Cognitive Processing in Chinese Literate and Illiterate Subjects: An fMRI Study

Geng Li,^{1,2*} Raymond T.F. Cheung,² Jia Hong Gao,³ Tatia M.C. Lee,⁴ Li Hai Tan,⁵ Peter T. Fox,³ Clifford R. Jack Jr.,⁶ and Edward S. Yang¹

¹The Jockey Club MRI Center, Faculty of Medicine, The University of Hong Kong, Hong Kong

²Division of Neurology, Department of Medicine, The University of Hong Kong, Queen Mary Hospital, Hong Kong

³Research Imaging Center, University of Texas Health Science Center at San Antonio, San Antonio, Texas

⁴Neuropsychology Laboratory and Institute of Clinical Neuropsychology, MacLehose Medical Rehabilitation Center, The University of Hong Kong, Hong Kong

⁵Department of Linguistics, The University of Hong Kong, Hong Kong

⁶Department of Diagnostic Radiology, Mayo Clinic and Foundation, Rochester, Minnesota

Abstract: Functional magnetic resonance imaging (fMRI) and positron emission tomography (PET) were used to map brain activation during language tasks. While previous studies have compared performance between alphabetic literate and illiterate subjects, there have been no such data in Chinese-speaking individuals. In this study, we used fMRI to examine the effects of education on neural activation associated with silent word recognition and silent picture-naming tasks in 24 healthy right-handed Chinese subjects (12 illiterates and 12 literates). There were 30 single Chinese characters in the silent word recognition task and 30 meaningful road-signs in the silent picture-naming task. When we compared literate and illiterate subjects, we observed education-related differences in activation patterns in the left inferior/middle frontal gyrus and both sides of the superior temporal gyrus for the silent word recognition task and in the bilateral inferior/middle frontal gyrus and left limbic cingulate gyrus for the silent picture-naming task. These results indicate that the patterns of neural activation associated with language tasks are strongly influenced by education. Education appears to have enhanced cognitive processing efficiency in language tasks. *Hum Brain Mapp* 27:144–152, 2006. © 2005 Wiley-Liss, Inc.

Key words: silent word recognition task; silent picture-naming task; education; neural activation

INTRODUCTION

Using functional magnetic resonance imaging (fMRI) or positron emission tomography (PET), much knowledge has been gained in understanding how the brain is activated during controlled experiments of language tasks in educated healthy subjects [Gabrieli et al., 1998; Petersen et al., 1988; Petersson et al., 1999, 2000, 2001] and in uneducated healthy subjects [Castro-Caldas et al., 1998, 1999, 2004; Reis and Castro-Caldas 1997]. Verbal information preferentially activates the left inferior frontal cortex (IFC), the left medial temporal lobe (MTL), and the left temporal occipital area [Booth et al., 2002; Jobard et al., 2003]. The task generated

Contract grant sponsor: Hong Kong Jockey Club Charities Trust.

*Correspondence to: Dr. Geng Li, The Jockey Club MRI Centre, Faculty of Medicine, The University of Hong Kong, Room 204, Chow Yei Ching Bldg., Pokfulam Road, Hong Kong.
E-mail: ligeng@eee.hku.hk

Received for publication 28 August 2004; Accepted 2 May 2005

DOI: 10.1002/hbm.20173

Published online 2 August 2005 in Wiley InterScience (www.interscience.wiley.com).

greater activation in the fusiform gyrus for written words, in the superior temporal gyrus for spoken words, in the superior temporal gyrus for visual rhyming, and in the fusiform gyrus for auditory spelling [Booth et al., 2002]. On the other hand, picture information (e.g., scene and object) preferentially activates the right IFC and bilaterally the MTL [Kelley et al., 1998; Milner 1971, 1972, 1982; Wagner et al., 1998a,b] in educated healthy subjects. Word recognition predominately activates the left MTL [Cohen et al., 2004; Fiez and Petersen, 1998; Jobard et al., 2003; Priece et al., 2003], scene and object recognition activates the MTL bilaterally, and unfamiliar face recognition predominately activates the right MTL [Brewer et al., 1998; Gabrieli et al., 1997; Kelley et al., 1998; Martin et al., 1997; Stern et al., 1996; Wagner et al., 1998b]. Learning an alphabetic written language modulates the auditory-verbal language system in an important way; meanwhile, the functional architecture of the brain is adjusted by literacy [Petersson et al., 2000, 2001].

Previous neuroimaging studies have implicated different patterns of brain activation between native speakers of Mandarin Chinese (pictographic symbols) and those of English (alphabetic words) [Kuo et al., 2001; Tan et al., 2000, 2001a,b, 2003]. Activation of the left middle frontal cortex (Brodmann's area (BA) 9) by a variety of linguistic tasks is pronounced in the former but absent or weak in the latter [Kuo et al., 2001; Tan et al., 2000, 2001a,b, 2003]. Localized differences in the brain morphology between Chinese-speaking Asians and English-speaking Caucasians have been reported recently [Kochunov et al., 2003].

It has been postulated that organization of language systems is different between native Chinese speakers and native English speakers. The written Chinese language is composed of pictographic symbols, while written English words are composed of an alphabet [Tan and Perfetti, 1998; Weber-Fox and Neville, 1996]. Chinese characters possess a number of strokes that are packed into a square shape; they map onto morphemes with their meaning suggested by visual configurations [Rayner and Pollatsek, 1989]. Brain activation during reading aloud of Chinese characters is bihemispheric [Tan et al., 2001]. However, silent reading of Chinese is dominated by the activity of the left hemisphere [Tan et al., 2000], in particular the left middle frontal gyrus (BA 9) [Kuo et al., 2001; Tan et al., 2000, 2001a,b, 2003], which differs from the pattern observed during processing of alphabetic words.

Previous language-processing activation studies in behavioral and functional neuroimaging were performed on alphabetic literate and illiterate subjects [Castro-Caldas et al., 1999, 2004; Petersson et al., 1999, 2000, 2001; Reis and Castro-Caldas, 1997]. Significantly different activation patterns were found between the groups of literates and illiterates. The authors concluded that education determines the functional organization of the adult brain and the effects of literacy and that formal schooling influences not only language-related skills but also other cognitive domains.

The purpose of the present study is to investigate the impact of education on brain activation patterns for a picto-

graphic language system. Specifically, we use Chinese word recognition and picture-naming tasks on two groups of subjects: literate and illiterate. The similarities and differences of the brain activation maps generated by this study on the pictographic language system and the previous study of an alphabetic language system [Petersson et al., 1988, 1999, 2001] are discussed. Similar studies in subjects asked to process written Chinese characters have not been reported.

SUBJECTS AND METHODS

Participants

The subjects were screened with two semistructured interviews. A sociocultural interview assessed relevant sociocultural variables (e.g., literacy level or, in illiterate subjects, the reasons for illiteracy, such as parent's literacy level, etc.). In a medical interview, health and medical variables were assessed (e.g., past medical history, medications, social and family history, the Clinical Dementia Rating Scale (CDR = 0.4) and the Global Deterioration Scale (GDS = 1), etc.). All subjects were healthy Chinese by birth that grew up in Hong Kong and spoke only Chinese in the Cantonese dialect fluently. None of them can write or speak a second language. No subjects were using drugs or alcohol and all had no history of neurological disease, systemic disease known to involve central nervous system functioning, clinically significant head injury, or mental retardation. None of them had a driving license in their lifetimes.

Subjects were classified as illiterate if they had never received formal education and had no knowledge of reading or writing. Subjects whose illiteracy was due to overt low intelligence, learning disability, or similar factors were excluded. All illiterate subjects were fully socially functional, and the absence of reading and writing skills was not a significant handicap in their everyday life. In the course of the selection process, all subjects underwent simple single Chinese character recognition tasks. Illiterate subjects were included if they were unable to recognize any of the single Chinese characters. The ability to write their names by themselves was not an exclusion criterion. For inclusion in the study, both literate and illiterate subjects must have performed in the normal range (± 1 SD, norms according to age and literacy group) on all subtests of a short test battery including simple tasks (e.g., oral naming of real objects, colors, and body parts, object identification, phrase comprehension, repetition of words and phrases, limb and oral praxis, general knowledge and episodic memory tasks) [Castro-Caldas et al., 1998; Garcia and Guerreir, 1983].

Twenty-four healthy Chinese volunteers (12 educated: 6 males; age: 67 ± 8 years; median educated for 13 ± 4 years; and 12 uneducated: 6 males; age: 70 ± 6 years) were selected and participated in the fMRI study with informed written consent. For the illiterate subjects, we explained the details of the information form and the consent form for them before we obtained their fingerprints. The protocol was approved by the Ethics Committee of the University of Hong Kong. The two groups did not differ statistically in age (F

Figure 1.

Examples of single Chinese characters for the silent word recognition task and road-signs for the picture-naming task: (A) “xìng” (family name); (B) road-sign.

= 1.163, $P = 0.292$). They were right-handed as judged by the handedness inventory devised by Snyder and Harris [1993]. In this inventory, we tested nine items involving unimanual tasks. A 5-point Likert-type scale was used, with “1” representing exclusive left-hand use and “5” representing exclusive right-hand use. The items were: writing a letter, drawing a picture, throwing a ball, holding chopsticks, hammering a nail, brushing teeth, cutting with scissors, striking a match, and opening a door. The scores on the nine items were summed for each subject, with the lowest score 9 indicating exclusive left-hand use for all tasks and the highest score 45 indicating exclusive right-hand use. All subjects had scores higher than 40. Prior to the fMRI study, it took each subject 25 min of training in order to become familiarized with the silent word recognition task, the silent picture-naming task, and the experimental procedures in order to minimize anxiety and enhance task performance. The light in the room was turned off during the MR study in order to reduce eye movements or visual sensory effects.

Image Acquisition

All MRI studies were performed on a 1.5 T GE Signa scanner at Queen Mary Hospital, Hong Kong (Signa Horizon Echo Speed with v. 5.51 software, General Electric Medical Systems, Milwaukee, WI) with a maximum gradient strength of 23 mT/m. A quadrature birdcage head coil was used. A sagittal spin echo (TR = 500 ms; TE = 8 ms) localizer image was acquired initially. fMRI was performed in the transverse plane, parallel to the anterior-posterior commissura (AC-PC) line. For fMRI scan, 24-slice T_2^* -weighted echo-planar images (EPI) were acquired with the following scan parameters: TR = 3000 ms; TE = 60 ms; flip angle

= 60°; matrix = 64×64 ; field of view = 24 cm $\times$ 24 cm; slice thickness = 5.0 mm; without interslice gap. Anatomical whole brain MRI was acquired using a T_1 -weighted, spin-echo sequence with TR = 240 ms and TE = 4.2 ms.

fMRI Task Design

Sixty-four fMRI volume images were collected during each run. The first four fMRI volume images of each run were discarded to ensure steady-state magnetization. Each fMRI run consisted of a silent word recognition task and a silent picture-naming task. A block design of RARA was used in both tasks with R representing rest period and A representing stimulation period; each period lasted 45 s. The subjects were asked to fix on a small crosshair during the resting period. There were 30 frequently used single Chinese characters for the silent word recognition task and 30 meaningful and easily named road-signs for the silent picture-naming task in each stimulation period (Fig. 1). Each character or road-sign was shown through the projector for 250 msec. The screen then went blank and the subject silently rehearsed the one-character Chinese word or the road-sign for 1,250 msec [Tan et al., 2000] (Fig. 2). The task of silent reading kept processing demands close to those of normal reading but prevented acquisition of behavioral data during scanning. This disadvantage was considered unproblematic, as reading was an obligatory response to visual words [Kronbichler et al., 2004].

Statistical Test

Postprocessing of fMRI data was performed using Matlab software (v. 6.1; MathWorks, Natick, MA) and the Statistical Parametric Map (SPM) software package (Wellcome Department of Cognitive Neurology, Institute of Neurology, Queen Square, London, UK). Each of the 60 fMRI image volumes was automatically realigned to the first image of the time series to correct for head movements during the fMRI acquisition. The time series volumes were then registered to the brain template adopted by the International Consortium for Brain Mapping (ICBM) [Mazziotta et al., 1995] with spatial normalization into Talairach space [Talairach et al., 1988]. The spatially normalized EPI volumes were smoothed by an 8-mm full-width-half-maximum Gaussian kernel. Physiological noise was filtered using a window function

Figure 2.

Sequence design in the fMRI experiment.

Figure 3.

Functional brain maps during the silent word recognition task. Averaged brain activation involved in the silent word recognition task compared to fixation. Mean normalized brain maps overlaid on the corresponding T_1 -weighted images (in gray scale) showing significant activation (in color; $P < 0.001$, uncorrected) for 12 literate subjects (**A**) and 12 elderly illiterate subjects (**B**). L, left hemisphere; R, right hemisphere.

that corresponds to a hemodynamic impulse response function (HRF). The BOLD (blood oxygenation level-dependent) response was modeled with a canonical hemodynamic response function within SPM99, which is composed of a mixture of Gamma functions. The onset time of the canonical HRF was set to 6 s, which was found to fit most of our subjects [Friston et al., 1994]. A first level SPM t -contrast map was generated for each subject under each task state using a boxcar function convolved with an empirically derived HRF at a threshold of $P = 0.01$ (corrected). The threshold was adjusted for different spatial extents of activation. The size of each activation cluster was corrected according to its statistical significance so that a larger activation cluster implies higher statistical significance [Friston et al., 1994]. A second-level analysis of random effects was used for within-group and between-group comparisons of each task. Within group comparisons, the statistical significance was thresholded at $P = 0.001$ (uncorrected). BA designations were applied using the Talairach Daemon [Lancaster et al., 2000]. Clusters of activated pixels were detected for each pair of activation tasks (literate and illiterates) using multiple comparisons of one-way ANOVA in SPSS 11 (Chicago, IL) [Shaywitz et al., 1995; Stevens et al., 1998]. We split each group (literate and illiterates) into two halves and compared the average map from each half to rule out individual variability effects because aged subjects tend to have larger variability in task performance. No statistically significant differences were found among the groups ($P > 0.05$). Analyses using a random effect model showed the same pattern of results.

RESULTS

Significant activations have been detected for both tasks (word recognition and picture-naming) in the two groups of subjects (literate and illiterates). Figures 3 and 4 show the average activation maps ($n = 12$) for word recognition and

picture-naming tasks, respectively. Regions of significant activation during the silent word recognition task and the silent picture-naming task relative to the respective resting state in literates and illiterates are shown in Table I.

Silent Word Recognition Task

In the literate subjects (Fig. 3A), the main activation is found in the left middle frontal gyrus (BA 9/46, 44). Relatively small activation is seen in the left inferior frontal gyrus (BA 45), the left inferior parietal lobule (BA 40), the left parietal postcentral gyrus (BA 40), and the left superior temporal gyrus (BA 42, 22). In addition, there is weak activation in the right limbic cingulate gyrus (BA 32) and the left middle temporal gyrus (BA 37). For the illiterate subjects (Fig. 3B), main activation is found in the left and right inferior parietal lobules (BA 40). Relatively small activation is seen bilaterally in the superior (BA 22) and middle (BA 37) temporal gyri. Weak activation is noted in the left and right inferior frontal gyri (BA 9), the left frontal precentral gyrus (BA 44), and the right limbic cingulate gyrus (BA 32). Figure 5A shows education-related differences in activated pixels ($t = 6.48$, $P < 0.001$) in the left inferior/middle frontal gyrus (BA 9/46, 45) and both sides of the left superior temporal gyrus (BA 22) in the comparison of illiterate with literate subjects.

Picture-Naming Task

In the literate subjects (Fig. 4A), the main activation was observed in the left and right middle frontal gyri (BA 9/46). Weak activation was seen in the left inferior frontal gyrus (BA 45) and the left middle temporal gyrus (BA 37). For the illiterate subjects (Fig. 4B), only very weak activation was found in the left inferior parietal lobule (BA 40), the left inferior frontal gyrus (BA 9), the left middle temporal gyrus (BA 37), and the left middle occipital region (BA 19). Figure 5B shows education-related differences in activated pixels

Figure 4.

Functional brain maps during the picture-naming task. Averaged brain activation involved in the picture-naming task compared to fixation. Mean normalized brain maps overlaid on the corresponding T_1 weighted images (in gray scale) showing significant activation (in color; $P < 0.001$, uncorrected) for 12 literate subjects (A) and 12 illiterate subjects (B). L, left hemisphere; R, right hemisphere.

($t = 6.48$, $P < 0.001$) in the bilateral middle frontal gyrus (BA 9/46, 45) and the left limbic cingulate gyrus (BA 32) in the comparison of illiterate subjects with literate subjects.

DISCUSSION

The acquisition of literacy over years of education is based on the development of elaborate links between vision and language. The visual system learns how to rapidly identify letters and letter clusters across a wide range of shapes and viewing conditions. At the same time, the verbal system learns how to segment the speech stream into discrete units such as syllables and phonemes [Morais and Kolinsky, 1994]. Associations are established between letter strings and sounds and between letter strings and lexical entries in memory. This enables pronunciation of newly encountered strings and provides access to the stored knowledge attached to familiar words [Cohen et al., 2003]. This perceptual expertise requires more than 5 years of academic training in a specific writing system [Aghababian and Nazir, 2000]. The outcome of this perceptual development process is an abstract representation of letter identities that has been termed the visual word form [Riesenhuber and Poggio, 1999; Warrington and Shallice, 1980]. The visual word form is different for literate and illiterate individuals.

Unlike previous studies of language tasks in alphabetic-language speakers, our work focused on the effects of education on neural activation in pictographic-language speakers. Our findings in literate subjects indicate that processing the silent word recognition task involves the principal anterior and posterior language areas. Syntactic operations engage both Broca's and Wernicke's areas. Processing of the picture-naming task in the literate subjects involves bilateral prefrontal cortex including the principal anterior language areas. Literacy and formal schooling determine the patterns of neural activation during the silent word recognition and picture-naming tasks. The implication is that an individual's

brain plasticity resulting from this learning process has long-lasting effects on the patterns of neural activation over an individual's life span.

Silent Word Recognition

Previous studies in young literate subjects have implicated an important role for the left inferior and middle frontal gyri (BA 9/46, 44) in processing pictographic language information [Kochunov et al., 2003; Tan et al., 2000, 2003] and alphabetic language information [Paulesu et al., 1993; Petersen et al., 1988; Poldrack et al., 1999; Vandenberghe et al., 1996]. A lexical effect and sublexical phonological decoding were demonstrated in these regions [Hagoort, 1999; Fiez, 1999]. Processing of pictographic languages activates the left middle frontal cortex (BA 9) [Kochunov et al., 2003; Tan et al., 2000, 2003]. Activation of these regions was largely absent in processing English and other alphabetic languages [Castro-Caldas, 2004; Gabrieli et al., 1998; Kim et al., 1997; Petersen et al., 1988; Poldrack et al., 1999; Reis and Castro-Caldas, 1997; Vandenberghe et al., 1996], although very weak activations are possible in some native English readers [Paulesu et al., 1993; Poldrack et al., 1999]. The present results extend this observation to elderly literate subjects.

Visually presented words or pictures can be transformed into phonological codes to access short-term memory through the subvocal rehearsal system, even though there is no direct auditory stimulation [Paulesu et al., 1993]. Activation of the left superior temporal gyrus (BA 22/42) during the silent word recognition task in literate subjects indicates phonological processing [Paulesu et al., 1993, 1996].

Weak activation in the right limbic cingulate gyrus (BA 32) is associated with demand for attention to the task [Belmonte and Yurgelun-Todd, 2003]. The fusiform regions (BA 37) have been hypothesized to play a role in naming of word, object, letter, and color [Price and Friston, 1997]; read-

TABLE I. Regions of significant activation ($T > 4.02$, uncorrected; $P < 0.001$) during the silent word recognition and the picture-naming task relative to the respective resting state in elderly literates and illiterates

	BA	Literates (N = 12)		Illiterates (N = 12)	
		Coordinates		Coordinates	
		x, y, z	Vol. (mm ³)	x, y, z	Vol. (mm ³)
Silent word recognition					
Right inferior frontal gyrus	45	58, 20, 6	800	—	
		—45, 22, 6	1200	—	
Left inferior frontal gyrus	45	—58, 20, 18	200	—	
	9	—		—58, 12, 30	96
Right inferior frontal gyrus	9	—		58, 12, 30	96
	46	—50, 40, 18	1200	—	
Left middle frontal gyrus	946	—52, 35, 30	5680	—	
Right middle frontal gyrus	946	52, 35, 30	200	—	
Left frontal precentral gyrus	44	—45, 18, 6	800	—45, 18, 6	64
Left inferior parietal lobule	40	—62, —30, 30	1200	—62, —30, 30	1272
Right inferior parietal lobule	40	—		62, —30, 30	424
Left parietal postcentral gyrus	40	—65, —20, 18	1200	—65, —20, 18	112
Right parietal postcentral gyrus	40	65, —20, 18	176	—	
	42	—60, —30, 6	176	—	
Left superior temporal gyrus	22	—65, —40, 18	1200	—65, —40, 18	848
Right superior temporal gyrus	22	—		65, —40, 18	424
Left middle temporal gyrus	37	—58, —64, 6	600	—58, —64, 6	568
Right middle temporal gyrus	37	—		58, —64, 6	288
Right limbic cingulate gyrus	32	3, 25, 30	64	3, 25, 30	88
Picture-naming task					
Left inferior frontal gyrus	45	—45, 22, 6	112	—	
	9	—		—45, 4, 30	18
Right middle frontal gyrus	46	50, 40, 18	8	—	
Left middle frontal gyrus	46	—50, 40, 18	112	—	
	946	—52, 35, 30	5112	—	
Right middle frontal gyrus	946	52, 35, 30	4544	—	
Left inferior parietal lobule	40	—		—62, —30, 30	112
Left middle temporal gyrus	37	—52, —62, 6	18	—52, —62, 6	18
Left middle occipital gyrus	19	—		—44, —82, 6	18

—, not available

ing tasks not requiring overt naming [Buchel et al., 1998]; and naming of tactile and auditory stimuli [Buchel et al., 1998]. The present results suggest that the left fusiform region mediates phonological/lexical processes involved in the silent word recognition task. Silent reading utilizes an inferior temporal pathway, while reading aloud engages a network for phonological decoding involving superior temporal and inferior parietal cortex [Bookheimer et al., 1995; Price et al., 1997; Rumsey et al., 1994]. Interpreting the significance of activation patterns is one of the important challenges facing cognitive neuroscience research on education.

Our results confirm that education plays a significant role in modifying neural circuits for specific cognitive operations. Differences in the frontal and temporal regions are particularly noticeable. Finding bilateral activation over the inferior parietal lobule (BA 40) and the superior temporal gyrus (BA 22) (greater on the left) in the illiterate subjects suggests the involvement of phonological processing and short-term memory storage when attempting to recognize unfamiliar pictographic characters [Gabrieli et al., 1997, 1998; Schacter and Wagner, 1999]. A plausible explanation is diminished long-term verbal memory in the illiterate sub-

jects. Weak activation over the left and right inferior frontal gyri (BA 9) reveals the underlying word encoding and phonological encoding (left BA 9) as well as picture encoding and working memory (right BA 9) [Gabrieli et al., 1998]. Bilateral activation of the middle temporal gyrus (BA 37) indicates visuospatial attention [Buchel et al., 1998; Belmonte and Yurgelun-Todd, 2003]. Thus, illiterate subjects utilize nonverbal and verbal operations to assist with the processing of the silent word recognition stimuli.

Picture-Naming Task

Previous studies in young literate subjects have confirmed the involvement of the left inferior frontal cortex (BA 9/46, 44) and left anterior fusiform region (BA 37) in encoding of words [Kelley et al., 1998; Wagner et al., 1998ab]. These cortical regions respond preferentially to word encoding and maintenance of phonological codes [Paulesu et al., 1993; Poldrack et al., 1999; Wagner et al., 1998]. On the other hand, the right inferior frontal cortex (BA9/46, 44) responds preferentially to picture encoding such as of unfamiliar faces [Buckner et al., 1998; Kelley et al., 1998; Tulving et al., 1994; Vandenberghe et al., 1996], maintains items in the working

Figure 5.

Mean pixel values of the inferior frontal gyrus (IFG), the middle frontal gyrus (MFG), and the superior temporal gyrus (STG) for silent word recognition task (A) and silent picture-naming task (B) for the literate ($n = 12$) and the illiterate ($n = 12$) groups.

memory [Owen et al., 1996a,b], and supports access to visuospatial and visuo-object representations. Encoding of nameable line-drawn objects, which are amenable to both verbal and nonverbal encoding, yields bilateral dorsal frontal activation [Kelley et al., 1998]. Our results are consistent with previous studies that encoding of picture-naming yields bilateral frontal activation due to both verbal and nonverbal encoding.

The picture-naming task was probably difficult or meaningless to the illiterate subjects, producing only very weak activation. Activation of the left inferior parietal lobule (BA 40) and the left inferior frontal gyrus (BA 9) suggests very weak phonological processing with engagement of short-term but not long-term memory [Gabrieli et al., 1998]. The left middle occipital region (BA 19) and the left fusiform region (BA 37) appear to mediate phonological/lexical processes during the nonverbal task [Buchel et al., 1998; Price and Friston, 1997]. This is in contrast to the literate subjects in whom symmetrical activation occurred in regions (BA 9/46) involved in phonological and picture encoding as well as engagement of working memory and maintenance of visuo-object representations [Gabrieli et al., 1998].

Previous studies [Petersson et al., 2001] in alphabetic speakers have found that there was a more prominent left

inferior parietal activation in the literate group, but significant activation was only seen in the middle frontal region in the illiterate group. Our result in pictographic speakers is consistent with that in alphabetic speakers. This indicates that the functional architecture of language processing may be influenced by education. There may exist a relationship between the acquisition of pictographic symbol knowledge and some aspects of pictographic processing.

CONCLUSION

The present results suggest that education affects the patterns of neural activation during the silent word recognition and picture-naming tasks. Education-induced brain plasticity may enhance efficiency and increase connectivity supporting essential cognitive operations.

ACKNOWLEDGMENT

We thank the reviewers for their help and constructive comments.

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