participants had a larger mean age ($t\,(22) = -2.73, p = .010$) and a smaller forward digit span ($t\,(22) = 3.93, p = .002$) than the native participants, their non-verbal IQ (measured by Block Design) and the VSL scores were comparable to those of native participants (also see Table 2).

3.2. Behavioral results of the fMRI paradigm

Both accuracy and reaction times of pronunciation and color verification in the MRI scanner were recorded for both groups of participants (see Fig. 2). To determine whether native and non-native participants performed differently across the three tasks, separate two-way (nativity and task) ANOVAs were used to analyze data for accuracy and reaction times. For accuracy, the ANOVA results showed that the nativity main effect was far from significance ($F(1, 22) < 1$), assuring that the non-native participants shared similar knowledge of OPC of Chinese (pseudo) phonograms as the native participants. On the other hand, the task main effect ($F(2, 44) = 15.807, p < .001$) was significant, indicating that color verification of Korean characters was easier than color verification of Chinese pseudo-phonograms ($p < .01$), which was in turn easier than pronunciation verification of the same set of pseudo-phonograms ($p < .01$). The interaction between nativity and task was not significant ($F(2, 44) = 1.749, p > .207$).

The ANOVA results of the reaction time data demonstrated a similar but exaggerated pattern as that of the accuracy data (see Fig. 2). Specifically, the main effects of both nativity ($F(1, 22) = 20.436, p < .001$) and task ($F(2, 44) = 91.223, p < .001$) were significant, as well as the interaction between the two factors ($F(2, 44) = 5.688, p = 0.006$). Further comparisons indicated that non-native participants had longer reaction times than native participants in all three tasks ($ps < .001$). Although the reaction times of color verification of Korean characters were faster than those of the same judgment on Chinese pseudo-phonograms for non-native participants ($p = 0.047$), the same trend was not significant for native participants ($p > 0.44$). The reaction times of color verification of Chinese pseudo-phonograms were faster than those of pronunciation verification on the same set of pseudo-phonograms for both groups of participants ($ps < .001$). Direct comparisons between the two groups of participants in all three tasks were highly significant ($ps < .002$), confirming that non-native participants reacted more slowly than native participants in the experiment regardless the nature of the tasks, though the difference was larger in the PV than the CV and CV_K tasks.

Table 2
Means and standard deviations of age and behavioral measurements of native and non-native participants.

	Natives (N = 12)		Non-natives (N = 12)		Two sample t - test	
	Mean (N)	SD	Mean(N)	SD	t - value	p - value
Age	22.42	2.91	25.58	2.78	−2.73	0.01
Block Design	55.83	8.67	58.00	8.71	−6.11	0.55
Forward Digit Span	8.50	1.51	6.58	1.16	3.49	0.002
Visual Statistical Learning	0.70	0.20	0.76	0.17	−0.83	0.42

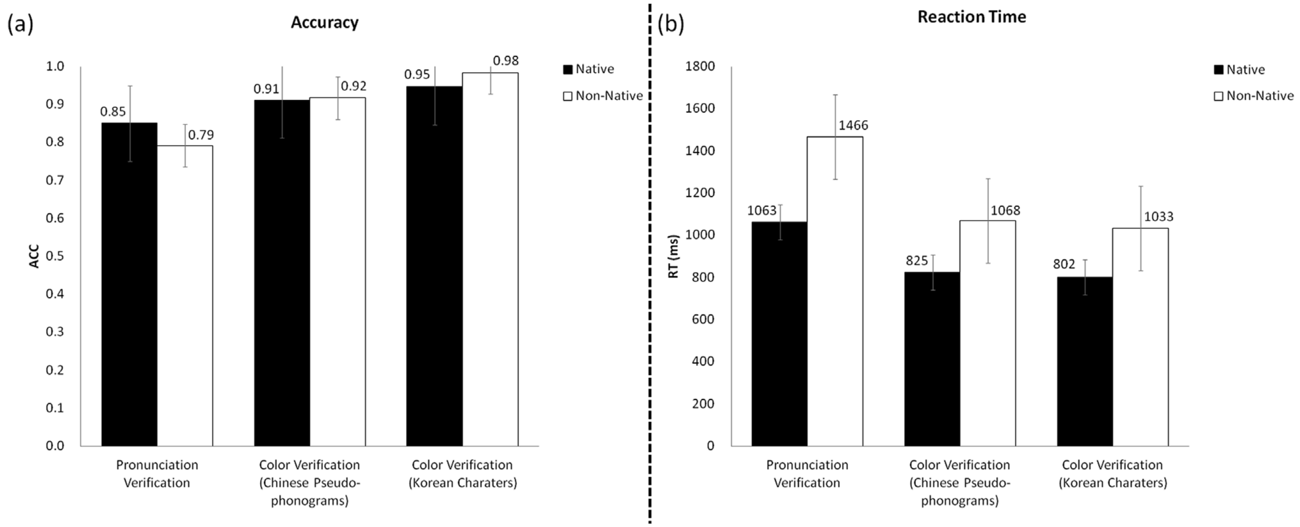

Fig. 2. Behavioral performance of the two groups of participants – native and non-native/foreign readers, in terms of (a) percent accuracy (ACC) and (b) reaction times (RT) for the three fMRI tasks of pronunciation verification (PV), color verification of Chinese pseudo-phonograms (CV) and of Korean characters (CV_K). The error bars indicate standard errors.

3.3. Imaging results

3.3.1. Neural correlates of pronunciation and color verification of Chinese pseudo phonograms (PV > CV_K & CV > CV_K)

We performed comparisons of the brain activation of the PV and CV tasks with Chinese pseudo-phonograms against that of the CV_K task which was included as the baseline. Overall, the imaging results revealed a typical neural network underlying the OPC processing when the brain activity of the PV task was contrasted with that of the CV_K task (PV > CV_K) in both native and non-native readers of Chinese, though the similar patterns were more extensive and bilateral in non-native participants (see Fig. 3a). In the native readers, pronunciation verification in comparison to color verification on Korean characters showed engagement of a left lateralized network comprised of a left frontal cluster peaking at the inferior frontal gyrus (BA 48) and the precentral gyrus (BA 6), a cluster at the left inferior temporal gyrus (BA 37), a cluster at the left middle occipital gyrus/inferior parietal gyrus (BA 7), and bilateral supplementary motor regions (BA 6) (at cluster-level threshold of FDR, $p < 0.05$) (see Table 3a).

In non-native readers, in the PV > CV_K comparison, overall the pattern of activation was more bilateral in nature than that in native readers, but also showed higher variation as indicated by the t maps (see Fig. 3a). Non-natives engaged the following brain regions some of which were in the right hemisphere: bilateral superior parietal lobules (BA 7), left inferior parietal lobule (BA 40), left precentral gyrus (BA 6/44), left insula (BA 48), left inferior/middle temporal gyrus (BA 37), right inferior frontal gyrus (BA 45/48), right middle frontal gyrus (BA 45), (see Table 3b). This bilateral and extensive nature of the network underlying the PV task may indicate the effortful OPC processing in non-natives. Post-hoc correlation analyses of reaction times with task related activity (PV > CV_K) revealed that this linear, positive relationship with effort in terms of higher reaction times was found only in the left inferior parietal region, confirming the link between effortful processing and activity in the brain. Although other regions did not share this pattern of linear relationship, our results indicated that elevated extent of activation might be a signature of ‘non-native OPC processing in Chinese’.

When the brain activity of the color verification tasks in Chinese and Korean were compared (CV > CV_K), no significant activation was detected for either native or non-native participants at the conventional threshold. When a relatively liberal threshold was adopted (i.e., uncorrected $p < .001$, $k > 10$), less widespread activation was observed in native readers, including left inferior temporal gyrus (BA 37), right fusiform gyrus/inferior occipital region (BA 19) and bilateral superior parietal lobules (BA 7). For non-natives, the same contrast yielded activity only in right inferior frontal region (see Fig. 3b & Table 3). Such results are not surprising, as the OPC processing of Chinese pseudo phonograms in the color verification task might not be automatic or demanded particularly for the non-native participants.

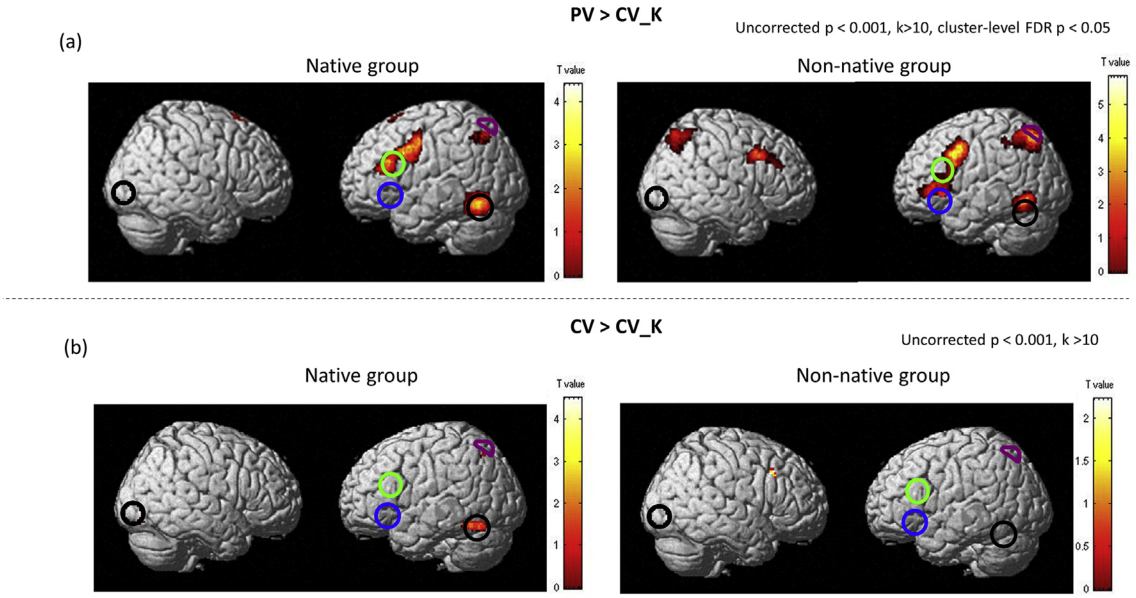

Fig. 3. Rendering displaying brain regions which showed higher activity during (a) pronunciation verification (PV) compared to color verification on Korean characters (CV_K) (b) and color verification on Chinese pseudo-phonograms (CV) compared to color verification on Korean characters (CV_K). Five of the six regions of interest (ROIs) (except for the medical frontal gyrus, which is not shown in the lateral view) are also plotted: Left inferior frontal gyrus (blue), left middle frontal gyrus (green), left inferior/superior parietal lobule (purple), and left/right fusiform gyri (black). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 3

Summary of peak activations in the (a) native and (b) non-native groups, during the PV and CV tasks in comparison to the baseline of the CV_K task. The respective thresholds used for analyses are also reported.

(a)

Anatomical label	L/R	BA	MNI Co-ordinates			Cluster size (k)	Peak T - value
			x	*y*	*z*		
Native group PV > CV_K p < .001, k > 10 (Cluster-wise FDR p < .05)							
Inferior temporal gyrus	L	37	−48	−54	−16	716	7.15
Precentral gyrus	L	6	−42	2	32	1238	6.39
Inferior frontal gyrus (triangular)	L	48	−40	26	28		5.52
Precentral gyrus	L	6	−46	−2	42		5.47
Middle occipital gyrus	L	7	−26	−60	42	445	5.66
Inferior parietal lobule	L	7	−30	−52	44		4.67
Supplementary motor area	L	6	−2	8	58	529	4.83
	R	–	0	22	58		4.51
	L	6	−6	14	72		4.18
Native group CV > CV_K p < .001, k > 10							
Inferior temporal gyrus	L	37	−48	−54	−16	178	4.70
Fusiform gyrus	R	–	34	−46	−2	16	4.50
Inferior occipital gyrus	R	19	38	−82	−14	11	4.02
Superior parietal lobule	L	7	−22	−56	46	31	3.85
	R	7	−32	−66	50	14	3.79

(b)

Anatomical label	L/R	BA	MNI Co-ordinates			Cluster size (k)	Peak T - value
			x	*y*	*z*		
Non-native group PV > CV_K p < .001, k > 10 (Cluster-wise FDR p < .05)							
Superior parietal lobule	L	7	−26	−68	48	1150	9.99
Inferior parietal lobule	L	40	−36	−54	50		5.42
	L	–	−44	−42	48		4.07
Middle temporal gyrus	L	37	−52	−58	−14	559	7.21
Inferior temporal gyrus	L	37	−46	−54	−10		6.91
Precentral gyrus	L	6	−48	4	42	1967	7.12
	L	44	−44	10	36		6.87
Insula	R	48	−34	22	6		6.10
Inferior frontal gyrus (opercular)	R	–	54	18	40	444	6.44
	R	44	46	12	38		5.51
Middle frontal gyrus	R	45	50	32	32		4.61
Superior parietal lobule	R	7	28	−70	56	483	5.68
	R	–	30	−70	48		4.76
	R	7	34	−58	56		4.41
Non-native group CV > CV_K p < .001, k > 10							
Inferior frontal gyrus (triangular)	R	–	54	20	40	21	4.13

3.3.2. Direct comparisons between pronunciation and color verification tasks of Chinese pseudo phonograms (PV > CV) in native and non-native participants

The effect of explicit OPC processing was examined by directly comparing the brain activity associated with the tasks of pronunciation and color verification (PV > CV) in the two groups of participants separately. While natives showed no significant differences in activation between these tasks, non-natives exhibited widespread activation in the left inferior frontal gyrus (BA 45), the right middle frontal gyrus, the left superior temporal gyrus, bilateral inferior temporal gyrus (BA 37), the left superior parietal lobule (BA 7), the left middle occipital gyrus (BA 18), the right insula (BA 47) as well as motor regions (see Table 4 and Fig. 4).

3.3.3. ROIs analyses

Based on a previous study conducted by Booth et al. (2006), six brain areas that are involved in rhyming judgment on Chinese two-character words (i.e., LIPL, LIFG, LMFG, LMedFG, LFG, and RFG) were selected as ROIs for further analyses. Mean beta values from all three tasks in these six regions were extracted for each participant and were submitted to separate 2 (native vs. non-native) x 3 (PC vs. CV vs. CV_K) ANOVAs to examine how brain activation was modulated by nativity and task demands in individual ROIs.

Table 4
Peak activations in the non-native group during explicit OPC processing (PV > CV) at FDR p < 0.05, k > 10.

Anatomical label	L/R	BA	MNI Co-ordinates			Cluster size (k)	Peak T - value
			x	*y*	*z*		
Superior parietal lobule	L	7	−26	−68	48	1504	13.59
Inferior temporal gyrus	L	–	−50	−56	−14	673	8.72
Supplementary motor area	L	8	−4	20	50	341	8.27
Inferior temporal gyrus	R	37	52	−60	−8	112	6.42
Precentral gyrus	L	6	−50	4	44	450	6.32
Insula	L	48	−34	22	6	247	5.99
Superior temporal gyrus	L	–	−68	−26	14	53	5.55
Middle frontal gyrus	R	–	56	16	42	82	5.45
Postcentral gyrus	R	–	36	−46	66	329	4.95
Insula	R	47	44	18	−4	80	4.82
Inferior frontal gyrus (triangular)	L	45	−46	32	10	31	4.57
Middle occipital gyrus	L	18	−36	−94	0	30	4.56
Inferior frontal gyrus (triangular)	L	45	−48	36	22	11	4.32

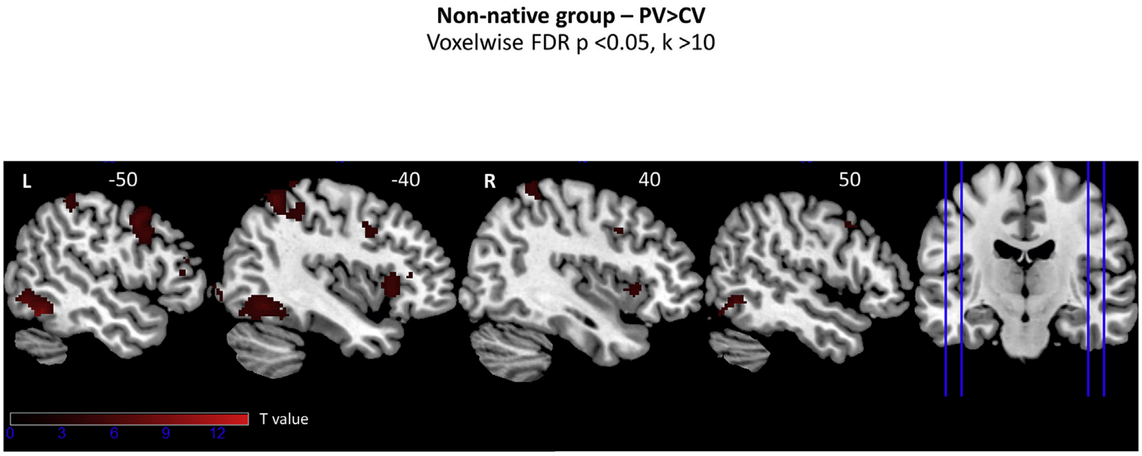

Fig. 4. Sections showing brain regions activated for explicit OPC processing of Chinese pseudo-phonograms (PV > CV), with higher activity in the non-native than the native group. In this contrast, no brain region in natives showed higher activity than non-natives.

When concerning the effect of nativity, except for the right fusiform gyrus all ROIs showed group differences in activity across the three tasks generally ($ps < .033$, Fig. 5). When concerning the effect of task demands, comparisons between the two color verification tasks (CV and CV_K) showed no significant differences between beta values in all six ROIs. On the other hand, the beta values associated with PV were significantly higher than those associated with both CV and CV_K (all $ps < .01$, except for RFG, which only showed a significant difference between PV and CV_K).

The interactions between the effects of nativity and task demands in the six ROIs indicated that LIPL ($F(2, 44) = 4.660$, $p = .015$) and LFG ($F(2, 44) = 2.920$, $p = .065$, marginal significance) was differentially involved in the three tasks between the two groups of participants (Fig. 5). Further analysis revealed that in LIPL, non-native participants showed higher activation than native participants in both the PV and CV_K tasks ($ps < .022$) but not in the CV task ($p > .268$). More important, non-native participants showed significant activation differences across the three tasks ($F(2, 44) = 9.414$, $p < .001$, PV > CV = CV_K, $ps < .01$), while native participants showed no difference in this ROI ($F(2, 44) < 1$). A similar pattern was found in LFG: non-native participants showed higher activation than native participants in both the PV and CV_K tasks ($ps < .015$) but not in the CV task ($p > .302$). Non-native participants showed significant activation differences across the three tasks ($F(2, 44) = 11.610$, $p < .001$, PV > CV = CV_K, $ps < .01$), while native participants only showed difference between PV and CV_K in this ROI ($F(2, 44) = 6.415$, $p = .004$, PV > CV_K, $p < .01$).

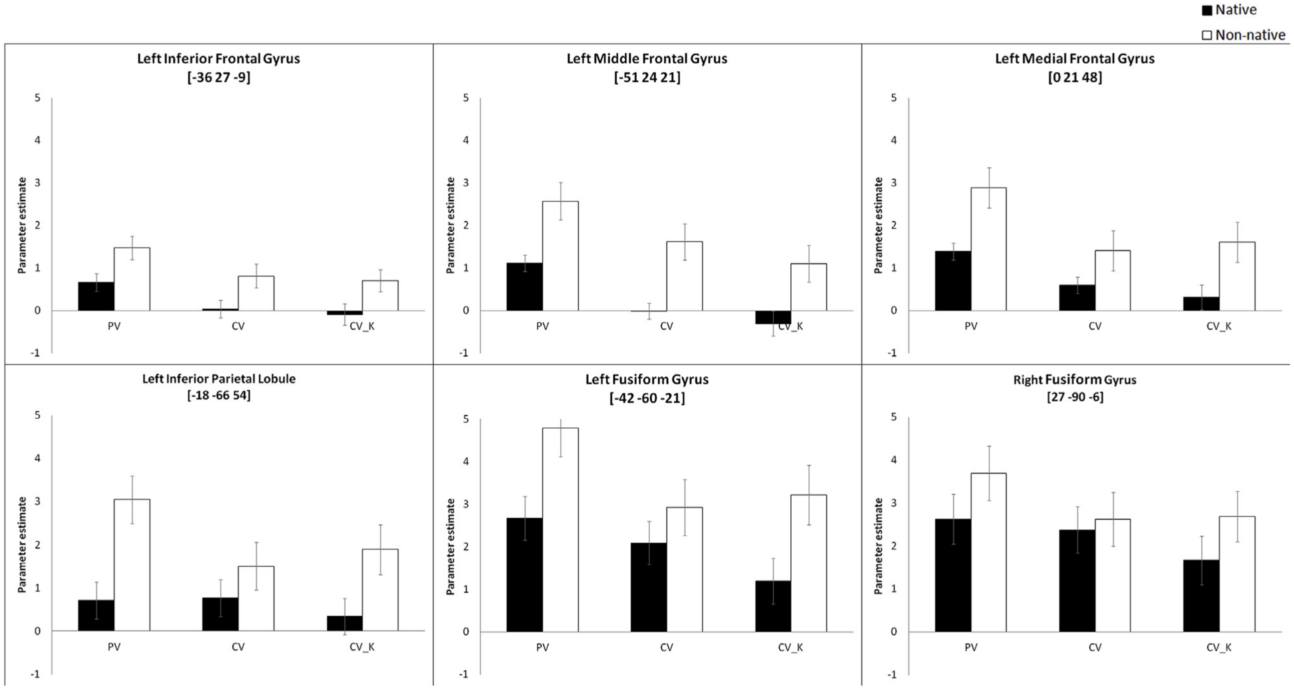

Fig. 5. Mean beta values in six regions of interest – LIFG (left inferior frontal gyrus), LMedFG (left medial frontal gyrus), LFG (left fusiform gyrus), LIPL (left inferior parietal lobule), LMFG (left middle frontal gyrus) and RFG (right fusiform gyrus), identified as major OPC processing regions, are shown.

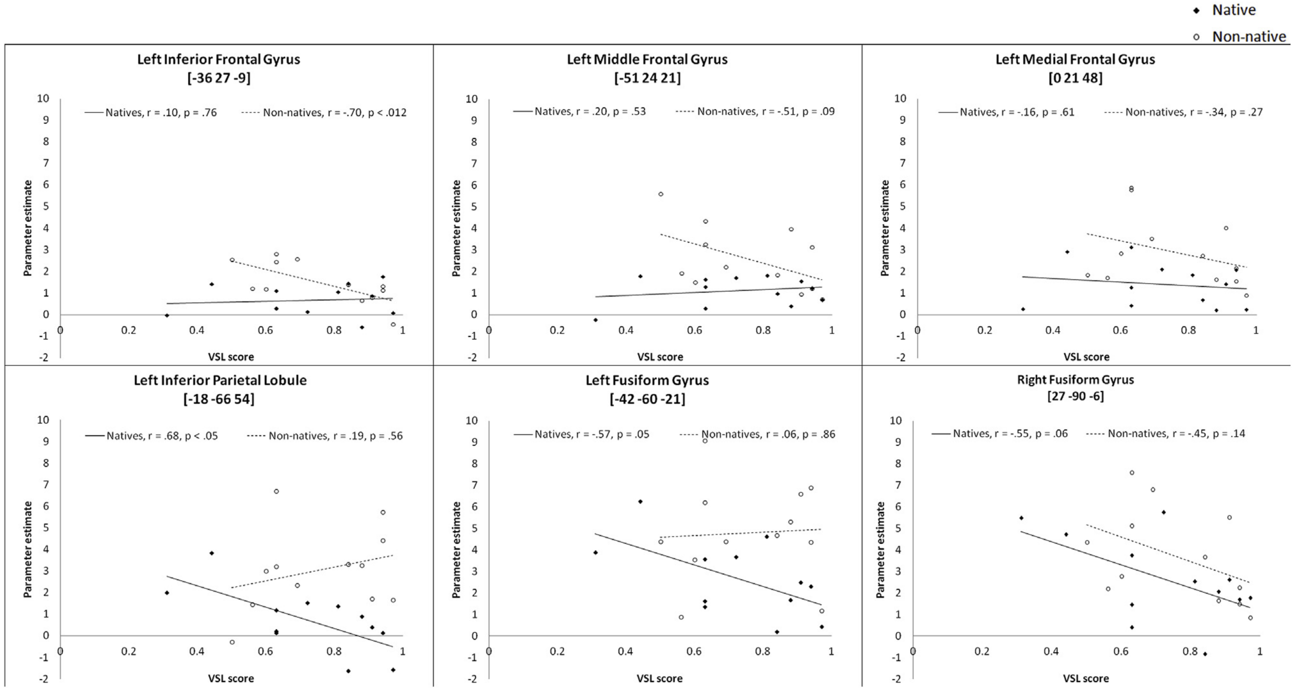

Fig. 6. Correlation between VSL scores and mean brain responses in the pronunciation verification task in all six regions of interest (ROIs) for the native (solid diamond) and non-native (empty circle) groups. The *p* and *r* values for the correlation are also provided.

3.3.4. Correlation between VSL and OPC processing in ROIs and whole-brain analyses

A two-tailed correlation analysis was conducted between the beta values and the VSL scores of individual participants. For native participants, their VSL scores were significantly correlated with the brain activity associated with the pronunciation verification (PV) task in the left inferior parietal lobule (LIPL: $r(11) = -.680$, $p = .015$) and marginally significant with that in bilateral fusiform gyri (LFG: $r(11) = -0.575$, $p = .051$; RFG: $r(11) = -.550$, $p = .064$). These results suggested that for native participants who are more sensitive to visual regularity embedded in nonverbal shapes, the OPC processing in the LIPL and bilateral FGs was more efficient (hence less activation required) to verify the pronunciation of Chinese pseudo-phonograms. On the other hand, the VSL scores of these participants were only marginally correlated with the brain activity in the color verification (CV) task of Chinese pseudo-phonograms in the left fusiform gyrus (LFG: $r(11) = -.557$, $p = .060$), likely due to the relatively low demand of OPC processing by this task particularly for native participants (see Fig. 6). Importantly, the correlation between VSL scores and brain activities in LIPL was not mediated by general cognitive abilities, as the brain activities in this region were not significantly correlated with individuals' IQ or forward digit span ($ps > .800$), nor was it driven by few outliers.

For non-native participants, their VSL scores were significantly correlated with the brain activity associated with the pronunciation verification (PV) task in left inferior frontal gyrus (LIFG: $r(11) = -.694$, $p = .012$) and marginally correlated with that in left middle frontal gyrus (LMFG, $r(11) = -.506$, $p = .094$). As for the color verification (CV) task, the brain activity in none of the ROIs was correlated with the VSL scores (all $ps > .200$) (see Fig. 6). Again, the correlation between VSL scores and brain activities in LIFG was not mediated by general cognitive abilities or Chinese proficiency, as the brain activities in this region were not significantly correlated with individuals' IQ, forward digit span, or vocabulary size ($ps > .150$), nor was it driven by few outliers. Critically, direct comparisons between the correlations between VSL scores and beta values in these ROIs of native and non-native participants confirmed that statistical learning abilities were significantly correlated with brain activation extracted from the left inferior frontal gyrus in the PV task only in non-native but not in native participants ($z = 2.02$, $p = .043$). In contrast, statistical learning abilities were significantly correlated with brain activation extracted from the left inferior parietal lobule in the PV task only in native but not in non-native participants ($z = 2.38$, $p = .017$).

In addition to investigating the link between VSL and activity in the literature-guided ROIs, correlation analysis was performed at the whole-brain level ($p < .001$, $k > 10$, cluster-level corrected FWE $p < .05$ to be conservative for this exploratory analysis, especially when the number of participants was small in the present study). The findings from this analysis revealed significant brain regions that are partially distinct from the pre-determined ROIs. A strong negative correlation of VSL with activity in the left inferior parietal region [-36, −56, 40] (BA40) and the left mid cingulum [-6, −42, 56] was observed in native participants, while a similar negative relationship was observed between VSL and the brain activity in the right insula [40, 6, −4] (BA 48) and the right middle temporal gyrus [44, −62, 4] (BA 37) for non-native participants (see Fig. 7).

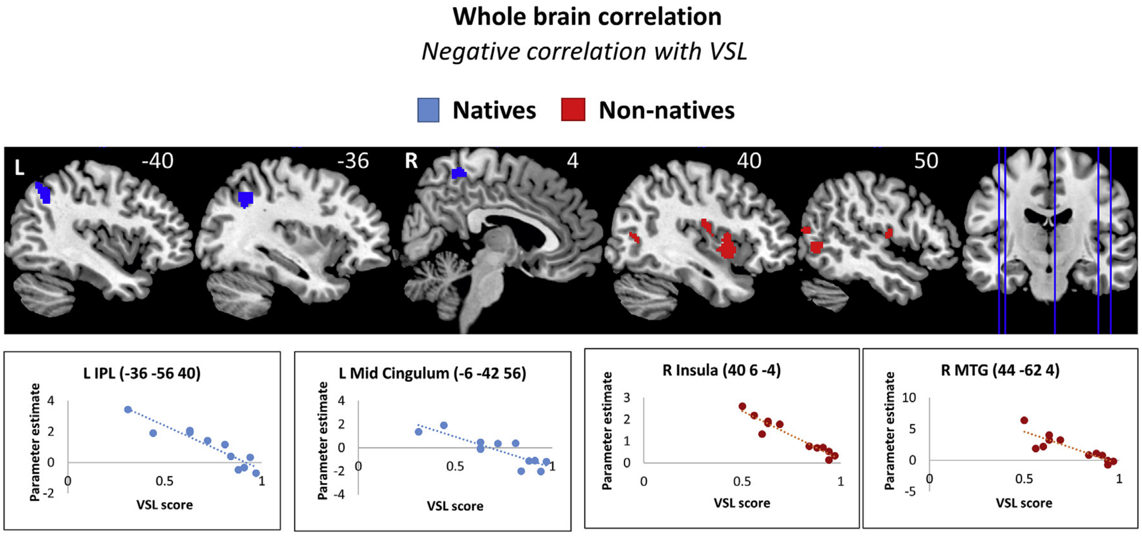

Fig. 7. Summarized results of whole-brain correlation analyses showing brain regions whose activity correlated with VSL scores in the native (blue) and the non-native group (red). Scatter plots are shown to demonstrate the negative trend in correlation with VSL scores in both groups. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

4. Discussion

The present study measured native and non-native readers of Chinese on statistical learning skills behaviorally, and their OPC processing using pseudo-phonograms in pronunciation/color verification tasks. It aimed to investigate (1) the OPC processing network in L2 learners of Chinese, which was compared with that in native readers, and (2) the link between statistical learning skills (VSL) and the brain activity that supports OPC processing. The comparable accuracy of pronunciation verification on Chinese pseudo-phonograms between native and non-native participants confirmed that the foreign learners of Chinese recruited in this study have sufficient knowledge of Chinese orthography to complete the tasks, though their proficiency did not reach the native level as they exhibited longer reaction times on both the pronunciation and color verification tasks. Among behavioral measures, the forward digit span task showed a significant group difference, with better performance in the native than the non-native group. This was not surprising, given the past evidence showing an advantage of Mandarin speakers in comparison with English speakers on forward digit span, likely due to shorter syllable length of digits in Mandarin than in English as well as other Indo-European languages (e.g., Chen, Cowell, Varley, & Wang, 2009; Ting, Hameed, Tan, Gabriel, & Doshi, 2014).

The following were the main activation patterns recorded in the pronunciation and color verification tasks with Chinese pseudo-phonograms (PV and CV, respectively), as well as color verification on Korean characters (CV_K) as a baseline: (1) The PV task elicited activity in left fronto-temporo-parietal regions in native readers, while in non-natives this pattern was extended to the right hemisphere as well. These results not only confirm the contribution of this network to reading Chinese pseudo-phonograms in both native and non-native readers, they also reflect the higher efforts of non-natives than natives to recognize Chinese characters. (2) The whole-brain analysis did not detect any difference between the PV and CV tasks in natives, while only the ROI analyses revealed higher activation in the PV than the CV task in the left inferior, middle, and medial frontal gyri. These results suggest that OPC processing might be automatic and equally engaged in pronunciation and color verification of Chinese characters for native participants. (3) Non-natives consistently showed higher activity in the left fronto-temporo-parietal network in response to the higher demand of OPC processing in the PV than the CV task, indicating these regions to be involved to the mapping between orthography and phonology especially in non-native readers of Chinese. (4) According to the ROI analysis, the frontal regions were more involved in the PV than the CV and CV_K tasks in both natives and non-natives, despite that the overall activation in non-natives was significantly higher than that in natives. On the other hand, for non-natives the PV task elicited higher activation than the CV and CV_K tasks particularly in the left parietal lobule and the left fusiform gyrus, but such pattern was less obvious in natives.

In addition to identifying the neural network associated with OPC processing in native and non-native readers of Chinese characters, one important finding from the present study is the significant correlation between VSL scores and the brain activation in specific regions within the reading network in native and non-native participants. Specifically, such significant correlation in the left inferior frontal gyrus in non-natives suggests that this brain region is likely to subserve the sensitivity to picking up systematic correspondence between Chinese word forms and sounds, which is particularly important for Chinese learners to recognize pseudo characters. For native participants, on the other hand, VSL did not correlate with the activation of the left inferior frontal gyrus, but with that of left inferior parietal lobule, which has been argued to subserve the mapping between orthography and phonology in both Chinese (Booth et al., 2006) and English (Booth et al., 2003). Based on the findings summarized above, non-native readers engage similar brain regions as natives during OPC processing, but show a higher extent of activity, probably due to their reduced proficiency of Chinese. Moreover, within the common neural network supporting OPC processing of Chinese character recognition, natives and non-natives rely on distinct brain areas for the critical computations. These findings are also compatible with the idea that nativity does not ensure a certain exclusive neural signature absent in non-native readers, who learn the L2 much later in life.

The involvement of regions such as middle and inferior frontal regions of the left hemisphere in OPC processing is consistent with results from previous studies on Chinese character recognition (Booth et al., 2006; Kuo et al., 2004; Lee, Huang, Kuo, Tsai, & Tzeng, 2010; Lee et al., 2007, 2005). The left inferior frontal gyrus has been found to be crucially engaged in phonological processing, and previous literature has suggested an anatomical dissociation at this region: the anterior ventral portion is involved with semantic access (Tan et al., 2001), while the posterior dorsal portion is involved with phonological access and processing (Booth et al., 2006). Inspection of Fig. 3 indeed suggests that the contrast of PV > CV_K might be associated with more extensive and more inferior/ventral activation in non-native than native participants. However, because direct comparisons of the beta values in all three frontal ROIs did not detect any interaction between nativity and task demands but only confirmed overall higher activation in non-native than native participants, it might be premature to speculate that different sectors within the left inferior frontal gyrus are recruited across the two groups. As for the function of the left middle frontal gyrus, it has been argued to be responsible for addressed phonology (Tan, Laird, Li, & Fox, 2005), syllable processing (Siok, Jin, Fletcher, & Tan, 2003), and speech production for the part located in the premotor regions (Mechelli, Josephs, Lambon Ralph, McClelland, & Price, 2007). In the PV task of the present study, both natives and non-natives showed a left-lateralized cluster ranging from the inferior/middle frontal gyri to the precentral gyrus (BA6), similar to the previously reported frontal involvements in OPC processing. Given that the ROI analyses did not detect any significant interaction between nativity and tasks in the frontal regions, the results support native-like activity in Chinese learners.

The activation in the left inferior parietal lobule was also associated with the OPC processing in the PV task in both natives and non-natives in the present study. In addition to the function of mapping orthography to phonology as shown in different languages (Booth et al., 2003, 2006), this region has been previously identified as a phonological processing region specifically in Chinese pinyin reading (Fu, Chen, Smith, Iversen, & Matthews, 2002). Moreover, in non-natives the involvement of this region in the PV task extended to the left superior lobule (BA7), which has been reported in previous studies that employed Chinese characters (e.g., Siok et al., 2003). Because this region has been associated with visual spatial processing consistently (Booth et al., 2006), it is possible that non-natives engage this region to decode the relatively complex stroke patterns of Chinese characters in particular. In contrast to natives demonstrating a typical neural network underlying OPC processing in the PV task, additional activation of the precuneus, the cingulate region, and the cerebellum was also found in non-natives, suggesting higher engagement of phonological processes as summarized in a meta-analyses study compiling reports on Chinese reading (Wu et al., 2012).

The correlation analyses found that VSL scores had a significant negative correlation with activity levels in some regions of a neural network identified in a previous study contrasting rhyming judgment of Chinese characters with line judgment (Booth et al., 2006). Specifically, correlating activity in the ROIs and VSL measures verified that individuals with higher SL scores exhibited lower levels of activity, reflecting their increased sensitivity to structure of Chinese language, such as consistency of Chinese OPC mapping. Both ROI and whole-brain correlations confirmed a negative link between VSL skills and the activation in the left parietal lobule (BA40) in native participants. Such result not only supports the link between statistical learning and the activity in this region to process regularity between orthography and phonology, it also challenges the claim that this region serves as a “phonological store” to facilitate a direct “look-up” procedure between Chinese orthography and phonology (Tan et al., 2005). Because the stimuli employed in the present study were pseudo-phonograms, participants would not have existing memory of the sounds of these stimuli stored in the brain. Also, more experienced readers should have more rule-based knowledge than less experienced readers to support OPC processing necessary for pronunciation verification of pseudo-phonograms. Given that we observed significant correlation between VSL and the activation in the left inferior parietal lobule only in natives but not in non-natives, we reason that the function of this region is to support the mapping between orthography and phonology not only in Chinese but also in other languages (Booth et al., 2003, 2006).

For non-native participants, their VSL scores were found to be correlated with the activation in the left frontal regions significantly. Similar to the negative correlation between statistical learning abilities and the brain activation of the left parietal regions in native participants, non-native participants who had high scores in the VSL test exhibited decreased activation in the left inferior and middle frontal gyri. The left inferior frontal gyrus has been reported to subserve the function of phonological processing across alphabetic and logographic languages (Booth et al., 2006; Cabeza & Nyberg, 2000; Fiez, 1997; Pugh et al., 1996). It has also been shown that Chinese characters with low frequency or with inconsistent phonetic radicals elicited higher activation than characters with high frequency or with consistent phonetic radicals did in this region (Kuo et al., 2004; Lee et al., 2004). Indeed, the relationship between VSL scores and OPC processing of Chinese pseudo-phonograms demanded by the pronunciation verification task in the present study is in line with the general findings that the left inferior frontal gyrus demonstrated greater activation for more difficult tasks (Booth et al., 2003).

Whole brain correlation analyses confirmed findings from the ROI analysis that VSL is critical to both L1 and L2 readers of Chinese. Further, it also reiterated the fact that distinct regions may be responsible at the neural level to the increased sensitivity to statistical regularities in Chinese in L1 and L2 readers. This analysis confirmed the link between the left inferior parietal region and VSL in native readers, while also revealing a novel association between activity in right temporal and insular regions with VSL in non-native readers of Chinese. These findings suggest that L2 learning of Chinese relies on right hemisphere regions, not found in native readers. Interestingly, this is in agreement to previous reports in L2 Chinese reading, where increased right hemispheric activity was found to be a distinct marker of L2 readers of Chinese (Ding et al., 2003).

It should be noted that the present findings should be interpreted with caution, given the admittedly limited pool of participants of both native and non-native Chinese readers. Therefore, absence of significant effects in the current study cannot be assumed to be proof of null effects, until further studies with a larger sample size are conducted. However, it is also important to note that this study was designed to reduce the impact of the limitation of small sample by recruiting participants with similar L1 backgrounds, in that they were all readers of alphabetic languages using Roman orthography. This relatively controlled selection of participants might have helped reduce potential false observations on group differences, due to increased diversity in OPC processing strategies within the non-native group. Also, the significant correlation between VSL performance and the activation of brain regions subserving OPC processing in both native and non-native readers of Chinese, despite the small sample size, suggests that sensitivity to regularity in (non-verbal) materials is critical to learning and representing systematic correspondence between orthography and phonology even for a semi-regular writing system.

5. Conclusions

The present study reveals the neural network engaged in OPC processing in Chinese L2 learners and provides novel evidence by comparing the network with that in native readers. Several studies in the past had reported such networks in L1 readers (Lee et al., 2005, 2004; Tzeng & Lee, 2012), but the evidence from L2 learners is lacking. The present study fills the gap by providing empirical findings of sensitivity to OPC knowledge in adult participants with an alphabetic language background. Overall, we found a consistent pattern of higher brain activity in the neural correlates of explicit OPC processing in less experienced L2 learners as compared to native readers. Interestingly, activity in the left inferior parietal lobule and the left inferior frontal gyrus within the OPC processing network also correlated with VSL skills measured behaviorally in native and non-native participants, respectively. This indicates the pivotal role played by VSL in Chinese literacy acquisition, specifically in OPC processing, which is related to the sensitivity to consistency of phonetic radicals. Moreover, the distinction of neural substrates linked with VSL in natives and non-natives, as evidenced by our findings from the correlations analyses with VSL scores in the ROIs and at the whole-brain level, suggests that the computation demands might be placed on different loci within the common neural network for OPC processing in Chinese readers with different degrees of proficiency. To summarize, our current findings are congruent with previous studies which reported significance of VSL in L2 learning in another alphabetic orthography (Frost et al., 2013). Future studies should consider a larger sample size, especially regarding the relationship between statistical learning and OPC processing, and address the question of how the link between VSL and OPC may change in various writing systems with different sound-letter mapping rules.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jneuroling.2018.07.002.

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