Different Patterns and Development Characteristics of Processing Written Logographic Characters and Alphabetic Words: An ALE Meta-Analysis

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Abstract: The neural systems for phonological processing of written language have been well identified now, while models based on these neural systems are different for different language systems or age groups. Although each of such models is mostly concordant across different experiments, the results are sensitive to the experiment design and intersubject variability. Activation likelihood estimation (ALE) meta-analysis can quantitatively synthesize the data from multiple studies and minimize the interstudy or intersubject differences. In this study, we performed two ALE meta-analysis experiments: one was to examine the neural activation patterns of the phonological processing of two different types of written languages and the other was to examine the development characteristics of such neural activation patterns based on both alphabetic language and logographic language data. The results of our first meta-analysis experiment were consistent with the meta-analysis which was based on the studies published before 2005. And there were new findings in our second meta-analysis experiment, where both adults and children groups showed great activation in the left frontal lobe, the left superior/middle temporal gyrus, and the bilateral middle/superior occipital gyrus. However, the activation of the left middle/inferior frontal gyrus was found increase with the development, and the activation was found decrease in the following areas: the right claustrum and inferior frontal gyrus, the left inferior/medial frontal gyrus, the left middle/superior temporal gyrus, the right cerebellum, and the bilateral fusiform gyrus. It seems that adults involve more phonological areas, whereas children involve more orthographic areas and semantic areas. *Hum Brain Mapp 35:2607–2618, 2014.* © 2013 Wiley Periodicals, Inc.

Key words: fMRI; activation likelihood estimation; meta-analysis; language; phonology; Chinese; Alphabetic; development; children; adults

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INTRODUCTION

The neural systems of phonological processing have been investigated using neuroimaging methods in various studies for several decades (Petersen et al., 1988), and the results are in general agreement pertaining to the major regions of the brain. These regions lead to different models for different language systems or age groups. Although the activated cortical areas are mostly consistent among different experiments, the results are sensitive to the experiment design and intersubject variability. Activation likelihood estimation (ALE) meta-analysis can quantitatively synthesize data from functional neuroimaging studies and minimize the interstudy or intersubject differences (Turkeltaub et al., 2002). In a previous meta-analysis study, Tan et al. (2005) analyzed 13 literatures of either alphabetic language or Chinese language work, which were published before 2005. In this study, we performed meta-analysis on neural activation patterns of phonological processing using each of two different language systems from papers published after 2005 and made a comparison to the previous analysis (Tan et al., 2005). In addition, we also performed an analysis by applying the same stimuli on different age groups, i.e., children and adults, to investigate the development characteristics of phonological processing in the human brain where the development characteristics were independent.

Alphabetic language (e.g., English and French) and logographic language (e.g., Chinese, Japanese, and Korean) are two different types of written languages, especially in morphologies and mappings among orthography, phonology, and semantics. Most alphabetic languages have a serial left to right structure of letter strings and use grapheme (letters) mapping onto the phonemes (Perfetti et al., 2005). On the other hand, in the writing system of logographic languages, characters are the basic writing units and encode no clear phonological information at the subsyllabic level though most characters have a phonetic radical that can give hints about the pronunciation. Compared to alphabetic languages, logographic languages have less systematic information on phonology (Booth et al., 2006). Two earlier meta-analyses of fMRI studies on phonological processing showed both similarities and differences between the two types of languages (Bolger et al., 2005; Tan et al., 2005). The analysis of Tan (Tan et al., 2005) showed that both languages activated the left fusiform gyrus and the left inferior frontal gyrus. Furthermore, the study of Bolger (Bolger et al., 2005) suggested that both English and Chinese activated the left middle frontal gyrus, the left inferior frontal gyrus, the mid/anterior portion of the left posterior superior temporal gyrus, and the left occipito-temporal region. The two meta-analyses also reported some cross-language differences that Chinese activated more significantly in the left middle frontal gyrus, and English activated more significantly in the left temporo-parietal and supramarginal area.

No matter which language system is used, children normally receive training of reading during their early education. Therefore, we would explore the processing model of children and how such model changes with the development into adults to investigate the nature of the brain's organization for processing languages. Some earlier literatures on development studies of brain phonological processing have reported that both children and adults have activation during the rhyming task in the left middle/inferior frontal gyri, the medial frontal gyrus, the left fusiform gyrus, and the bilateral middle occipital gyri (Bitan et al., 2009; Cao et al., 2009; Chee et al., 1999; Chen et al., 2002; Hoeft et al., 2006; Kuo et al., 2004; Shaywitz et al., 2007; Tan et al., 2001; Tan et al., 2003; Temple et al., 2001). It has been shown later that adults activated more greatly in the right middle occipital gyrus on the rhyming task (Cao et al., 2009; Cao et al., 2010), which implies the increased involvement over age of visuo-orthographic analysis. A more recent study has reported that there are developmental decreases in the activation of the left middle occipital gyrus in the rhyming task, suggesting that the development of reading is marked by the reduced involvement of orthographic representations (Cao et al., 2011). In addition, there appears to be a developmental difference in the phonological processing of the written languages, but due to the differences of the experiments or the intersubject variability, the left inferior occipital gyrus and the left superior temporal gyrus were found to decrease in different studies (Cao et al., 2010; Cao et al., 2011). To statistically integrate the results of these literatures from both alphabetic and logographic language systems, we performed ALE meta-analysis across two age groups. The goal of this experiment was to determine the changes of neural activation patterns of phonological processing of written languages during the development.

In this study, we conducted two experiments: one to verify the different phonological processing models of different types of written languages which were compared with a previous work (Tan et al., 2005), and the other to analyze the development patterns of the phonological processing during the reading of both language systems.

MATERIALS AND METHODS

Literature Selection

Candidate literatures were identified using an online citation indexing service (web of science, SCI) offered by Thomson Reuters with the following Boolean operation: ("brain mapping" OR "fMRI" OR "functional magnetic resonance imaging") AND (language OR "word recognition" OR "Chinese reading" OR Chinese OR English OR "Alphabetic words" OR Alphabet) AND ("phonological processing" OR phonological OR phonetic OR phonology) AND ("2005": "2011/12/31"), which was conducted on the topics of the literatures. This step yielded 661 papers. After the languages were changed from Chinese and alphabetic to Japanese and Korean, 68 results were found. The following inclusion and exclusion criteria were used to finalize the articles.

The inclusion criteria:

1. fMRI as the imaging modality;
2. Normal and healthy subjects;
3. Phonological judgment task involvement in the experiments;
4. Visual presentation method;
5. The image data acquisition over the whole brain.

The exclusion criteria:

1. Case study;
2. Analysis with prespecified anatomically limited ROIs;
3. Inexplicit coordinate space that the images were normalized to.

Only the papers associated with positive performances of the participants were kept, because we believed those positive responses could be more pertinent to the neural correlates under study. The experiments were excluded if the established ROIs were anatomically prespecified, but functionally selected ROIs were considered as acceptable.

According to these criteria, the titles and the abstracts from these studies were first evaluated, and the unidentifiable ones were left for the full-text examination. After this step, only 150 papers were kept. The full-text articles especially the experiment designs were evaluated based on the criteria listed above. Finally, we obtained 15 papers with 19 experiments for alphabetic languages and nine papers with 13 experiments for logographic languages (Table I).

For the cross-language difference analysis, we chose the experiments from the selected papers where the participants were adults. Eleven experiments for the logographic language group and eight experiments for the alphabetic language group were finalized, respectively (Table I). We analyzed these results to identify the cross-language differences in phonological processing in the brain and compared them with the previous studies (Tan et al., 2005).

For the second experiment, we classified the papers into two age groups regardless of the language types: there were 14 experiments for the children group (three on logographic languages and 11 on alphabetic languages), and 19 experiments for the adults group (11 on logographic languages and eight on alphabetic languages). The experiments published before 2005 were included by combining the adults group experiments mentioned above with the previous meta-analysis in the published studies on adults (seven for Chinese and 12 for alphabetic words) (Tan et al., 2005). Yet, two cases were exclude due to the ROI analysis (Gold and Buckner, 2002) and the missing of standard coordinate space referred to explicitly (Petersen et al., 1988). To cover the earlier publications for the children group, we conducted the Boolean operation mentioned above, adding "child" and changing the publication date to the year before 2005. After filtering with inclusion and exclusion criteria, only three experiments on alphabetic languages were left for the analysis. In summary, 17 experiments were identified for the children group (three logographic and 14 alphabetic) and 38 experiments were identified for the adults group (18 logographic and 20 alphabetic). To balance the experiment amount between the language types, we randomly chose four out of 18 experiments on the logographic languages for the adults group, resulting in 24 final experiments (20 alphabetic and four logographic) in this group(Table I).

To view the meta-analysis results, we used the desktop version of Mango (Multi-Image Analysis GUI, http://ric.uthscsa.edu/mango/).

Activation Likelihood Estimation

For each study, we analyzed all the reported experiments meeting the inclusion criteria. The MNI coordinates were converted into Talairach space using the icbm2tal transform (Lancaster et al., 2007) implemented in the GingerALE software package (Eickhoff et al., 2011; Eickhoff et al., 2009). ALE maps were generated using the activation likelihood estimate (ALE) method (Turkeltaub et al., 2002), which was implemented in the GingerALE software package, with the subject-based FWHW values (Eickhoff et al., 2009; Eickhoff et al., 2011), 10 mm additional FWHM, 0.05 FDR threshold and 100 mm^3 minimum volume size. The ALE method treats each reported coordinate as the center of a Gaussian probability distribution and uses a permutation test of randomly distributed foci to determine the statistical significance. ALE maps were created for logographic characters and alphabetic words, respectively. The same method was used for both the adults and children groups. For the contrary analysis, all parameters were the same as above except that the threshold was set to uncorrected P value of 0.001.

RESULTS

Cross-Language Analysis

Table II and Figure 1 illustrate the results of our ALE meta-analysis of the studies published in the chosen literatures corresponding to our first experiment design for cross-language investigation, which are consistent with the results reported in the articles. Specifically, the activation regions for phonological processing of logographic characters were from left precentral gyrus (BA6), left middle frontal gyrus (BA46,9), right middle occipital gyrus, left insula (BA13), left fusiform gyrus (BA37), left inferior frontal gyrus (BA44), and left sublobar extranuclear (BA47) in our analysis. As for the experiments on alphabetic words, the ALE analysis resulted in eight clusters of significant ALE values: left inferior frontal gyrus (BA46), left middle temporal gyrus (BA21), left angular gyrus (BA39),

TABLE I. Summary of literature selected for meta-analysis

Literature	*N*	Task	Baseline	Language Cateragy
Cross language analysis				
Alphabetic words				
Aparicio et al., 2007	12	Rhyming judgment	Identical strings judgment	English
Bitan et al., 2005	14	Rhyming judgment	Line pattern matching	English
Booth et al., 2007	14	Rhyming judgment	Line judgment	English
Burton et al., 2005	12	Rhyming judgment	Symbol font discrimination	English
Cousin et al., 2007	11	Rhyme detection	Visual detection	French
Gitelman et al., 2005	14	Homophone judgment	String matching task	English
Tham et al., 2005	6	Homophone matching	Fixation	English
Logographic characters				
Booth et al., 2006	13	Rhyming judgment	Line pattern judgment	Chinese
Cao et al., 2009	13	Rhyming judgment	Line pattern judgment	Chinese
Cao et al., 2010	20	Rhyme judgment	Spelling	Chinese
Dong et al., 2005	12	phonological matching	Fixation	Chinese
Liu et al., 2006	12	Phonological decision	Orthographic decision	Chinese
Liu et al., 2009	16	Rhyme judgment	Line matching	Chinese
Matsuo et al., 2010	33	Homophone judgment	Null	Japanese(Kanji)
Tham et al., 2005	6	Homophone matching	Fixation	Chinese
Development analysis				
Adult				
Aparicio et al., 2007	12	Rhyming judgment	Identical strings judgement	English
Bitan et al., 2005	14	Rhyming judgment	Line pattern matching	English
Booth et al., 2002a	13	Rhymejudgment	Line pattern matching	English
Booth et al., 2002b	13	Rhymejudgment	Spelling	English
Booth et al., 2004	16	Rhymejudgment	Letter case decision	English
Booth et al., 2007	14	Rhyming judgment	Line judgment	English
Burton et al., 2005	12	Rhyming judgment	Symbolfontdiscrimination	English
Cousin et al., 2007	11	Rhyme detection	Visual detection	French
Gitelman et al., 2005	14	Homophonejudgment	String matching task	English
Poldrack et al., 2001	8	Rhymejudgment	Letter case decision	English
Price et al., 1997	6	Syllable decision	Semantic judgment	English
Sergent et al., 1992	8	Lettersound decision	Letter spatial decision	English
Tan et al., 2003	12	Rhymejudgment	Font size decision	English
Tham et al., 2005	6	Homophone matching	Fixation	English
Xu et al., 2001	12	Homophone matching	Fixation	English
Xu et al., 2002	18	Rhymejudgment	Letter feature search	English
Booth et al., 2006	13	Rhyming judgment	Line pattern judgment	Chinese
Cao et al., 2009	13	Rhyming judgment	Line pattern judgment	Chinese
Liu et al., 2006	12	Phonological decision	Orthographic decision	Chinese
Tham et al., 2005	6	Homophone matching	Fixation	Chinese
Child				
Bitan et al., 2006	15	Rhyming judgment	Line pattern	English
Bitanet al., 2007a	38	Rhyming judgment	Symbols /spelling judgment	English
Bitan et al., 2007b	36	Rhyming judgment	Fixation	English
Bitan et al., 2009	36	Rhyming judgment	Fixation	English
Booth et al., 2004	16	Rhyme judgment	Letter case decision	English
Cao et al., 2006	14	Rhyming judgment	Fixation	English
Cao et al., 2008	12	Rhyming judgment	Fixation	English
Georgiewa et al., 1999	17	Phonological transformation	Letter identification	German
Hoeft et al., 2006	10	Rhyming judgment	Fixation	English
McNorgan et al., 2011	26	Rhyming judgment	Fixation	English
Temple et al., 2001	15	Rhyming judgment	line matching	English
Cao et al., 2009	8	Rhyming judgment	Line pattern judgment	Chinese
Siok et al., 2008	12	Rhyme judgment	Font-size decision	Chinese
Xue et al., 2005	12	Rhyming judgment	Fixation	Chinese

N: number of subject.

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

Anatomical region	Brodmann area	x	y	z	ALE (10^{-2})	Volume (mm^3)
Alphabetic words						
L Middle Frontal Gyrus	46	−44	24	20	1.46	1752
L Middle Temporal Gyrus	21	−62	−34	−2	1.45	712
L Angular Gyrus	39	−44	−70	30	0.97	704
L Middle Temporal Gyrus	39	−46	−70	26	0.91	
L Cerebellum		−42	−56	−20	1.46	648
L Medial Frontal Gyrus	8	−14	30	44	1.21	520
L Superior Frontal Gyrus	10	−10	58	22	1.07	472
R Superior Frontal Gyrus	8	8	30	50	0.89	384
L Lentiform Nucleus	–	−28	−16	−4	0.80	248
L Hippocampus		−24	−16	−10	0.73	
Logographic characters						
L Precentral Gyrus	6	−46	4	34	3.35	4768
L Middle Frontal Gyrus	46	−42	26	20	2.08	
L Middle Frontal Gyrus	9	−40	18	26	1.99	
L Middle Frontal Gyrus	9	−44	16	32	1.80	
R Middle Occipital Gyrus	-	26	−86	0	1.62	1344
L Insula	13	−30	18	10	1.96	968
L Fusiform Gyrus	37	−40	−54	−18	1.30	752
L Inferior Frontal Gyrus	44	−50	6	18	1.58	728
Adult						
L Middle Frontal Gyrus	46	−44	24	16	2.59	10728
L Middle Frontal Gyrus	46	−50	24	26	2.57	
L Inferior Frontal Gyrus	44	−50	10	22	2.55	
L Precentral Gyrus	6	−42	0	30	2.41	
L Precentral Gyrus	6	−48	0	42	1.49	
L Precentral Gyrus	6	−42	−10	48	1.14	
L Superior Temporal Gyrus	22	−52	12	0	1.01	
L Cerebellum Declive		−42	−56	−20	3.65	2784
L Superior Frontal Gyrus	6	−2	14	50	1.50	1568
L Superior Frontal Gyrus	6	−2	4	56	1.21	
R Cerebellum Uvula	-	8	−68	−30	2.60	1496
L Medial Frontal Gyrus	8	−12	28	44	1.40	1400
R Superior Frontal Gyrus	8	4	28	48	0.98	
R Middle Occipital Gyrus	18	20	−86	−8	1.46	1160
L Inferior Parietal Lobule	40	−54	−44	22	2.20	1112
L Middle Temporal Gyrus	21	−62	−34	−2	1.74	784
L Angular Gyrus	39	−26	−54	32	1.40	680
L Middle Temporal Gyrus	22	−46	−40	2	1.30	648
R Inferior Frontal Gyrus	47	36	24	−2	1.18	504
L Extra-Nuclear	47	−36	24	−4	1.29	328
L Middle Occipital Gyrus	18	−22	−84	−10	1.05	312
L Angular Gyrus	39	−44	−70	30	0.98	232
L Middle Temporal Gyrus	39	−46	−70	26	0.92	
L Superior Frontal Gyrus	10	−10	58	22	1.08	224
Child						
L Inferior Frontal Gyrus	46	−46	26	14	4.34	2864
L Fusiform Gyrus	37	−40	−50	−16	2.56	2456
L Cerebellum Declive	-	−42	−64	−14	1.83	
L Medial Frontal Gyrus	6	−6	4	56	2.63	2384
L Precentral Gyrus	6	−44	2	34	1.87	2296
L Inferior Frontal Gyrus	9	−46	10	28	1.51	
R Insula	13	34	22	4	2.39	2104
L Superior Temporal Gyrus	22	−56	−42	10	2.2	1824
R Fusiform Gyrus	19	26	−84	−12	1.31	952
L Inferior Occipital Gyrus	19	−34	−76	−6	1.38	456

TABLE II. (continued).

Anatomical region	Brodmann area	*x*	*y*	*z*	ALE (10^{-2})	Volume (mm^3)
R Cerebellum Culmen		32	−50	−14	1.57	432
Adult-Child						
L Middle Frontal Gyrus	9	−48	28	30	2.76	1200
L Inferior Frontal Gyrus	9	−54	18	22	2.21	
L Inferior Frontal Gyrus	45	−56	14	20	2.16	
R Cerebellum Pyramis	-	12	−70	−24	2.15	744
R Cerebellum Pyramis	-	13	−73	−30	2	
R Cerebellum Uvula	-	10.42	−65.5	−31.33	1.91	
L Superior Frontal Gyrus	8	−12	30	48	1.98	576
L Medial Frontal Gyrus	8	−14	30	40	1.69	
L Cerebellum Tuber	-	−45	−60	−24	1.97	408
L Cerebellum Tuber	-	−38	−60	−24	1.9	
Child-Adult						
R Claustrum		29	20	10	3.01	1288
R Inferior Frontal Gyrus	45	32	28	8	2.75	
L Inferior Frontal Gyrus	13	−44	26	4	2.51	1192
L Inferior Frontal Gyrus	46	−51	26	10	2.3	
L Medial Frontal Gyrus	6	−12	6	52	3.04	1144
L Middle Temporal Gyrus	22	−52	−36	8	2.77	976
L Superior Temporal Gyrus	22	−56	−42	8	2.65	
R Cerebellum Culmen	-	30.8	−48	−11.6	2.18	432
R Fusiform Gyrus	37	36	−49	−12	2.1	
L Fusiform Gyrus	37	−38	−46	−12	2.03	280
L Inferior Frontal Gyrus	9	−44	12	30	2.3	240

L: left, R: right

cerebellum, left medial frontal gyrus (BA8), bilateral superior frontal gyrus (BA10, BA8), and left lentiform nucleus.

Development Analysis

First, we performed the ALE analysis of the selected experiments on phonological processing of the printed words for the adults and children groups, respectively, and then compared the two groups. Table II and Figure 2 illustrate the regions of the two groups and their subtractions. The activation for the adults group was of extremely high concordance in the left frontal lobe (BA46, BA44, BA6, and BA47), left superior temporal gyrus (BA22), bilateral cerebellum, left medial frontal gyrus and superior frontal gyrus (BA8), right middle occipital gyrus (BA18), left inferior parietal lobule (BA40), left middle temporal gyrus (BA21, BA22), and left angular gyrus. The ALE analysis of the adults group demonstrated the highest convergence in the left dorsal frontal gyrus (BA46) with a cluster size of 10728 mm^3 and ALE value 0.026.

The ALE apparent activation of the children group indicated high convergence in the left inferior frontal gyrus (BA46), fusiform gyrus (BA37) and cerebellum, left medial frontal gyrus (BA6), left precentral gyrus (BA6) and left inferior frontal gyrus (BA9), right insula (BA13), left superior temporal gyrus (BA22), right fusiform gyrus (BA19), left inferior occipital gyrus (BA19), and right cerebellum. The highest convergence was obtained in the inferior frontal gyrus, with a cluster size of 2864 mm^3 and ALE value 0.043.

Both the adults and children groups showed great activation in the left inferior frontal gyrus (BA46, BA44, BA47), left precentral gyrus (BA6), left medial frontal gyrus (BA6, BA8), left superior/middle temporal gyrus (BA22), and bilateral middle/superior occipital gyrus (BA18, BA19).

The contrast between the adults and children groups showed significant differences between their relative ALE maps (Fig. 2). The left middle/inferior frontal gyrus (BA9, BA45) was more consistently activated in the phonological processing of the adults group. Other areas included the bilateral cerebellum and left superior frontal gyrus (BA8). Brain regions that were more concordantly implicated by the children group included right claustrum and inferior frontal gyrus (BA45). In addition, another four clusters were involved in the left inferior frontal (BA13, BA46), left medial frontal gyrus (BA6), left middle/superior temporal gyrus (BA22), right cerebellum, bilateral fusiform gyrus (BA37), and left inferior frontal gyrus (BA9).

DISCUSSION

Cross-Language Analysis

For both language systems, the activation was concordantly shown in left frontal gyrus and left temporal gyrus.

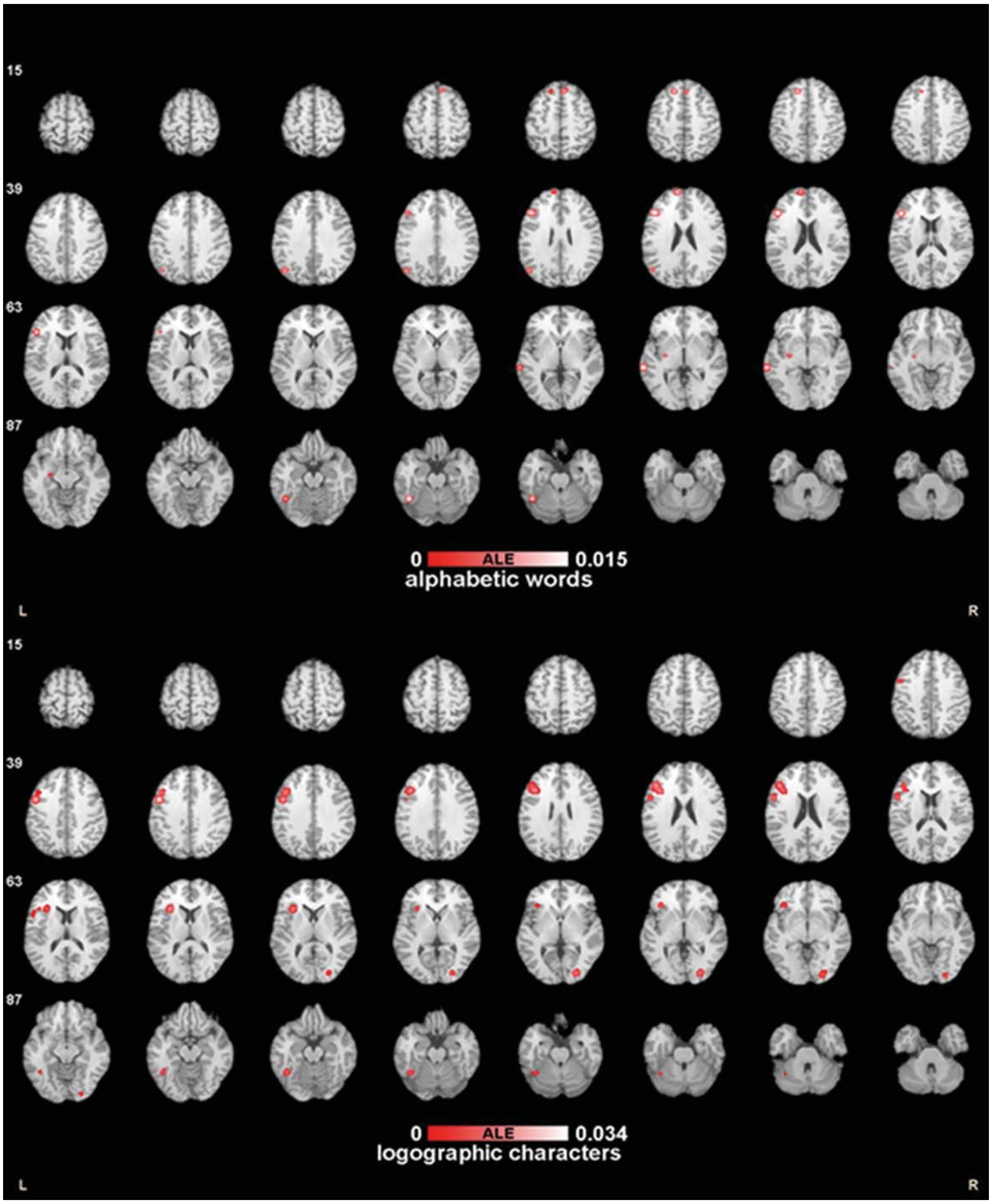

Figure 1.
The ALE maps of the different language systems.

For alphabetic languages, the clusters were consistently in middle frontal gyrus and temporal gyrus, and for logographic language system, the clusters were most consistently in left precentral/middle frontal gyrus (BA6/46/9). These patterns were consistent with the result of the previous work (Tan et al., 2005), which demonstrated that the results of the studies after 2005 (see Table I) were in general the same as previous ones (Booth et al., 2002a; Booth et al., 2004; Booth et al., 2002b; Georgiewa et al., 1999; Gold and Buckner, 2002; Petersen et al., 1988; Poldrack

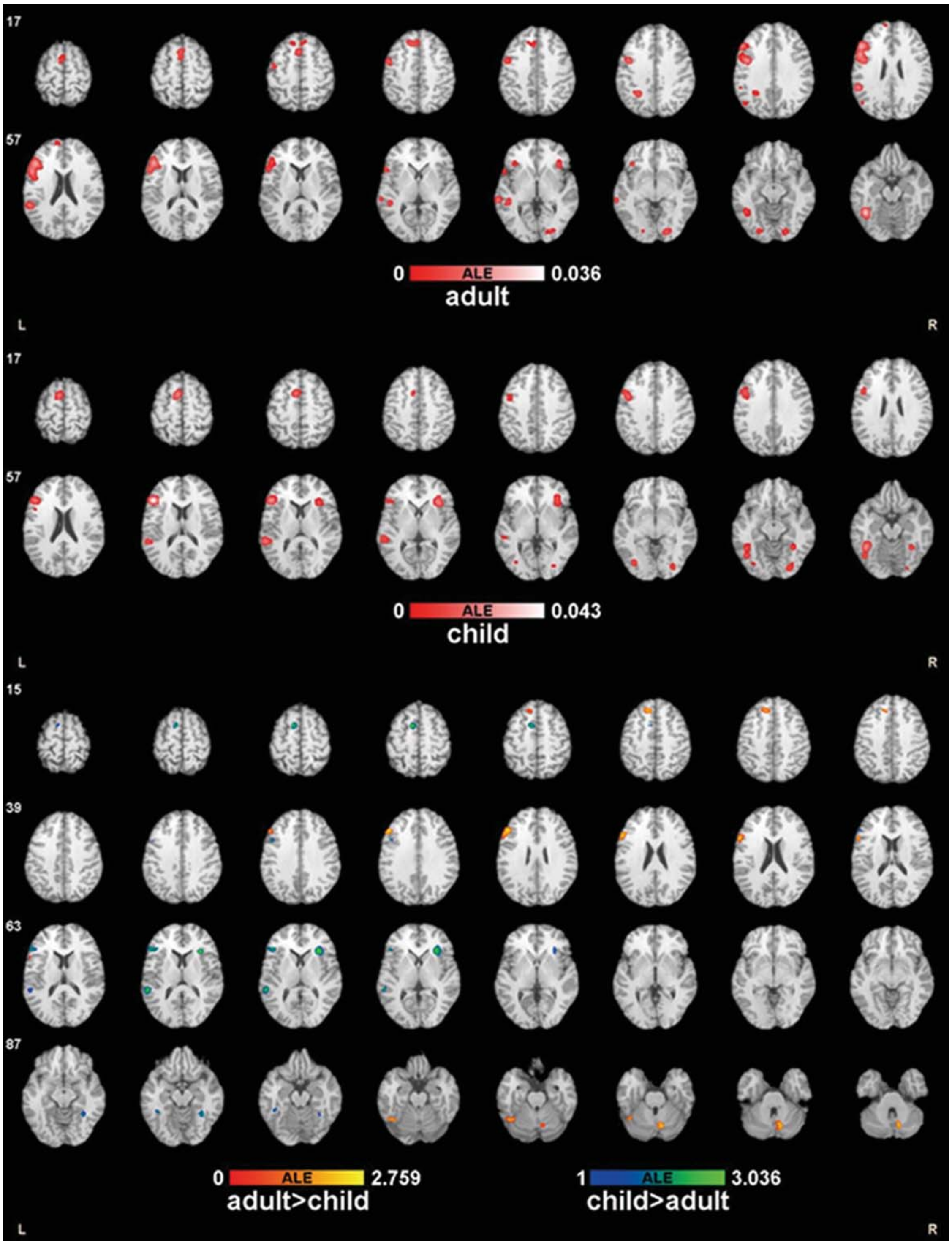

Figure 2.
ALE maps across ages of phonological processing of written word.

et al., 2001; Price et al., 1997; Sergent et al., 1992; Siok et al., 2003; Tan et al., 2001; Tan et al., 2003; Temple et al., 2001; Xu et al., 2001; Xu et al., 2002).

Development Analysis

Both children and adults showed activation in the left inferior frontal gyrus, left precentral gyrus, left medial frontal gyrus, left superior/middle temporal gyrus, and bilateral middle/superior occipital gyrus. This activated pattern was consistent with the previous results (Chee et al., 1999; Hoeft et al., 2006; Shaywitz et al., 2007; Tan et al., 2005).

In a previous work (Cao et al., 2010), the left inferior frontal gyrus showed increased activation with development. However, the result of our ALE meta-analysis demonstrated that there was not only a simple increase of activation in the activated areas during the development but also a shift of activation areas to the dorsolateral prefrontal cortex, from BA13/46 to BA 9/8/45. In the earlier studies, the left inferior frontal gyrus (pars operculars) was suggested as part of the phonological routes to subserve the phonological decoding of words (Cao et al., 2008), and the left inferior frontal gyrus (pars triangularis) was reported as part of the lexico-semantic routes for the semantic retrieval of words (Bokde et al., 2001). Hence, the inferior frontal gyrus was associated with the search and retrieval of information about meanings, and syntactic and phonological patterning. It makes sense that the activation of this area is increased with age and reading proficiency.

Another region showing increased activation in our analysis was bilateral cerebellum. The cerebellum is an important region for language process. In 2001, Marien et al. (2001) proposed the concept of a "lateralized linguistic cerebellum". And in the same year, Middleton and Strick (2001) demonstrated that the cerebellum is anatomically projected to the prefrontal cortex of the primate and influences several areas of prefrontal cortex via the thalamus. Further studies also demonstrated that the cerebellum is associated with semantic discrimination (Xiang et al., 2003) and phonemic process (Leggio et al., 2000). In our meta-analysis, developmentally increased activation was showed in the cerebellum, which may be involved in the development of processing ability of the frontal gyrus.

Moreover, developmental decrease of neural activation were found in the following regions : right claustrum/inferior frontal gyrus (BA45), left middle/superior temporal gyrus (BA22), bilateral fusiform gyrus (BA37). A recent published study reported that the right superior frontal gyrus was involved in processing orthography and visuospatial attributes of Chinese characters for literate and illiterate subjects, respectively (Wu et al., 2012). We hypothesized that although the experiment design on phonological processing was intended to avoid orthography processing, during the experiments children still tended to process the visuospatial attributes automatically, whereas adults did not process the orthography. Therefore, the developmental decrease of activation in the right inferior frontal gyrus was of significance. As for the left middle/superior temporal gyrus, the development characteristics are ambiguous. According to many studies, the activation of these regions was increased during an early age (before school age) and was stable across infancy (Bitan et al., 2007a; Hoeft et al., 2006; Petitto et al., 2012; Shaywitz et al., 2007; Turkeltaub et al., 2003). This enhanced the previous evidence that posterior language areas mature earlier than the anterior parts (Balsamo et al., 2002; Simos et al., 2001). However, our study found the activation of left middle/superior temporal gyrus decreased developmentally, which is consistent with previous studies (Bitan et al., 2007a; Cao et al., 2010). Temporo-occipital regions (including fusiform gyrus) segment the linguistic stream into elementary phonetic-syllabic units and their underlying phonemic categories (Petitto et al., 2012). The activation of these regions was decreased with the development in the phonological processing, suggesting the reduced reliance on phonological information with age and reading skills (Cao et al., 2011). The neural activation of the left middle/superior temporal gyrus (BA22) may increase during early ages and then decrease until mature. In a recent study, Cao et al. (2010) has presented this development attribute. The increase during early age may result from the lack of top-down control and the decrease indicates developmental increase in top-down control.

In addition, we noted that the phonological processing during reading showed different patterns between the adults and children groups. Adults engaged more to phonological areas (dorsal inferior frontal gyrus), whereas children engaged more to orthographic areas (fusiform gyrus) and semantic areas (ventral inferior frontal gyrus and middle temporal gyrus). In a previous study, Cao et al. (2009) compared the activation areas between children and adults during rhyming task and reported a greater specialization of phonological processing in adults. In another study, Bitan et al. (2007a) found that children involve more of phonological and semantic processing in the rhyming task. The developmental decreases in the activation of the left fusiform gyrus in the rhyming task were observed, which suggests that the development of reading is marked by reduced involvement of orthography (Cao et al., 2011). These experimental results demonstrated that during rhyming task children engage more orthographic and semantic areas to mapping orthography to phonology and to help identify the phonology; however, adults engage more phonological areas, due to their skilled reading abilities.

Limitations of this Study

It should be noted that this work only focuses on the phonological processing patterns of different language systems for adults and development characteristics based on alphabetic and logographic languages. Limited by the insufficient literatures, the analysis of cross-cultural impact on adults and development characteristics was not conducted. As mentioned in the previous work, the left dorsal lateral frontal system is responsible for the logographic language, and the posterior sites of temporoparietal regions are essential for the alphabetic language (Tan et al., 2005). Given the cross-language differentiations for the adults, there could be cross-language differences on the development characteristics too. It has been found that the left inferior frontal gyrus increases and left superior temporal gyrus decreases with age in both English and Chinese phonological processing patterns (Bitan et al., 2007b; Cao et al., 2010). However, we notice that the left posterior parietal cortex increases with age in English language system (Bitan et al., 2007b), which could be caused by the developmental difference of the cultures.

CONCLUSIONS

In this study, we performed two ALE meta-analysis experiments: the first one examined the neural activation patterns of two language systems for phonological processing of written languages, and the second one examined the development characteristics based on both alphabetic language and logographic language. By conducting the first experiment, we found that logographic languages significantly activated the left middle-superior frontal lobe, the right middle occipital gyrus, and the left fusiform gyrus, whereas the alphabetic languages led to significant activations in the left inferior/medial frontal gyrus, left middle temporal gyrus, left angular gyrus, cerebellum, bilateral superior frontal gyrus, and left lentiform nucleus. The second experiment on the development analysis has suggested that both adults and children showed noticeable activations in the left frontal lobe, left superior/middle temporal gyrus, and bilateral middle/superior occipital gyrus. The neural activation of the left middle/inferior frontal gyrus was found to increase with the development. Moreover, we found that the activation decreased in the following regions: right claustrum and inferior frontal gyrus, left inferior/medial frontal gyrus, left middle/superior temporal gyrus, right cerebellum, bilateral fusiform gyrus, and left inferior frontal gyrus. It seems that adults engage more to phonological areas (dorsal inferior frontal gyrus), whereas children engage more to orthographic areas (fusiform gyrus) and semantic areas (ventral inferior frontal gyrus and middle temporal gyrus).

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