Neuroanatomical Correlates of Phonological Processing of Chinese Characters and Alphabetic Words: A Meta-Analysis

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Abstract: We used the activation likelihood estimation (ALE) method to quantitatively synthesize data from 19 published brain mapping studies of phonological processing in reading, six with Chinese and 13 with alphabetic languages. It demonstrated high concordance of cortical activity across multiple studies in each written language system as well as significant differences of activation likelihood between languages. Four neural systems for the phonological processing of Chinese characters included: (1) a left dorsal lateral frontal system at Brodmann area (BA) 9; (2) the dorsal aspect of left inferior parietal system; (3) a bilateral ventral-occipitotemporal system including portions of fusiform gyrus and middle occipital gyrus; and (4) a left ventral prefrontal system covering the superior aspect of inferior frontal gyrus. For phonological processing of written alphabetic words, cortical areas identified here are consistent with the three neural systems proposed previously in the literature: (1) a ventral prefrontal system involving superior portions of left inferior frontal gyrus; (2) a left dorsal temporoparietal system including mid-superior temporal gyri and the ventral aspect of inferior parietal cortex (supramarginal region); and (3) a left ventral occipitotemporal system. Contributions of each of these systems to phonological processing in reading were discussed, and a covariant learning hypothesis is offered to account for the findings that left middle frontal gyrus is responsible for addressed phonology in Chinese whereas left temporoparietal regions mediate assembled phonology in alphabetic languages. Language form, cognitive process, and learning strategy drive the development of functional neuroanatomy. *Hum Brain Mapp 25:83–91, 2005.* © 2005 Wiley-Liss, Inc.

Key words: fMRI; neuroimaging; culture; phonological processing; word recognition; Chinese reading; English reading

INTRODUCTION

The goal of this study was to determine the patterns of convergence in neuroanatomical circuits underlying phonological processing in reading alphabetic words and logographic characters. We utilized the activation likelihood estimation (ALE) method, a newly-developed meta-analytic technique to quantitatively synthesize results across 19 relevant published neuroimaging studies [Laird et al., 2005; Turkeltaub et al., 2002]. We selected experiments with alphabetic languages and logographic Chinese for this meta-analysis, because these two types of writing systems differ markedly in how they represent the phonology (speech sounds) of the spoken language. These differences, as described below, are resonated in cognitive systems for lan-

Contract grant sponsor: Hong Kong Government Research Grants Council; Contract grant number: HKU 7133/01H; Contract grant sponsor: National Library of Medicine; Contract grant number: RO1-LM6858.

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Received for publication 7 January 2005; Accepted 1 February 2005
DOI: 10.1002/hbm.20134
Published online in Wiley InterScience (www.interscience.wiley.com).

guage processing, and are important in advancing our knowledge of the universality and particularity of neural circuits for language.

Words in alphabetic languages use graphemes (printed letters) as visual symbols that map onto phonemes (minimal sound units) of the spoken language and follow grapheme-to-phoneme conversion rules. Alphabetic words thus are predominantly read out by assembling fine-grained phonemic units, i.e., by assembled phonology [Coltheart et al., 1993; Patterson, 1982]. Written Chinese uses characters as a basic writing unit that possesses a number of intricate strokes packed into a square configuration, often having their meaning suggested by visual shapes. Chinese characters map onto phonology at the (mono-)syllable level, with no parts in a character corresponding to phonological segments such as phonemes. Although 85% of present-day Chinese characters are compounds containing a phonetic component that can give information about the pronunciation of the compound, estimates of the validity of this information reveal that only 28% of phonetic components sound the same as their resultant whole characters. Moreover, it is never the case in Chinese that a phonetic component maps onto a subsyllabic phonological representation in the way that a letter maps onto a substring of a word's phonological form in an alphabetic system [Perfetti et al., 2005]. For instance, in the English word *beech*, the *b* corresponds to /b/, and the latter is a segment of the word. For the Chinese compound 理 (pronounced /li3/, meaning reason; the numeral here refers to Chinese tone), the phonetic component located on the right (also pronounced /li3/, meaning inside) does not correspond to a piece of the word's phonological form; it is the syllable that maps onto both components and whole characters. Chinese writings thus do not allow a true segmental analysis that is fundamental to alphabetic systems, and grapheme-to-phoneme conversion rules that exist in all alphabetic languages are impossible in Chinese. With this design principle in logographs, phonological codes of Chinese characters are accessible only by recourse to the direct retrieval of phonological information stored in the cognitive network. This kind of phonological codes, addressed phonology, is generated by a look-up procedure after visuo-orthographic information of the appropriate lexical candidate has been completely activated [Tan et al., 1995].

In the brain-mapping literature, many studies with various paradigms such as reading aloud [Bookheimer et al., 1995; Dietz et al., 2005; Fiez et al., 1999; Hagoort et al., 1999; Herbster et al., 1997; Huang et al., 2001; Petersen et al., 1988; Price et al., 1996; Rumsey et al., 1997; Turkeltaub et al., 2002], rhyme judgment [Booth et al., 2002, 2004; Lurito et al., 2000; Petersen et al., 1989; Poldrack et al., 2001; Pugh et al., 1996; Seghier et al., 2004; Shaywitz et al., 1998; Tan et al., 2003; Xu et al., 2001, 2002], syllable decision [Gabrieli et al., 1998; Poldrack et al., 1999; Price et al., 1997], vowel feature judgment [Gold and Buckner, 2002], and letter transformation [Georgiewa et al., 1999] have been devoted to the identification of dedicated cortical regions responsible for phonological processing in recognizing alphabetic words and nonwords. These studies not only serve to inform cognitive models of reading and visual word recognition [Bookheimer, 2002; Fiez and Petersen, 1998; Fiebach et al., 2002; Jobard et al., 2003; Price, 2000; Turkeltaub et al., 2002], but also constitute an important part of ongoing efforts to understand the biological abnormality of impaired reading that is characterized by phonological deficits [Eden and Moats, 2002; Eden et al., 2004; Shaywitz et al., 2002; Siok et al., 2004; Temple et al., 2001, 2003; Turkeltaub et al., 2003].

In the last several years, neuroimaging investigations with Chinese characters have also been conducted, often with a focus on functional anatomy of phonological processing in reading [Chen et al., 2002; He et al., 2003; Kuo et al., 2004; Siok et al., 2003, 2004; Tan et al., 2001a, 2003]. Some of these studies have implicated significant differences in neural bases for reading in Chinese and English. For example, it has been found that strong cortical activations relevant to phonological processing of written Chinese as indexed by rhyme decision occurred in left middle frontal cortex at Brodmann area (BA) 9 and 46, left motor and supplementary motor cortex, and left inferior parietal lobule (BA40), with minor activations seen in left inferior prefrontal gyrus (BA45/47) [Tan et al., 2003]. In contrast, for native English speakers, phonological processing was mediated by the strong activations of left inferior prefrontal (BA44/45) and superior temporal gyri (BA22), with weak activity in left middle frontal cortex [Tan et al., 2003]. This pattern of brain activations suggests that neural systems for phonological processing are constrained by language.

We sought to combine results across a number of studies to compare the neural circuits involved in phonological processing of written Chinese and alphabets. The striking differences in linguistic characteristics and cognitive processes between the two writing systems will allow us to gain a better understanding of the organization principle of written languages in the brain.

MATERIALS AND METHODS

Literature Selection

There were nine neuroimaging studies of phonological processing of printed Chinese characters, all using functional magnetic resonance imaging (fMRI). Among these studies, six used an explicit, phonology-related decision task [Chen et al., 2002; Kuo et al., 2004; Siok et al., 2003, 2004; Tan et al., 2001a, 2003], two used reading aloud [He et al., 2003; Tan et al., 2001b], and one used silent reading [Kuo et al., 2001]. We decided to enter the data of the six studies employing an explicit phonological judgment task into the meta-analysis (Table I), and excluded the three studies with the silent-reading or reading-aloud paradigm, because we believed that reading aloud is relevant not only to phonological processes in visual character identification, but also to auditory and (passive) language production processes. It is unclear what processes are involved in silent reading, because subjects' performance is often not monitored.

TABLE I. Neuroimaging studies selected for the meta-analysis

Study	Reference	Language	n	Scanner	Experimental task	Baseline
1	Chen et al., 2002	Chinese	9	3T MRI, Oxford	Sound-like judgment	Fixation
2	Kuo et al., 2004	Chinese	10	3T MRI, Taipei	Homophone judgment	Character form judgment
3	Siok et al., 2003	Chinese	11	2T MRI, Beijing	Homophone judgment	Font size decision
4	Siok et al., 2004	Chinese	8	2T MRI, Beijing	Homophone judgment	Font size decision
5	Tan et al., 2001a	Chinese	6	2T MRI, San Antonio	Homophone judgment	Fixation
6	Tan et al., 2003	Chinese	12	2T MRI, San Antonio	Rhyme judgment	Font size decision
7	Booth et al., 2002a	English	13	1.5T, Chicago	Rhyme judgment	Line pattern match
8	Booth et al., 2002b	English	13	1.5T, Chicago	Rhyme judgment	Spelling
9	Booth et al., 2004	English	16	1.5T, Chicago	Rhyme judgment	Letter case decision
10	Georgiewa et al., 1999	German	17	1.5T, Germany	Letter transformation	Letter identification
11	Gold and Buckner, 2002	English	24	1.5T, St. Louis	Phonological decision	Letter decision
12	Petersen et al., 1989	English	7	PET, St. Louis	Rhyme judgment	Fixation
13	Poldrack et al., 2001	English	8	1.5T MRI, Stanford	Rhyme judgment	Letter case decision
14	Price et al., 1997	English	6	PET, London	Syllable decision	Semantic judgment
15	Sergent et al., 1992	English	8	PET	Letter sound decision	Letter spatial decision
16	Temple et al., 2001	English	15	3T MRI, Stanford	Letter rhyme	Line match
17	Tan et al., 2003	English	12	2T MRI, San Antonio	Rhyme judgment	Font size decision
18	Xu et al., 2001	English	12	PET, NIH	Rhyme judgment	Letter feature search
19	Xu et al., 2002	English	18	1.5T MRI, NIH	Rhyme judgment	Letter line decision

According to the above criteria, a set of 13 studies with English or German was selected for the analysis, all of which utilized an explicit phonology-related judgment task. For these 13 studies, 9 utilized fMRI and 4 utilized positron emission tomography (PET) to acquire functional images. Several previous investigations with an explicit phonological task were excluded due to one of two considerations: (1) 3D coordinates (x, y, z) were not reported so that meta-analyses were impossible [Pugh et al., 1996; Shaywitz et al., 1998, 2002]; or (2) only part of the brain was covered during MRI scan [Poldrack et al., 1999]. The selected studies for the meta-analysis had different baseline conditions; however, the phonological process explicitly required by the experimental tasks helped determine neural signatures critically involved in phonological computation.

Activation Likelihood Estimation

ALE maps were created as described by Turkeltaub et al. [2002] and Laird et al. [2005] using a full-width half-maximum (FWHM) of 10 mm. Statistical significance was determined using a permutation test of randomly distributed foci. The test was corrected for multiple comparisons using the false discovery rate method. ALE maps were computed for studies with Chinese characters, studies with alphabetic words, and direct contrasts of these two writing systems. The pooled images were thresholded at $P < 0.05$ corrected. For detailed procedures of using ALE, readers are referred to Laird et al. [2005].

RESULTS

ALE meta-analysis of phonological processing of printed Chinese characters (as illustrated in Figure 1) indicated high convergence in left middle frontal gyrus (BA9), bilateral occipital gyri (BA18), bilateral fusiform gyrus (BA37), left medial frontal gyrus (BA6, 9), left inferior frontal gyrus (BA47), and the dorsal aspect of left inferior parietal cortex (BA40) (Fig. 1a; Table II). Extremely high concordance was seen in the left middle frontal gyrus (BA9) with a cluster size of 7,664 mm^3.

For phonological processing of alphabetic words, 12 clusters of activation likelihood were seen in left inferior frontal gyrus (BA44), left fusiform gyrus (BA37), cerebellum, left mid-superior temporal regions (BA21, 42), ventral aspect of left inferior parietal cortex (involving supramarginal gyrus, BA40), left medial frontal gyrus (BA6, 8), right superior temporal gyrus (BA22), and right mid-inferior occipital gyrus (BA18) (Fig. 2b). The highest convergence was obtained in left inferior frontal gyrus, with a cluster size of 11,408 mm^3.

Direct contrasts of Chinese characters and alphabetic words showed significant differences between their relative ALE maps (Fig. 2c). Left middle frontal gyrus (BA9) and bilateral inferior occipital cortices (BA18) were involved more consistently in phonological processes of Chinese characters. Other regions heavily mediating Chinese reading were left premotor cortex, cingulate, left medial fusiform gyrus (BA19; $x = -34$, $y = -52$, and $z = -6$), dorsal aspect of left inferior parietal lobule (BA40; $x = -36$, $y = -42$, $z = 48$), and right fusiform gyrus (BA37). Brain areas that were more concordantly implicated for phonological processes of alphabetic words included left inferior prefrontal cortex (BA44, 45, 46), cerebellum, left lateral fusiform gyrus (BA37; $x = -44$, $y = -56$, $z = -12$), left mid-superior temporal gyrus (BA21, 42), left supramarginal region, left ventral aspect of inferior parietal lobule (BA40; $x = -56$, $z = -40$, $y = 24$), and right superior temporal gyrus (BA22).

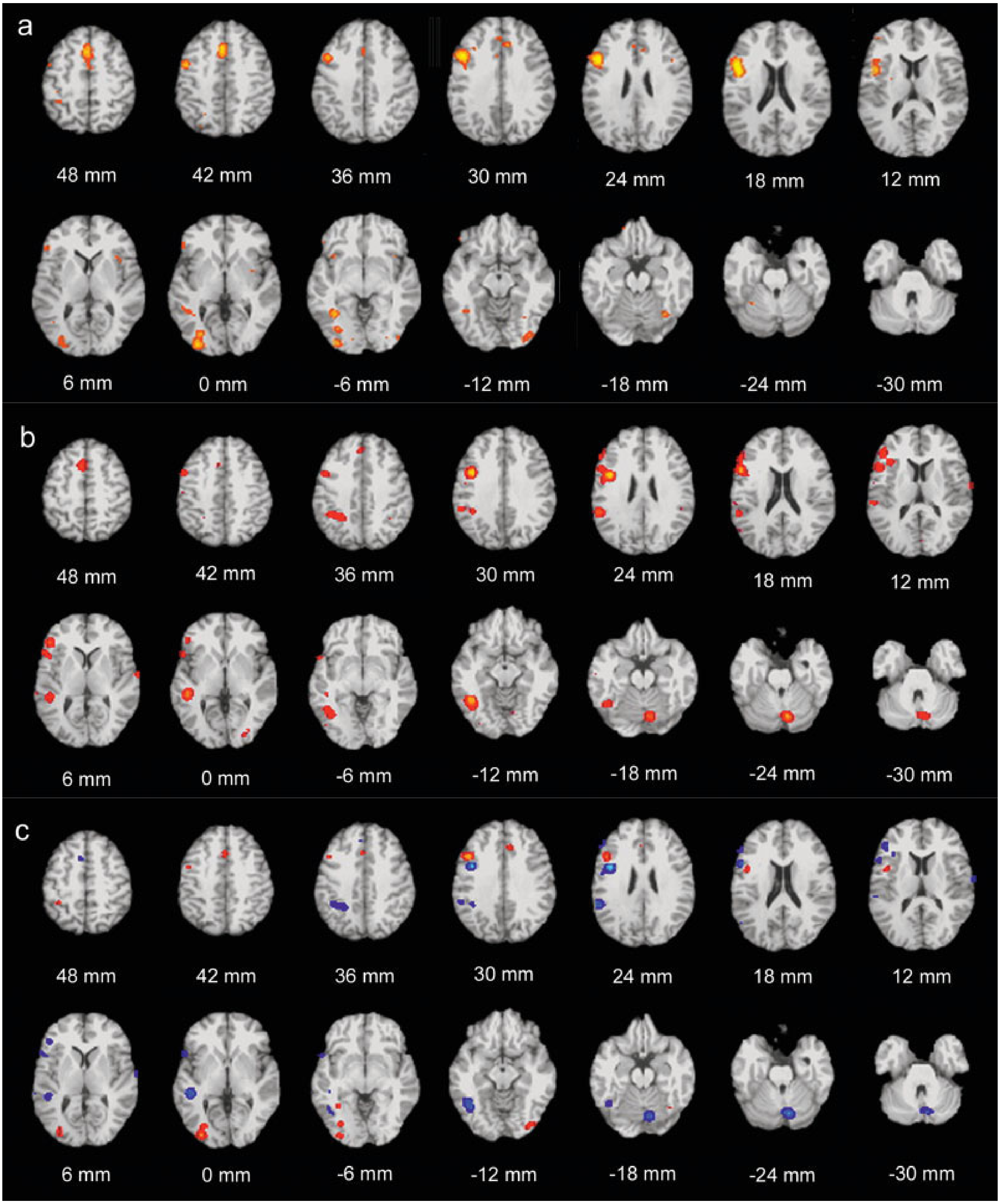

Figure 1.
ALE maps showing significant activation likelihood across studies of phonological processing of written words ($P < 0.05$, corrected). **a:** Chinese characters. **b:** Alphabetic words. **c:** Direct contrast of the two writing systems (warm color, Chinese minus alphabetic; cold color, alphabetic minus Chinese).

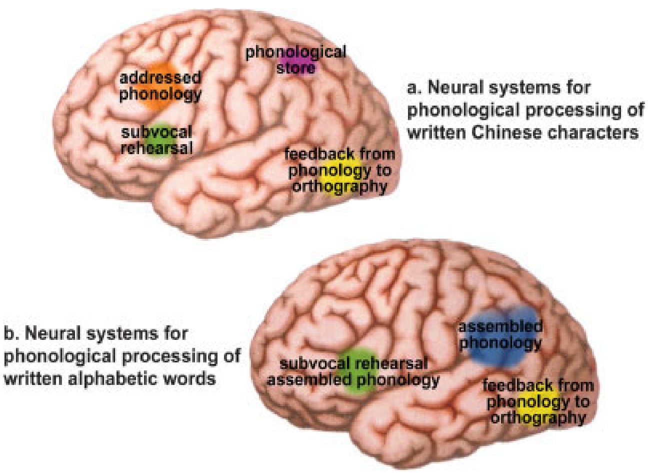

Figure 2.
Neural systems for phonological processing of Chinese characters and alphabetic words.

DISCUSSION

The present meta-analysis of the functional neuroanatomy of phonological processing in visual word recognition has demonstrated high concordance of brain activation across multiple studies in each of the two writing systems. Furthermore, this analysis has suggested significant differences of activation likelihood between Chinese and alphabetic languages.

Interdependence of Form, Process, and Location in Neural Systems

Brain regions identified in this study may be assembled into four neural systems for phonological processing of Chinese characters: (1) a left dorsal lateral frontal system (BA9); (2) the dorsal aspect of left inferior parietal system; (3) a bilateral ventral occipitotemporal system including portions of fusiform gyrus and middle occipital gyrus; and (4) a left ventral prefrontal system covering superior portions of inferior frontal gyrus. For phonological processing of written alphabetic words, cortical areas demonstrated here are congruent with the three neural system hypothesis that assumes the following cortical circuits, all primarily in the left hemisphere [Shaywitz et al., 1998; Pugh et al., 2000]: (1) a ventral prefrontal system involving posterior portions of inferior frontal gyrus; (2) a dorsal temporoparietal system including mid-superior temporal gyri and supramarginal regions; and (3) a ventral occipitotemporal system. Figure 2 illustrates similarities and differences in neural systems across the two writing systems.

We have hypothesized that the left dorsal lateral frontal system is responsible for the visuospatial analysis of Chinese characters and the orthography-to-phonology mapping at the syllable level, which are demanded by the logographic and monosyllabic nature of written Chinese [Siok et al., 2003, 2004; Tan et al., 2001a, 2003]. This dorsal lateral frontal system is assumed to serve as a long-term storage center for phonological representations of Chinese words, specifically, for addressed phonology.

The left posterior sites of temporoparietal regions were important for alphabetic languages, but not for Chinese characters, as shown in this meta-analysis. This posterior brain system is known to mediate grapheme-phoneme conversions and fine-grained phonemic analysis [Booth et al., 2004; Eden et al., 2004; Poldrack et al., 2001; Price, 2000; Shaywitz et al., 1998; Simos et al., 2000, 2002; Temple et al., 2001, 2003; Tan et al., 2003; Xu et al., 2001, 2002]. It is thus highly responsible for assembled phonology.

The posterior neural system involving the dorsal aspect of left inferior parietal regions subserves phonological processing of Chinese but not alphabetic words. Brain imaging research has documented well that this region's general function is to temporarily store phonological information in working memory [Ravizza et al., 2004; Smith and Jonides, 1999]. Because the processing of Chinese characters' phonology is not based on rules but instead relies exclusively on a direct "look-up" or mapping procedure in the left dorsal lateral frontal system, this may obligate readers to maintain phonological codes for a short term to accomplish the required tasks. The dorsal inferior parietal system serves this function. Phonological processing of alphabetic words may not require this short-term maintenance in that readers may access phonology by recourse to a moment-to-moment assembling procedure.

The ventral prefrontal system comprising the superior part of left inferior frontal cortex contributes to phonological processing of both Chinese and alphabetic words, although it plays a much greater role in alphabetic languages. This system, along with the supplementary motor cortex (BA6), is relevant to grapheme-to-phoneme conversions [Fiez et al., 1999] and subvocal rehearsal component of phonological processes [Chein et al., 2003; Smith and Jonides, 1999]. Its subvocal rehearsal function is language general, whereas its function in phonemic processing is associated only with alphabetic words. This explains why the ventral prefrontal system is far more important for alphabets than it is for logographs.

Finally, the ventral temporooccipital system typically involved in visual word form identification [Cohen et al., 2000] is related to phonological processes of Chinese and alphabetic languages, although its activity is bilateral for Chinese characters. There are also minor differences in spatial locations across the two kinds of writings; for instance, the left medial fusiform gyrus is more relevant to Chinese whereas the left lateral fusiform cortex is associated more with English. Dietz et al. [2005] found that this system, particularly the left posterior fusiform cortex, was uniquely modulated by varying phonological processing demands. This neural circuit thus may be universally tuned to the phonological properties of words and responsible for the feedback of phonology to orthography, whether at the syllable or phoneme level. Comparisons of words of various difficulty levels may demonstrate the involvement of this region. The role

TABLE II. ALE meta-analysis of phonological processing in visual word recognition

Anatomical region	BA	Coordinates			ALE ($\times 10^{-2}$)	Volume (mm^3)
Chinese characters						
L middle frontal gyrus	9	−46	23	24	1.80	7,664
L middle occipital gyrus	18	−34	−88	−2	1.43	3,008
L medial frontal gyrus	6	−2	18	44	1.49	2,920
L fusiform gyrus	37	−36	−54	−6	1.27	1,264
R inferior occipital gyrus	18	36	−82	−12	0.92	720
R medial frontal gyrus	9	8	28	28	1.06	552
L inferior frontal gyrus	47	−50	30	2	0.93	544
R fusiform gyrus	37	34	−62	−18	0.99	440
Cingulate gyrus	32	−2	36	28	0.80	352
L inferior parietal lobule	40	−36	−42	48	0.81	304
Alphabetic words						
L inferior frontal gyrus	44	−47	14	19	4.12	11,408
L fusiform gyrus	37	−44	−54	−12	2.61	3,272
Cerebellum	—	8	−72	−24	2.46	3,264
L medial frontal gyrus	6	−6	14	50	1.91	2,208
L middle temporal gyrus	21	−46	−35	1	2.25	2,048
L supramarginal gyrus	40	−56	−30	14	1.29	1,800
L inferior parietal lobule	40	−55	−41	24	1.86	1,592
L superior temporal gyrus	42	−56	−30	14	0.81	424
R superior temporal gyrus	22	66	−10	8	1.28	368
L medial frontal gyrus	8	−4	36	36	0.78	216
R middle occipital gyrus	18	27	−84	1	0.76	208
R inferior occipital gyrus	18	30	−78	−2	0.73	104
Chinese > alphabetic						
L inferior occipital gyrus	18	−32	−82	0	1.39	2,264
L middle frontal gyrus	9	−46	18	28	1.46	1,736
L premotor cortex	6	−44	6	16	1.45	712
Cingulate gyrus	32	−2	20	40	0.98	504
R inferior occipital gyrus	18	36	−82	−12	0.90	472
L fusiform gyrus	19	−34	−52	−6	0.98	216
L inferior parietal lobule	40	−36	−42	48	0.82	168
R fusiform gyrus	37	34	−60	−18	0.83	144
L precentral gyrus	6	−46	2	44	0.90	112
Alphabetic > Chinese						
Cerebellum	—	8	−72	−24	2.46	2,936
L fusiform gyrus	37	−44	−56	−12	2.13	2,152
L inferior frontal gyrus	44	−42	4	26	3.58	1,856
L inferior frontal gyrus	44	−54	14	18	1.82	1,528
L middle temporal gyrus	21	−46	−34	0	2.20	1,464
L supramarginal gyrus	40	−40	−44	34	1.28	1,320
L inferior frontal gyrus	46	−46	34	10	1.40	1,280
L inferior parietal lobule	40	−56	−40	24	1.81	1,232
L medial frontal gyrus	6	−6	12	52	1.50	808
R superior temporal gyrus	22	66	−10	8	1.28	320
L superior temporal gyrus	42	−60	−28	14	0.79	176
L inferior frontal gyrus	45	−36	22	14	0.94	136

BA, Brodmann area.

of other mid-inferior occipital regions as indicated in our meta-analysis agrees with this proposal suggesting the dependence of phonological processing on visuospatial analysis of language stimuli.

In summary, our meta-analytic study suggests that although there are overlapping cortical regions such as left temporooccipital circuits mediating phonological processing of both alphabetic and logographic scripts, the surface form of written languages influences neuroanatomical signatures in a significant way. Form, process, and structure are interrelated. Future studies should examine the time course of activations of the four neural systems for Chinese reading. Profiles of high spatiotemporal activation will tell us how these systems link with one another [Liu and Perfetti, 2003].

The Covariant Learning Hypothesis

Crucial for advancing our understanding of these differential brain activities is to answer the question of why the left middle frontal gyrus is so important for syllable-level phonological processing in Chinese whereas the left temporoparietal system is fundamental to phoneme-level phonology in reading English. Previous imaging researchers have assumed that the left temporoparietal circuit plays an important role in grapheme-to-phoneme transformations, because this system is strategically situated between regions for orthographic representations (i.e., fusiform gyrus) and regions for phonological processing of auditory stimuli (i.e., mid-superior temporal gyrus) [Booth et al., 2002a; Simos et al., 2002]. When investigating with the Chinese language as demonstrated here, we found this assumption less tenable. Brain scans with Chinese have indicated that left mid-superior temporal regions mediate Chinese listeners' phonological processing of auditory stimuli [Gandour et al., 2000, 2002, 2003], whereas left fusiform cortex serves orthographic organization of Chinese as shown above and in the study by Bolger et al. [2005]. This raises the question of why Chinese readers do not recruit posterior temporoparietal regions near the neural sites for phonological processing of auditory Chinese stimuli to perform phonology-related tasks in reading.

Here, we offer an account, a covariant learning hypothesis, by focusing on how learning strategies in reading acquisition tune brain systems [Kochunov et al., 2003]. A general assumption in this framework, as many researchers have proposed, is that a neural system is developmentally configured by tracking correlations of stimulus forms and their cognitive and learning processes. Language forms come to shape cognitive and learning strategies, which in turn alter the neural circuits involved in language processing. For children learning to read English and other alphabets, the most popular and effective approach emphasizes children's awareness of the phonological structure of speech, because this awareness helps establish the relationship between graphemes and phonemes and facilitates reading development. There thus exists a very close association between reading and listening across all alphabetic languages [Adams, 1990; Bradley and Bryant, 1983; Goswami, 1993; Perfetti, 1985]. Indeed, children in Western countries spend much time in primary school decoding and decomposing speech sounds. In our view, this learning strategy leads to a biological adaptation, that neural systems for phonological processing in visual (reading) and auditory (listening) modalities are spatially close or even integrated.

Nevertheless, learning to read Chinese is not associated closely with children's sensitivity to the phonological structure of spoken language. Because spoken Chinese is highly homophonic, in learning to read, a Chinese child is confronted with the fact that many written characters correspond to the same syllable. Relying on phonological units to access semantics of a printed character thus would produce an indeterminate meaning. The nature of rampant homophony of written Chinese, together with its visual-orthographic demands, has led to a prevalent strategy for learning to read in primary school that children are required to spend a great amount of time repeatedly copying, by writing down, exposed single characters. A recent cross-sectional behavioral study of Chinese reading acquisition has discovered that the ability to read in logographic Chinese is related strongly to a child's handwriting skills, whereas the contribution of phonological awareness is minor [Tan et al., 2005]. The extensive writing exercise during Chinese reading acquisition serves to shape the cortical center in the posterior portion of left middle frontal gyrus, a region just anterior to the premotor cortex that governs motor functions.

Conclusions

Reading universally makes use of phonology, which implies that some common cognitive processes and neuroanatomical substrates support reading performance across writing systems [Perfetti et al., 2005]. Reading is also a skill that is not innate; it is acquired with effort and with different instructional approaches for different writing systems [Eden and Moats, 2002]. As a consequence, the critical mechanisms that the brain will draw upon to accomplish reading tasks are likely to differ depending on the demands of a particular writing system. Results from the present study have generated evidence indicating that neural circuits for phonological processing in reading are different across languages. Language form, cognitive process, and learning strategy seem to drive the development of functional neuroanatomy.

ACKNOWLEDGMENTS

This study was supported by the Hong Kong Government Research Grants Council (HKU 7133/01H to L.H.T.) and by the National Library of Medicine (RO1-LM6858 to P.T.F.).

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