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Neural mechanisms underlying the processing of Chinese words: An fMRI study

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Abstract

The present study employed functional magnetic resonance imaging (fMRI) to investigate the neural mechanisms underlying orthographic, phonological and semantic processing of single character Chinese words. Twelve right-handed native Chinese speakers participated in the study. Three fundamental linguistic tasks including orthographic judgment, phonological matching and semantic association task were used. Our results demonstrated robust activation in the left posterior inferior temporal cortex (BA 37) for all three tasks. While the phonological matching task produced left-lateralized activation in the inferior frontal and parietal regions, semantic association task showed considerable bilateral activation in the inferior frontal and occipito-parietal regions. Direct comparison between phonological matching and semantic association task yielded semantic related activation in the anterior portion of the left inferior frontal gyrus (BA 47) and the right inferior frontal region (Broca's homology; BA 45). Behaviorally, there was no difference in response time between phonological matching and semantic association task. Our findings suggested that differential neural pathways were involved in the processing of meaning and sound of single-character Chinese words. The present study provided systemic information of the neural substrates underlying the processing of different components of Chinese language.

Keywords: Semantic association; Phonological matching; Orthographic judgment; Inferior frontal region; PITC; Broca's area

1. Introduction

Recently, a growing effort has been put to exploit functional brain imaging to investigate the central representations of Chinese language processing due to its unique characteristics. Most studies using brain imaging have not only reported common neural substrates shared by Chinese and alphabetical language, but also additional brain regions particularly involved in the processing of Chinese characters (Chee et al., 1999; Tan et al., 2000; Chen et al., 2002; Kuo et al., 2004). Despite the increasing number of studies, the neural mechanism for the processing of different components of Chinese language are incompletely understood compared to that of alphabetical language. Unlike alphabetical system, the Chinese language is composed of ideographic scripts and is based on the association of meaningful morphemes with graphic units. This inherent characteristic has led to the idea that the meaning of Chinese words might be accessed directly from orthography with less or without phonological mediation. Reading Chinese words may involve particular neural networks associated with its unique pictographic nature. Such reasoning is mainly based on the studies of Japanese Kanji (Japanese morphograms derived from Chinese characters). Neuropsychological studies with Japanese patients suggested that the right hemisphere has special advantage in processing Kanji, which may attribute to direct access to semantic system (Sasanuma and Monoi, 1975; Kawamura et al., 1989). In the present study, by using phonological matching and semantic

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association task, we attempt to identify the neural networks involved in the processing of phonology and semantics of Chinese words. Previous clinical observations and lesion data from Japanese patients indicated that the left posterior inferior temporal cortex (PITC) is the only region that is consistently correlated with the processing of Kanji (Soma et al., 1989; Sakurai et al., 1994). Recent fMRI studies using Japanese provided converging evidence that the same region played an import role in writing and mental recall of Kanji through retrieval of their visual graphic images (Nakamura et al., 2000, 2002). Another purpose of the study is to test the hypothesis that the left PITC plays an important role in orthographic processing of Chinese characters.

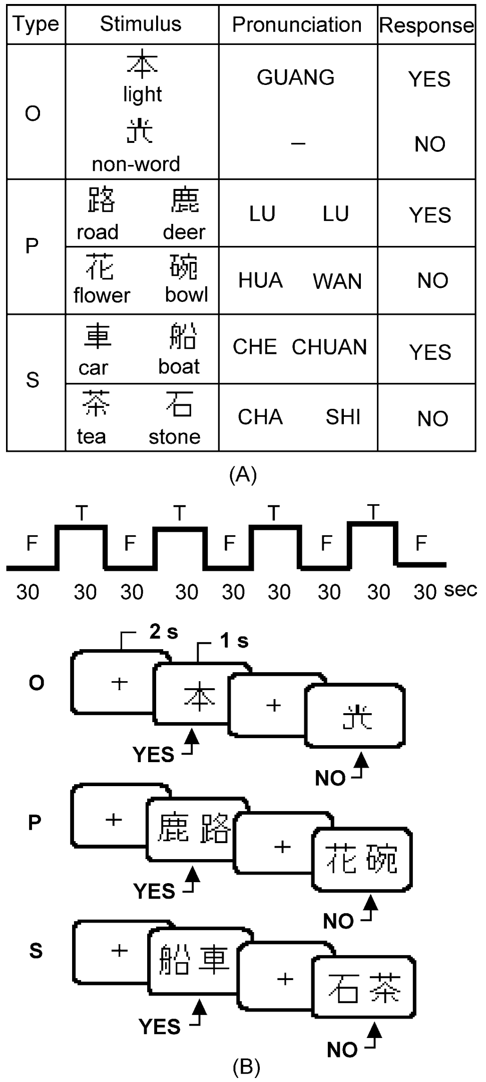
2. Materials and methods

Twelve healthy right-handed Chinese University Students (six male and six female; 33.0 ± 4.5 y.o.) participated in the study. All participants underwent a general physical examination and no abnormality was found. None of them had a history of neurological or psychiatric diseases. Handedness of the participants was tested by the Edinburgh handedness inventory (Oldfield, 1971), and all of them were judged to be right-handed (mean handedness score = 18.4 ± 0.83). Informed consent was obtained prior to the fMRI experiment. The protocol of this study was in accordance with the guidelines determined by the Committee of Medical Ethics, Graduate School of Medicine, Kyoto University.

2.1. Linguistic tasks

Three linguistic tasks, including orthographic judgment, phonological matching and semantic association task were used (Fig. 1a). The single-character words used in the study were selected from the standard Chinese elementary school textbook. They were commonly used and had the frequency of occurrence no fewer than 60 per million according to the Modern Chinese Frequency Dictionary. In the orthographic judgment task, either a single-character Chinese word or a non-word (the mirror image of a real word) was visually presented for 1 s. Participants were asked to decide whether a visually presented item is orthographically legal or illegal. In this orthographic judgment task, we decided to use the mirror image of a real word for non-word condition instead of using scrambled Chinese characters or creating other forms of nonsense characters to reduce the difference in stimulus difficulty and novelty between word and non-word condition. The mirror image of a real word is orthographically illegal and is easy to make a judgment on it (no difference in reaction time detected between word and non-word judgment when tested outside the scanner).

For both phonological matching and semantic association tasks, a pair of single-character Chinese words, which were composed of nouns with precise meaning, were presented for 1 s. For phonological matching, since the four tonal patterns (i.e., vowel inflections) of Chinese characters had lexical-semantic status, to avoid as much as possible automatic access to semantics, we asked the participants to determine whether the two words had same pronunciation at consonant level. In the semantic association task, participants needed to decide whether the two words were semantically related to each other. Passive viewing of a fixation cross was used as the baseline for all the three tasks. For each task, the same event sequence was employed for each trial: a single-character word or non-word (visual



Type	Stimulus	Pronunciation	Response
O	本 light	GUANG	YES
	non-word	–	NO
P	路 鹿 road deer	LU LU	YES
	花 碗 flower bowl	HUA WAN	NO
S	車 船 car boat	CHE CHUAN	YES
	茶 石 tea stone	CHA SHI	NO

(A)

(B)

Fig. 1. Exemplars of the stimuli used for the three tasks (A) and experimental design (B). (A) For orthographic judgment, the stimulus was either a word or non-word. Non-words were mirror inversion of real words. For both phonological matching and semantic association task, the stimuli were a pair of single-character Chinese words with precise meaning. (B) A block design was used. Each task condition, which lasted for 30 s, was alternating with a 30 s baseline condition. T: task condition; F: baseline (fixation cross). Each stimulus appeared for 1 s, followed by a response period with the fixation for 2 s. O: orthographic judgment; P: phonological matching task; S: semantic association task.

angle: 3 ± 1°, for orthographic judgment) or two single-character words (visual angle: 5 ± 1°, for phonological and semantic tasks) (Fig. 1b). The order of the three tasks was counterbalanced across the subjects. Two keys were placed under the subject's right index and middle fingers for recording the responses. The participants pressed the key with their index finger when the answer is 'yes', and pressed the key with their middle finger when the answer is 'no'. Reaction time (RT) and accuracy were collected.

2.2. FMRI procedures

FMRI scan was conducted with a 1.5 T whole-body MRI system (Horizon; GE Medical, Milwaukee, WI, USA) using a standard head coil optimized for whole-brain echo planar imaging. Each participant had a 15 min pre-scan training session. The linguistic tasks were generated using SuperLab installed on a Macintosh computer (Cedrus, Phoenix, AZ, USA). Then the stimuli were back-projected onto a screen using a video projection system via a mirror placed in the head coil. Functional imaging used a single shot echo planar imaging sequence with the following parameters: TR 6 s, TE 43 ms, flip angle 90°, field-of-view 22 cm × 22 cm, and 64 × 64 pixel matrix. Forty-five contiguous 3.5 mm thick slices covering the whole brain were obtained in the axial plane for each task. A T1-weighted 3D anatomical image of each participant was obtained as well.

2.3. Data analysis

After reconstruction, fMRI time series were analyzed using SPM96 software package (Wellcome Department of Cognitive Neurology, London, UK). Three initial images were excluded from further analysis because of the non-equilibrium of the magnetization. Then, images were realigned to correct for intra- and inter-scan head movements, re-sampled into every 2 mm thick slice, using bilinear interpolation, co-registered with each participant's structural MRI and spatially normalized to the standard brain space defined by the Montreal Neurological Institute (Friston et al., 1995). The images were then spatially smoothed with an isotropic 7.5 mm Gaussian filter to account for residual inter-subject difference. Statistical analysis of fMRI time series was performed at both intra- and inter-subject levels. For individual analyses, the fMRI time series of each subject were correlated with a box-car reference function, to which a high pass filter (0.5 cycles/min) and temporal smoothness were applied to remove low frequency noise, such as cardiac and respiratory noise, and to enhance the signal-to-noise ratio, respectively. The resulting correlation was transformed into a Z-score map (SPM{Z}) (Friston et al., 1994). The height threshold for a significant Z value was set at $Z > 3.09$ (corresponding to $p < 0.001$) at each voxel level, with $p < 0.05$ (spatial extent) correction for multiple comparisons following the theory of Gaussian random fields. Location of the activation was identified by transforming the Montreal Neurological Institute coordinates into the standard brain atlas of Talairach (Talairach and Tournoux, 1988). To disclose the precise location and spatial extent (number of voxels) of activations in the frontal region, a region of interest (ROI) was set within bilateral lateral frontal regions. According to the Talairach atlas, the boundary of ROI was defined as $-45\text{ mm} < x < -55\text{ mm}$, $5\text{ mm} < y < 40\text{ mm}$, $-12\text{ mm} < z < 32\text{ mm}$ on the left side; $45\text{ mm} < x < 55\text{ mm}$, $5\text{ mm} < y < 40\text{ mm}$, $-12\text{ mm} < z < 32\text{ mm}$ on the right side. The center of the ROI was approximate at Broca's area (BA 44/45). The anatomical location of the peak activation within the ROI was reported. Additionally, the number of voxels exceeding a statistical threshold of Z value of 3.09 (uncorrected for multiple comparisons) and encompassed by the boundary was counted. For multi-subject statistical analysis, the random effects kit for SPM96 was used. By convolving the fMRI time series of each subject with a box-car reference function, images of the individual level activation parameter were computed as an adjusted mean image per condition per scan for each subject. A t-test was applied to the condition-specific mean images. A statistical threshold (height threshold) of $Z > 3.09$ was used to determine the presence of significant activation foci. The extent of clusters (spatial extent) was corrected at $p < 0.05$ for multiple comparisons by referring to the probabilistic behavior of Gaussian random fields. Furthermore, a direct comparison was made between phonological matching and semantic association task. The threshold for this second level comparison was set at $p < 0.01$ without correction for multiple comparisons. RT and accuracy were analyzed by one-way ANOVA (analysis of variance). The statistical significance level was set at $p < 0.01$.

3. Results

Behavioral data showed no significant difference in accuracy among the three tasks [$F(2,30) = 1.30$, $p = 0.288$; Table 1]. Orthographic judgment required the longest time (1696 ms), followed by semantic association (1515 ms) and phonological matching task (1477 ms) [$F(2,30) = 29.06$, $p < 0.0001$; Table 1]. No difference in RT was found between phonological matching and semantic association task ($p = 0.224$).

Group analysis revealed that cortical regions commonly activated by the three tasks included bilateral inferior and middle occipital (BA 18, 19), left inferior temporal (BA 37),

Table 1
Behavioral data during task performance

Tasks	RT (ms) (mean ± S.D.)	Accuracy
Orthographic judgment	1696 ± 43	0.98 ± 0.02
Phonological matching	1477 ± 75	0.96 ± 0.04
Semantic association task	1515 ± 90	0.97 ± 0.05

RT: reaction time.

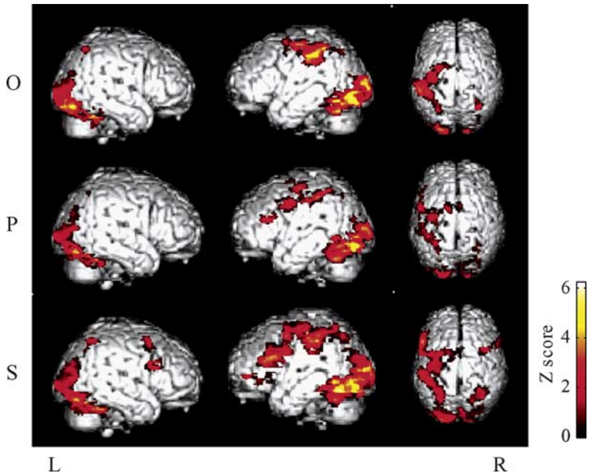


Fig. 2. Cortical activation relative to baseline for each task (activation rendered on standard 3D template) from group analysis. Orthographic judgment produced activation in the bilateral occipital, left inferior parietal and left basal temporal regions. Additionally, phonological matching task exhibited left-lateralized activation in the inferior frontal region (Broca's area). In contrast, semantic association task produced robust activation not only in the above regions, but also in the right superior parietal and the right inferior frontal regions. O: orthographic judgment; P: phonological matching task; S: semantic association task.

and left parietal regions (BA 40) (Fig. 2; Table 2). In particular, as we predicted, robust activation was detected in the left PITC. Among the three tasks, semantic association task produced the most extensive activation in this region (Fig. 3). The left inferior frontal regions were recruited in both phonological matching and semantic association task. Additionally, semantic association task produced robust activation in the right inferior frontal (Broca's homology; BA 45) and the right superior parietal (BA 7) regions. Furthermore, the anterior ventral portion of the left inferior frontal (BA 47) and the right inferior frontal (BA 45) activation remained significant when phonological matching was subtracted from semantic association task. Individual analyses revealed that nine of twelve subjects showed left-lateralized activation in the inferior frontal regions (BA 44/45, BA 46/9) for phonological matching task, while 10 of 12 subjects had bilateral distribution of the inferior frontal activation for the semantic association task (Fig. 4). Peak location in Talairach space and the number of activated voxels of bilateral frontal activation for each subject are listed in Table 3. Both individual and group level analyses found no reliable activation in the posterior superior temporal region.

4. Discussion

In the present study, we employed three fundamental linguistic tasks, namely, orthographic judgment, phonological matching and semantic association task to investigate the neural mechanisms of Chinese language processing. The left PITC activated by the three tasks was consistent with the findings from recent fMRI studies of Chinese word processing (Chee et al., 1999; Tan et al., 2000; Kuo

Table 2
Location of cortical activation for each task compared to fixation (group analysis by random effect model)

Regions	BA	Orthographic judgment				Phonological matching				Semantic association task			
		Talairach coordinates			Max Z	Talairach coordinates			Max Z	Talairach coordinates			Max Z
		X	Y	Z		X	Y	Z		X	Y	Z	
(L) IFG (Broca)	44/45	–	–	–	–	−40	26	19	4.88	−43	16	22	5.22
(L) IFG	47	–	–	–	–	–	–	–	–	−31	30	−2	4.76
(L) MFG	8/9	–	–	–	–	−11	3	49	5.06	−54	12	36	4.32
(R) MFG	8	–	–	–	–	–	–	–	–	40	10	52	4.70
(R) IFG	44/45	–	–	–	–	–	–	–	–	56	16	22	5.37
(L) Gprc	4	−32	−17	50	5.63	−37	−11	39	5.07	−29	−23	57	5.33
(R) CG	32	–	–	–	–	–	–	–	–	12	14	31	5.17
(L) CG	24, 32	−20	−7	36	4.86	–	–	–	–	−4	20	32	5.04
(L) FG	19, 37	−29	−77	−13	5.68	−36	−67	−11	4.97	−48	−62	−15	5.45
(L) PITR	37	−40	−58	−14	5.38	−40	−52	−15	4.74	−47	−56	−6	4.80
(L) IPL	40	−36	−46	45	5.76	−32	−40	43	5.03	−32	−48	52	5.49
(L) PCu	7	29	−62	46	4.88	22	−58	44	4.74	15	−62	47	5.41
(R) PCu	7	–	–	–	–	–	–	–	–	−25	−63	39	5.60
(R) SPL	7	–	–	–	–	–	–	–	–	31	−60	54	4.77
(L) GL	18	12	−89	−10	6.07	−17	−89	4	4.93	10	−83	−8	6.33
(R) GL	18	−10	−96	−2	5.76	10	−83	−8	5.61	17	−83	−13	6.19
(L) IOG	18	−20	−76	−10	4.78	−18	−78	−8	5.41	−36	−89	−4	5.43
(R) IOG	18	31	−83	−10	5.00	26	−85	1	4.88	4	−85	2	5.34
(L) MOG	18/19	−38	−62	−8	4.75	−40	−66	−8	5.03	−27	−85	6	5.37
(R) MOG	18/19	28	−75	4	4.86	25	−85	6	4.72	26	−81	6	5.14
(R) SOG	19	–	–	–	–	–	–	–	–	30	−70	30	4.30

IFG: inferior frontal gyrus; MFG: middle frontal gyrus; CG: cingulate gyrus; FG: fusiform gyrus; PCu: precuneus; IPL: inferior parietal lobule; SPL: superior parietal lobule; LG: lingual gyrus; IOG: inferior occipital gyrus; MOG: middle occipital gyrus; PITR: posterior inferior temporal region; Gprc: pre-central gyrus; SOG: superior occipital gyrus; BA: Brodmann's area; R: right hemisphere; L: left hemisphere.

Table 3
Frontal activation during phonological matching and semantic association task for individual subject

SI	Phonological matching								Semantic association task							
	LH				RH				LH				RH			
	Talairach coordinates			Voxel size	Talairach coordinates			Voxel size	Talairach coordinates			Voxel size	Talairach coordinates			Voxel size
	X	*Y*	*Z*		*X*	*Y*	*Z*		*X*	*Y*	*Z*		*X*	*Y*	*Z*	
ZH	−46	22	26	278	42	22	30	139	−44	12	28	375	52	8	28	121
DY	–	–	–	–	50	20	20	245	–	–	–	–	56	12	32	173
ZXF	−44	32	22	171	–	–	–	–	−40	46	0	79	50	16	28	316
CQ	−36	34	16	414	–	–	–	–	−44	26	−14	251	56	26	28	51
SZP	−46	20	28	416	–	–	–	–	−44	12	26	322	50	40	34	67
LJL	−46	14	28	70	–	–	–	–	−48	14	20	490	44	40	8	130
CJ	−46	26	6	213	–	–	–	–	−46	14	16	416	54	22	24	107
BJ	−42	20	20	482	38	30	−12	135	−52	14	22	790	46	18	−2	110
WY	−46	32	10	194	–		–	–	–42	28	14	699	46	30	12	141
ZXL	−54	16	28	400	–		–	–	−60	10	26	389	50	14	12	466
CL	−42	20	20	260	–		–	–	–	–	–	–	52	38	12	629
SZY	−48	26	20	668	–		–	–	−48	14	20	762	58	20	32	147

SI: subject initials; LH: left hemisphere; RH: right hemisphere.

et al., 2004). The location of the activation ($z = -12$) precisely overlapped with that found during both writing and mental recall of Japanese Kanji orthography (Nakamura et al., 2000, 2002). Lesion studies in Japanese patients revealed that focal damage to this region affected writing of Kanji rather consistently, and the impairments were considered to derive essentially from an inability to recall visual graphic forms of Kanji (Mochizuki and Ohtomo, 1988; Kawamura et al., 1989; Soma et al., 1989; Sakurai et al., 1994). The above findings from lesion studies indicate that the left PITC plays an important role in the retrieval of Kanji graphic forms. Corroborated by the aforementioned studies of Chinese characters and Japanese Kanji, our finding supports the role of the left PITC in the active retrieval of the orthographic architecture of Chinese characters.

The regions most prominently activated by phonological matching task are the left basal temporal, parietal and inferior frontal cortices. The left inferior frontal region (Broca's area) concurs with the left pre-motor and indicates articulatory rehearsal for phonological processing (Gabrieli et al., 1998; Poldrack et al., 1999). Consistent with previous fMRI studies using homophone judgment of Chinese words (Kuo et al., 2004), we detected robust activation in the dorsal visual stream. The strong engagement of the dorsal pathway during phonological matching, which has not been reported in the studies of alphabetical phonological processing (Gabrieli et al., 1998; Xu et al., 2001), suggests a fine visuospatial analysis involved in the transformation from orthography to phonology in Chinese. We found no obvious activation in the left superior temporal region, where has been suggested in the orthography-phonology transformation during Chinese reading in the study done by Kuo et al. (2004). The absence of activation in this region can be partially ascribed to scanner sensitivity (3 T versus 1.5 T), and/or statistical strategy (uncorrected versus corrected for multiple comparisons) used in different studies.

Semantic association task selectively activated the ventral part of the left inferior frontal region, which can be separated from posterior dorsal part activated by phonological matching task. In line with several imaging studies on alphabetical language, our finding supports the theory of a functional segregation in the left inferior frontal region: the anterior ventral part is associated with semantic processing while the posterior dorsal part is related to phonological processing (Gabrieli et al., 1998; Poldrack et al., 1999). A feature worthy to mention is the involvement of the right parietal and frontal network during semantic processing. Although several studies using alphabetical semantic tasks have reported activation in the same region and attributed the activation to 'task-difficulty' (Poldrack et al., 1999; Wagner et al., 2001), we argue strongly that the right parietal and frontal activation is associated with the specific processing of Chinese logographic system. Given the fact that Chinese characters are pictographic, there ought to be a greater linkage between the spatial construction of a word and its meaning than is the case for English words. For example, "馬" (meaning horse) is a pictograph that resembles an abstract figure galloping across the page. Thus, it is plausible that automatic decoding and analyzing of the spatial constitution of Chinese characters occurs as long as semantic contents are accessed. As documented in the literature, the right hemisphere is specialized for holistic, spatial processing, and coordinating spatial relations (Jonides et al., 1993; Smith et al., 1996). The observed right frontal and parietal network might participate in the mediation of spatial decoding and analyzing of Chinese characters, which occurred unconsciously when semantic information was demanded.

In the current study, we employed 'fixation cross' as the control condition instead of using pseudo-characters or scrambled real characters. The cortical activation pattern generated by orthographic and phonological tasks contrasted with fixation is rather consistent with that reported in the

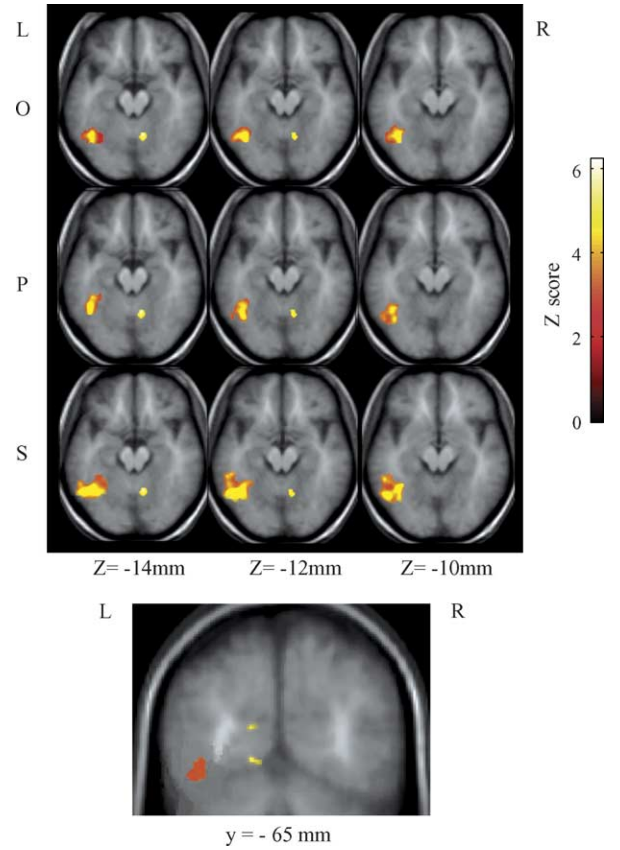
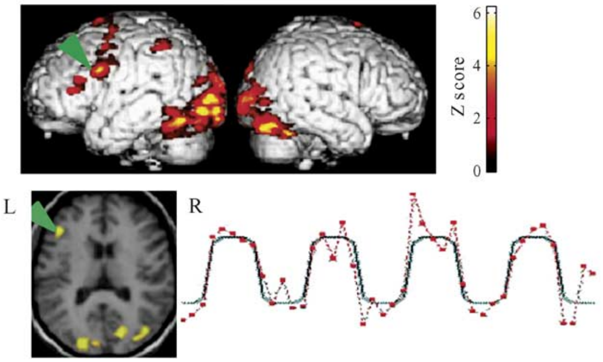


Fig. 3. Left posterior inferior temporal activation found in all three tasks. Activation was super-imposed on the standard T1-weighted structural MRI. Semantic association task produced most extensive activation in the left posterior inferior temporal region. There was an obvious overlap of activation by the three tasks. Orange represents the overlap (i.e., the activated focus in common). O: orthographic judgment; P: phonological matching task; S: semantic association task.

(A) Phonological Matching



(B) Semantic Association

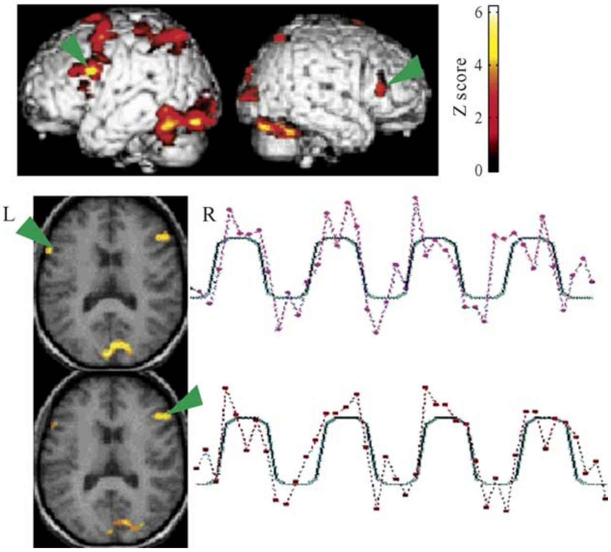


Fig. 4. Inferior frontal activation from a representative subject during phonological matching task (A) and semantic association task (B). (A) Activation of Broca's area (indicated by arrow) and the fitting curve of the peak activation in this area are shown. Note that there was no activation in Broca's homologous region in the right hemisphere during phonological matching task. (B) In contrast to phonological matching task, semantic association task produced bilateral inferior frontal activation. The fitting curves of the peak activation in Broca's area and its homologous area in the right hemisphere are illustrated. Dark blue solid lines indicate the box-car reference function. Broken lines represent the estimated hemodynamic responses. The tight fitting indicates high reliability of the signals. P: phonological matching task; S: semantic association task.

study done by Kuo et al. (2004), using homophone and character judgment task. The authors also reported activation in bilateral occipito-temporal, occipito-parietal and superior parietal regions when either pseudo-characters or nonsense forms of Korean letters was contrasted with fixation. However, when character judgment was contrasted with pseudo-character judgment or form judgment, no significant activation left in the occipito-parietal and temporo-parietal regions, which indicates that these areas might be largely related to logographic and/or pictographic processing. However, one should be cautious about using pseudo-characters as control condition is that they have some linguistic properties as well in which, subjects may automatically process beyond the task demand and manifest the engagement of language-related brain areas.

Although our interest has been focused on cortical areas involved in the processing of three fundamental linguistic components based on previous lesion and neuroimaging studies done in Chinese and Japanese, it is necessary to at least discuss some possible alternatives associated with the simplicity of our control condition-fixation cross.

Activation found in the motor and pre-motor areas in each of the three tasks compared to fixation cross was due to the difference in motor output (button press) between task and rest condition. Other than the plausible contribution in mediation of spatial decoding and analyzing of Chinese characters, the right middle frontal gyrus and right superior parietal region might also be engaged under the context of spatial working memory required while performing semantic association task (D'Esposito et al., 1998; Smith et al., 1995). Compared to the control condition, attention allocation was largely demanded in each task condition, which could explain the left inferior parietal activation found in the three tasks. Activation of the bilateral extrastriate areas, mainly bilateral secondary visual cortices, was associated with the extensive visual processing for Chinese characters relative to fixation cross.

In conclusion, our study demonstrates that the left PITC plays an important role in the active retrieval of Chinese orthography. The recruitment of brain regions related to spatial analysis of the architecture of Chinese characters suggests that specific processing requirements inherited in individual languages may shape the organization of the language system in the brain. Future study designed for control at different level of orthographic, phonologic and semantic processing is needed to further elucidate the central mechanisms underlying Chinese language processing.

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