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Dissociation in the neural basis underlying Chinese tone and vowel production

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Neuropsychologists have debated over whether the processing of segmental and suprasegmental units involves different neural mechanisms. Focusing on the *production* of Chinese lexical tones (suprasegmental units) and vowels (segmental units), this study used the adaptation paradigm to investigate a possible neural dissociation for tone and vowel production. Ten native Chinese speakers were asked to name Chinese characters and pinyin (Romanized phonetic system for Chinese language) that varied in terms of tones and vowels. fMRI results showed significant differences in the right inferior frontal gyrus between tone and vowel production (more activation for tones than for vowels). Brain asymmetry analysis further showed that tone production was less left-lateralized than vowel production, although both showed left-hemisphere dominance.

Introduction

In linguistics, each syllable is deemed to include two phonological units: a segmental unit such as a vowel and a consonant and a prosodic frame (or suprasegmental) unit such as pitch or tone or stress. In cognitive neuroscience, however, the question remains open as to whether these two phonological units involve different neural and cognitive mechanisms. Many behavioral studies (Ferrand and Segui, 1998; Meijer, 1996; Sevald et al., 1995), mostly based on European languages, have found evidence for separate storage and processing systems for the segmental and suprasegmental units. Based on such evidence, psycholinguistic phonological encoding models (Dell, 1988; Levelt, 1992; Levelt et al., 1999) have postulated that representations of the segmental and suprasegmental units of a syllable can, to a certain extent, be stored and retrieved independently. Consistent with these models based on behavioral studies, brain lesion studies with aphasic patients whose native language was a European language (Cappa et al., 1997; Laganaro et al., 2002) also found that lexical stress (suprasegmental unit) could be selectively impaired independent of their ability to process segmental units.

The possible dissociation in the neural bases of suprasegmental (i.e., lexical stress) and segmental units for European languages, however, may not extend to other languages. European languages are stress languages, in which stress typically has a fixed position within a word (e.g., stress on the second syllable in the word "tomato") and provides little additional lexical information. In contrast, tones in tonal languages are lexically distinctive. For example, in Mandarin Chinese, ma1 (high level tone), ma2 (low rising tone), ma3 (low falling rising tone), and ma4 (high falling tone) represent four different sets of words with distinct meanings. At least six different characters (some rarely used though) are pronounced as ma1. Common examples of ma1 are "mother" and "wipe." Four different characters are pronounced as ma2, with one of them having at least five meanings including "numb," "hemp," and "rough." Ma3 could be any of six different characters with meanings such as "horse," "units," and "ant." Finally, ma4 has a common character ("scold") and three less common uses (e.g., military rituals in ancient China). Clearly, tones are extremely important in distinguishing among these different sets of words. Because of their lexical significance, tones have sometimes been regarded by linguists to be phonemic and to act like segmental units. If tones indeed act like segmental units, neural mechanisms involved in the processing of tones may be the same as those for the processing of other segmental units such as vowels.

Results from several studies appear to be consistent with this view. For instance, Packard (1986) observed that Chinese aphasics with a brain lesion in the left hemisphere showed similar deficits in the production of tones and consonants. He argued that "tones, like consonants, are listed in the lexicon as unit phonemes." Based on

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their studies of "slips of tongue," Fromkin (1980) also concluded that tones, consonants, and vowels were equally susceptible to errors.

In contrast, Law and Or (2001) found differentiated impairment on segmental and suprasegmental units among patients who spoke Cantonese (a dialect of Chinese), and the same finding was reported by Liang and van Heuven (2004) for Standard Chinese-speaking patients. These results were similar to those for stress languages as mentioned above and suggest the possibility of different neural mechanisms underlying tone (suprasegmental) and segmental processing.

One possible reason for these conflicting results from brain lesion studies is that brain lesion sites may be different in different cases. This problem can be overcome by using modern neuro-imaging technology. So far, two neuroimaging studies (Gandour et al., 2000; Hsieh et al., 2001) have included results that are relevant to this issue. Using the PET technique, Hsieh et al. (2001) investigated the role of linguistic experiences (Chinese vs. English speakers) in the neural bases for the perception of Chinese tones, consonants, and vowels. They found that native Chinese speakers showed activation in similar brain areas (mainly left inferior frontal gyrus and left precentral gryus) when perceiving tones, consonants, and vowels. This result was consistent with that of Gandour et al. (2000) study of another tone language—Thai. Gandour et al. (2000) concluded that phonological units of language, whether suprasegmental or segmental, are processed in the perisylvian region near the Broca's area.

The conclusion from the studies of Hsieh et al. (2001) and Gandour et al. (2000), however, should be considered only as tentative for two reasons. First, they did not make direct comparisons in brain activation patterns among the three kinds of tasks (perception of tones, consonants, and vowels). Without direct comparisons, finer differences in neural mechanisms may have been missed. Second, they studied only speech perception, not speech production. Although both speech perception and production necessarily involve phonological processing, it would be informative to study the neural bases of segmental and suprasegmental processing with different tasks. Speech perception and production tasks differ in the processes such as phonological encoding, articulation plan, and vocalization.

To expand on and to provide refinements to the previous research, we used the adaptation paradigm to directly compare the brain activation patterns of vowel and tone production. The neural adaptation paradigm is believed to have higher spatial resolution and thus to be more sensitive than the conventional fMRI paradigm (Grill-Spector and Malach, 2001). It is based on the fact that, if a stimulus or a feature of a stimulus is repeated many times, neural response to this stimulus or feature will decrease (Buckner et al., 1998). In our study, we repeatedly presented the same tone with varying vowels (or the same vowel with varying tones) to the subjects. According to the adaptation paradigm, neural responses to the repeated tone with varying vowels – the vowel-change condition – should show a lower level of activation for the constant tone but remain sensitive to the varying vowels. The same logic applies to the tone-change condition.

In this study, we contrasted the production of tones (supra-segmental units) with that of vowels (segmental units), instead of consonants, because vowels (not consonants) are the segmental carrier of Chinese lexical tone. This closer connection between tones and vowels than that between tones and consonants should provide a conservative test of dissociation in neural mechanisms

involved in the processing of segmental and suprasegmental units. A 2 (tasks) × 2 (conditions) within-subjects block design was adopted. The two tasks were pinyin- and character-naming tasks. Chinese pinyin is a system used to transliterate Chinese ideograms into the Roman alphabet. It is similar to alphabetical languages in its relatively clear demarcation of consonants and vowels. In addition, tones are also specifically marked. Chinese children learn both pinyin and Chinese characters in parallel and thus are familiar with both systems. Because of a large number of homophones (see the above examples for ma), pinyin is less informative semantically than Chinese characters when they are not presented in linguistic contexts. By using both pinyin and characters as stimuli, we hoped to find consistent evidence of either similar or different neural circuitries for the processing of tones and vowels. Given the differences between pinyin and characters (e.g., clear separation between consonant and vowels for pinyin but not for characters and clear tone symbols for pinyin but not for characters), it is likely that the activation patterns as well as patterns of neural overlap or dissociation may be different for the two tasks. In other words, the pinyin condition allows us to study neural dissociation between tones and vowel at the most simplified level (no consonants and clear tone symbols), whereas the Chinese characters allow us to study the same issue with a natural logographic tonal language.

Based on the adaptation paradigm discussed above, pinyin and character stimuli were presented under two conditions: the tone- and vowel-change conditions. In the tone-change condition, the stimuli had the same vowel with varying tones. In the vowel-change condition, the stimuli had the same tone with varying vowels. No consonant was used in the pinyin-naming task; the consonant was fixed to be the same ("sh") in the character-naming task.

In sum, by improving on the research design (i.e., the use of adaptation paradigm, the inclusion of two tasks of speech production, and the use of direct comparisons), we believe that our study would provide clearer evidence relevant to the debates on the neural dissociation of the processing of segmental and suprasegmental units.

Methods

Participants

Ten participants (mean age 23.6 years, standard error 1.9 years), six male and four female, participated in the experiment. All participants were strongly right-handed as measured by Edinburgh Handedness Inventory (Oldfield, 1971), had normal vision, and did not have diagnosed problems in intelligence, reading ability, and oral language. Before the experiment, participants were also interviewed to ensure that they could speak Putonghua (Mandarin Chinese) with little dialectal accents.

Materials and tasks

The combinations of four vowel letters (a e u i) with four lexical tones yielded 16 different stimuli for the pinyin-naming task. Similarly, the combinations of four syllables (sha she shi shu) with four lexical tones resulted in 16 Chinese characters used in the character-naming task. The same consonant (sh) was

Table 1
Examples of the blocks in the tone-change and vowel-change conditions

Task	Examples of blocks	
	Tone-change condition	Vowel-change condition
Pinyin-naming task	á ǎ à ā á à ǎ á à ā ā à	á é í ú é í á ú é á ú í
Character naming task	沙(sha1) 傻 (sha3) 啥 (sha2) 霎(sha4) 啥 (sha2) 沙(sha1) 傻(sha3) 霎(sha4) 沙(sha1) 啥(sha2) 霎(sha4) 傻(sha3)	沙(sha1) 奢(she1) 失(shi1) 书(shu1) 奢(she1) 书(shu1) 沙(sha1) 失(shi1) 书(shu1) 失(shi1) 奢(she1) 沙(sha1)

Note. ¯ = high level tone; ´ = low rising tone; ˇ = high rising falling tone; ` = high falling tone. We used superscript in the experimental materials instead of "1,2,3,4" because Chinese people use superscript instead of "1,2,3,4" when they learn lexical tones as a child.

used for all character-naming tasks to reduce potential confounding from the consonant. The control task was to view the crosshairs passively.

The same set of stimuli was used in both experimental conditions (i.e., the tone-change and the vowel-change conditions). In the tone-change condition, the stimuli (either pinyin or characters) were grouped by vowels to allow tones to vary within each block, whereas in the vowel-change condition, the stimuli were grouped by tones to allow vowels to vary (see Table 1).

Experimental procedure

There were four fMRI runs for each participant, one for each task-by-condition combination. The order of the runs was counterbalanced across participants. Each run lasted 6 min and 24 s and consisted of 16 blocks (eight experimental blocks and eight control blocks). Scanning sessions alternated between experimental and control blocks. The block lengths ranged from 20 s to 28 s, but the control block immediately following the experimental block was of the same length as its corresponding experimental block. Before each block, 2 s were used for instruction ("Please name the following pinyin/words" for the experimental blocks and "Please look at the cross" for the control blocks). Each stimulus was presented for 1500 ms, followed by a 500-ms blank interval. Participants were given a brief practice session before the experiment for them to be familiarized with the procedure.

Data collection

All images were acquired using a 2 T GE/Elscint Prestige whole-body MRI scanner. Participant's head was secured by a foam rubber to minimize movement. A susceptibility-weighted single shot EPI (echo planar imaging) method with BOLD (blood oxygenation level-dependent) was used. The following scan parameters were used: TR = 2000 ms, TE = 45 ms, flip angle = 90°, FOV = 373 × 210 mm, matrix size = 128 × 72, and slice thickness = 6 mm. Eighteen contiguous axial slices were acquired to cover the whole brain at 192 time points during the total imaging time of 6 min and 24 s. At the end of the functional imaging session, a high-resolution, T1-weighted 3D image was acquired. The following scan parameters were used: TR = 25 ms, TE = 6 ms; flip angle = 28°, FOV = 220 × 220 mm, matrix size = 220 × 220, slice thickness = 2 mm, and number of slices = 89. Behavioral data (reaction time and error rates) were collected 2 weeks after the brain scans.

Imaging data analysis

The fMRI data analysis was performed using SPM99 (Friston et al., 1995). The main steps of image preprocessing included realignment,[1] anatomic-functional image co-registration, spatial normalization, and smoothing. The functional images were realigned to the last functional volume (the one closest to the T1 anatomical scan) in the scanning session. All statistical analyses were conducted on these movement-corrected images. An average functional image was generated, co-registered with structural images, normalized to the MNI stereotaxic template with 2 × 2 × 2 spatial resolution, and then smoothed with Gaussian filter of FWHM = 8 mm.

The General Linear Model was used to estimate the condition effect for individual subjects. Because block lengths varied within a condition, we followed the recommendations in the SPM99 Manual to analyze the smoothed data using event-related design with hrf as reference function. Individual results were acquired by defining four effects of interest for each subject (i.e., the tone-change condition minus baseline, the vowel-change condition minus baseline, the tone-change condition minus the vowel-change condition, and the vowel-change condition minus the tone-change condition). Group-averaged effects were computed with a random-effects model. Effects of interest were calculated for the same four contrasts as for individual results. For the contrasts between the experimental conditions and the baseline, clusters with more than 40 voxels (2 × 2 × 2 mm) activated above the threshold of $P < 0.0001$ (uncorrected) were considered as significant; for the contrasts between the two experimental conditions, clusters with more than 30 voxels (2 × 2 × 2 mm) activated above the threshold of $P < 0.01$ (uncorrected) were considered as significant.

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[1] The realignment step revealed that one of the 10 participants had relative large head motion with maximum displacement during the character-naming task (x = 8 mm; y = 6 mm; z = 4.5 mm; pitch = 2 degree; yaw = 3.5 degree; roll = 5 degree for the tone-change condition and x = 6 mm; y = 8 mm; z = 5.5 mm; pitch = 3 degree; yaw = 5 degree; roll = 4 degree for the vowel-change condition). These data were discarded. This participant showed relatively small head movement during the pinyin-naming task (the maximum displacement x = 1 mm; y = 0.5 mm; z = 1 mm; pitch = 0.2 degree; yaw = 0.5 degree; roll = 0.2 degree), thus data from these sessions were included in analyses. For all the other participants, no individual runs had more than 2 mm maximum displacement from the beginning to the end of the run in any plane. Furthermore, no individual runs had more than 2 degree of maximum displacement from the beginning to the end of the run for pitch, yaw, or roll.

Table 2
Brain activation in the Chinese pinyin-naming task relative to baseline (P < 0.0001, voxel size >40)

Comparison	Brain areas	BA	Coordinates ($x\ y\ z$)	t
Tone-change vs. baseline	(L) Inferior frontal gyrus/insula	44/45/13	−58 8 18	10.04
	(R) Insula/inferior frontal gyrus	13/45/44	38 2 16	9.80
	(R) Posterior cingulate gyrus	31	22 −62 14	9.31
	(L) Parahippocampal gyrus	28	−24 −24 −6	8.71
	(R) Middle frontal gyrus	32/6	2 8 46	8.54
	(L) Superior temporal gyrus	39/22	−42 −50 22	8.24
	(R) Anterior cingulate gyrus	24/32	8 4 32	8.23
	(L) Fusiform gyrus	37/19	−46 −48 −8	7.90
Vowel-change vs. baseline	(L) Insula/inferior frontal gyrus	13/45/44	−44 −24 22	23.39
	(L) Parahippocampal gyrus/fusiform gyrus	28/19/37	26 −20 −7	23.38
	(R) Insula/inferior frontal gyrus	13/45/44	36 −2 20	21.62
	(L) Medial frontal gyrus	9	−32 6 34	15.41
	(R) Anterior Cingulate Gyrus	32/24	6 18 30	14.39
	(R) inferior occipital gyrus	18/19	26 −84 −4	14.21
	(L) Precentral gyrus	4/6	−36 −14 42	12.88
	(R) Precuneus	31	14 −56 34	11.56
	(R) Medial frontal gyrus	6	6 −2 50	11.37

L, left hemisphere; R, right hemisphere; BA, Brodmann's area. Degree of freedom = [1.0 9.0].

ROI analysis

Based on previous findings about brain areas associated with speech production, five ROIs were identified: (1) the inferior frontal gyrus (Price et al., 1996; Salmelin et al., 1996); (2) the precentral gyrus (Levelt et al., 1998; Petersen et al., 1988); (3) the insula (Levelt et al., 1998; Price et al., 1996); (4) the superior temporal gyrus (Price et al., 1996; Salmelin et al., 1996); and (5) the middle temporal gyrus (Price et al., 1996).

ROIs were anatomically defined based on the aal template provided in the MRIcro software (Rorden, n.d.). For each ROI, regional activation volume size in each condition was computed based on the individual activation maps. Laterality was evaluated by calculating an asymmetry index (AI) for each subject under each condition based on the regional activation volume size (AI = voxels (L − R) / voxels (L + R)). The value of AI ranges from −1 to +1, with a negative value indicating right-hemispheric dominance and a positive value indicating left-hemispheric dominance.

Results

Behavioral results

Correct ratio was high (99%) for both the pinyin- and character-naming tasks under both vowel- and tone-change conditions. A two-way repeated measures analysis of variance on reaction times showed a significant main effect of task ($F(1, 9)$ = 6.889, P < 0.05). Participants were faster at naming characters (551 ms for the tone-change condition and 565 ms for the vowel-change condition) than naming pinyin (592 ms and 597 ms, respectively). Neither the main effect of the experimental condition nor its interaction with the task was significant.

Table 3
Brain activation in the Chinese character-naming task relative to baseline (P < 0.0001, voxel size >40)

Comparison	Brain areas	BA	Coordinates ($x\ y\ z$)	t
Tone-change vs. baseline	(R) Inferior frontal lobe/insula	9/13/45	38 6 24	20.37
	(R) Precuneus	7	16 −62 36	16.01
	(R) Middle occipital gyrus	18	26 −82 2	13.24
	(R) Parahippocampal gyrus	27	30 −18 −14	12.39
	(L) Insula/inferior frontal lobe	13/44/45/6	−34 2 14	12.34
	(L) Inferior parietal lobule	40	−44 −56 38	11.43
	(R) Anterior cingulate gyrus	32/24	8 30 20	10.87
	(R) Posterior cingulate	23/29	6 −38 24	10.59
Vowel-change vs. baseline	(L) Medial frontal/inferior frontal gyrus	10/11/46/47	−38 38 12	18.99
	(R) Precentral gyrus/inferior frontal gyrus	6/44/45	38 2 30	15.51
	(L) Caudate tail/parahippocampal gyrus	−/28	−36 −24 −8	12.61
	(R) Middle occipital/inferior occipital gyrus	18/19	26 −84 −6	14.90
	(L) Superior temporal gyrus/inferior parietal lobule	39/40	−38 −50 26	14.24
	(R) Hippocampus/parahippocampal gyrus	−/28	32 −34 0	14.23
	(R) Anterior cingulated gyrus	32/24	10 18 32	11.17
	(L) Precentral gyrus	6/4	−62 4 18	10.56
	(L) fusiform	37	−44 −64 −10	10.24

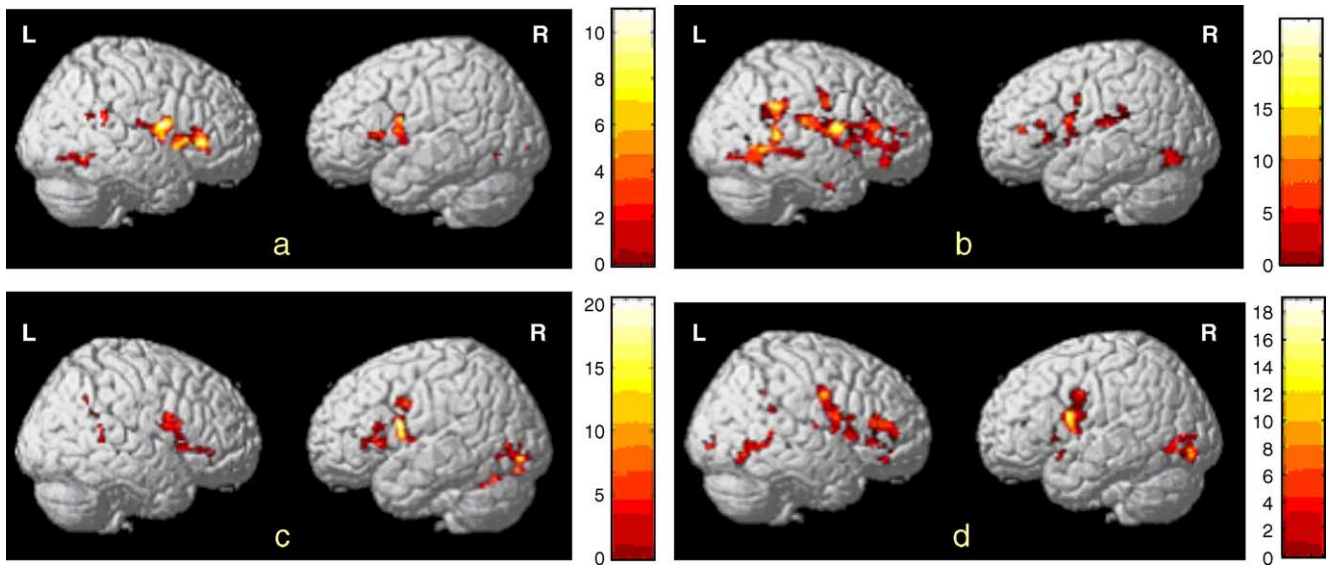L, left hemisphere; R, right hemisphere; BA, Brodmann's area. Degree of freedom = [1.0 8.0].

Fig. 1. Group-averaged *t*-maps (*P* < 0.0001, uncorrected) for tone-change minus baseline in the pinyin-naming task (a), vowel-change minus baseline in the pinyin-naming task (b), tone-change minus baseline in the character-naming task (c), and vowel-change minus baseline in the character-naming task (d).

fMRI results

Comparing the experimental conditions with the baseline, group-averaged results showed activation in a similar neural network for both tasks and under both conditions. The main areas of activation were the bilateral inferior frontal gyrus, insula, precentral gyrus, and some brain areas in the occipital lobe (see Tables 2 and 3 and Fig. 1).

Direct comparisons between the two conditions, however, revealed that, for the pinyin-naming task, the tone-change condition elicited greater activation than the vowel-change condition in the right inferior frontal gyrus, left cingulate gyrus, and right posterior cingulated gyrus, whereas the vowel-change condition elicited greater activation in the left middle frontal gyrus, left middle temporal gyrus, and left cingulate gyrus (see Table 4). For the character-naming task, the tone-change condition elicited greater activation in the right inferior frontal gyrus, left middle temporal gyrus, and left parahippocampal gyrus, but the vowel-change condition elicited greater activation in the left precentral gyrus (see Table 4). Taken together, the tone-change condition induced stronger right inferior frontal gyrus than did the

vowel-change condition during both pinyin- and character-naming tasks (see Fig. 2). In terms of hemispheric differences, the vowel-change condition induced more activation than the tone-change condition mainly in the left hemisphere, whereas the tone-change condition induced more activation in different regions of both hemispheres.

Comparisons between the two tasks showed similar activation patterns (see Fig. 1). Both tasks showed dissociation between tone and vowel processing in the right inferior frontal gyrus and other brain areas. In addition, they showed similar effects of experimental conditions on hemispheric dominance. These results provided converging evidence from different tasks for the neural dissociation between tone and vowel processing. It should be noted, however, that there were some differences between the two tasks as shown in the Fig. 1, probably due to the differences between the two tasks (e.g., characters vs. pinyin, with vs. without consonant).

Hemispheric asymmetry in tone and vowel processing

As mentioned above, direct comparisons between the tone- and vowel-change conditions showed differential hemispheric effects.

Table 4
Brain activation for direct comparisons between the two conditions in both pinyin-naming task and character-naming task (*P* < 0.01, voxel size >30)

Task	Comparison	Brain area	BA	Coordinates (*x y z*)	*t*
Pinyin-naming task	Tone-change vs. vowel-change	(L) Anterior cingulate gyrus	32	−14 28 26	9
		(R) Inferior frontal gyrus	13/45	41 23 8	6.07
		(R) Posterior cingulate gyrus	29	8 −45 7	3.91
	Vowel-change vs. tone-change	(L) Anterior cingulate gyrus	24/32	−12 4 31	6.96
		(L) Middle frontal gryus	10	−46 55 5	5.38
		(L) Middle temporal gyrus	21	−55 −44 6	4.71
Character-naming task	Tone-change vs. vowel-change	(L) Middle temporal gyrus	37	−50 −62 8	6.36
		(R) Inferior frontal gyrus	47	46 26 −2	5.54
		(L) Parahippocampal gyrus	27	−24 −33 −3	4.56
	Vowel-change vs. tone-change	(L) Precentral gyrus	6	−52 −2 30	5.40
		(L) Precentral gyrus	6	−42 0 44	3.75

L, left hemisphere; R, right hemisphere; BA, Brodmann's area. Degree of freedom = [1.0 9.0] for pinyin-naming task and degree of freedom = [1.0 8.0] for character-naming task.
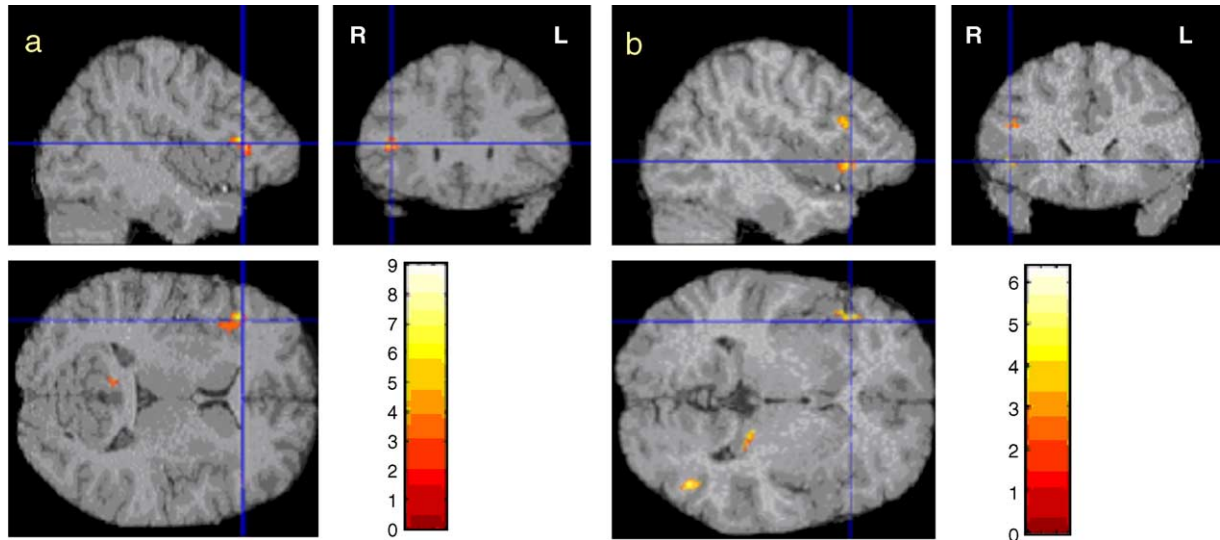
Fig. 2. Activation in the right inferior frontal gyrus ($P < 0.01$). The crosshairs mark the right inferior frontal gyrus. (a) Activation map for tone-change vs. vowel-change in the pinyin-naming task, superimposed over a canonical T1 image (at $x = 43$, $y = 29$, $z = 7$). (b) Activation map for tone-change minus vowel-change in the character-naming task, superimposed over a canonical T1 image (at $x = 44$, $y = 26$, $z = -2$).

To further examine these effects, we calculated brain asymmetry indexes (AIs) in the five regions of interest (ROIs) mentioned above. For the pinyin-naming tasks, the asymmetry indexes (AIs) in the five brain ROIs were 0.60 (the inferior frontal gyrus), 0.68 (the precentral gyrus), 0.33 (the insula), 0.40 (the superior temporal gyrus), and 0.86 (the middle temporal gyrus) for the tone-change condition, and 0.76, 0.66, 0.43, 0.50 and 0.87, respectively, for the vowel-change condition (see Fig. 3a). These results suggest that brain activation induced by both pinyin tones and vowels was left-lateralized. A repeated measures analysis of variance on AIs showed that compared to the vowel-change condition, however, the tone-change condition was less left-lateralized in the following three brain ROIs: inferior frontal gyrus ($F(1,9) = 11.098$, $P < 0.05$), insula ($F(1,9) = 6.579$, $P < 0.05$), and superior temporal gyrus ($F(1,9) = 7.840$, $P < 0.05$). The two conditions did not differ significantly in the other two brain ROIs.

Similar results were obtained for the character-naming task. The asymmetry indexes (AIs) in the five brain ROIs were 0.50 (the inferior frontal gyrus), 0.39 (the precentral gyrus), 0.29 (the insula), 0.60 (the superior temporal gyrus), and 0.89 (the middle temporal gyrus) for the tone-change condition and 0.76, 0.49, 0.39, 0.69, and 0.91, respectively, for the vowel-change condition (see

Fig. 3b). Although left dominance was obvious for all regions under both conditions, a repeated measures analysis of variance on AIs showed that compared to the vowel-change condition, the tone-change condition was significantly less left lateralized in four of the five ROIs: the inferior frontal gyrus ($F(1,8) = 5.563$, $P < 0.05$), the precentral gyrus ($F(1,8) = 5.788$, $P < 0.05$), the insula ($F(1,8) = 8.675$, $P < 0.05$), and the superior temporal gyrus ($F(1,8) = 12.356$, $P < 0.05$).

Discussion

Neuropsychologists have been interested in determining whether the processing of the segmental and suprasegmental units relies on the same neural circuitry. Using functional MRI technique, our study compared the neural mechanisms for Chinese tone (suprasegmental) production with those for Chinese vowel (segmental) production. We found that, at the gross level, tone and vowel production induced similar brain activation patterns across two different tasks. These results were generally in accordance with previous neuroimaging studies (Gandour et al., 2000; Hsieh et al., 2001) and a brain lesion study (Packard, 1986). Direct
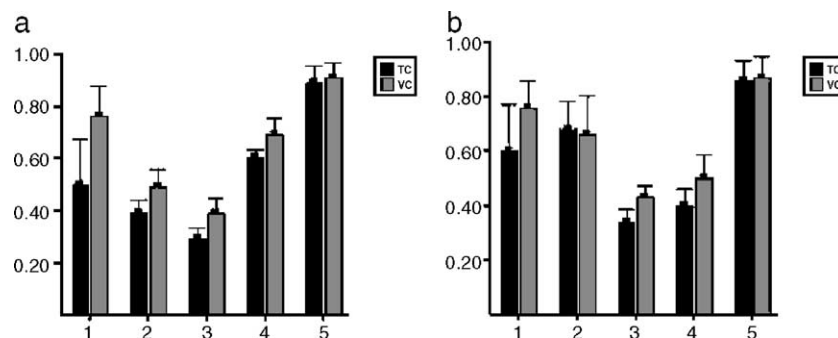

Fig. 3. Asymmetry indexes for the selected brain regions (ROIs) in the pinyin-naming task (a), and character-naming task (b). Areas are (1) the inferior frontal gyrus; (2) the precentral gyrus; (3) the insula; (4) the superior temporal gyrus; and (5) the middle temporal gyrus. Note: TC = Tone-change condition, VC = Vowel-change condition.

comparisons, however, showed significant differences between tone and vowel production in activation level. These results seem to support the notion of dissociation between tone and vowel processing based on several brain lesion studies (Cappa et al., 1997; Laganaro et al., 2002; Law and Or, 2001).

Further support for the relative neural dissociation between tone and vowel processing came from analyses of brain asymmetry. Tone production was less left-lateralized than vowel production. In fact, the tone-change condition induced stronger right inferior frontal gyrus than the vowel-change condition for both pinyin- and character-naming tasks (see Fig. 2). To our knowledge, our study is the first to document differences in hemispheric asymmetry between tone and vowel processing using neuroimaging method. All other studies (Booth et al., 2002; Lurito et al., 2000; Poldrack et al., 2001; Pugh et al., 1996a,b) showed left lateralization for both tone and vowel processing, but did not directly test their differences.

Our results of brain asymmetry analysis support Gandour et al.'s (2004) perspective. According to Gandour et al. (2004), hemispheric lateralization for speech prosody processing is based on both the high-level linguistic representations and the low-level encoding of acoustic cues. They thought that speech prosody perception is mediated primarily by the right hemisphere, but is left-lateralized (to task-dependent regions) when the task goes beyond the auditory analysis of the complex sound into the realm of language processing. According to this point of view, brain activation for tone and vowel production should be left-lateralized because such production involves language processing.

Why is then the brain activation for tone production less left-lateralized than that for vowel production? One explanation lies in the acoustic differences between tone and vowel. Tones are the modulation of fundamental frequency (F0). Stimuli based on fundamental frequency (F0) have generally been found to show right-hemisphere lateralization (e.g., Blumstein and Cooper, 1974, for intonation contours; Goodglass and Calderon, 1977, for musical notes; Mazzucchi et al., 1981, for synthesized tones). For example, prefrontal cortex in the right hemisphere has been linked to pitch judgment tasks (Zatorre et al., 1992) and music processing (Pugh et al., 1996a,b). Consequently, the right hemisphere, especially the right inferior frontal gyrus, can play a significant role in tone production. This conclusion is consistent with a training study by Wang et al. (2003). In their study to train Americans to learn Chinese lexical tones, Wang et al. found that the right inferior frontal gyrus was not activated before training but was activated after training.

In addition to the right inferior frontal gyrus, there were other areas with dissociation between tone and vowel production. In the pinyin-naming task, the left anterior cingulate gyrus and posterior cingulate gyrus were activated more in the tone-change condition than in the vowel-change condition (see Table 4). Activation of the anterior cingulate may be due to its role in the attention system (Posner and Petersen, 1990). However, our behavioral data did not show a significant difference between the two conditions. What's more, participants reported that tone-change condition was less difficult than vowel-change condition. There is no reason that tone-change condition needs more attention than vowel-change condition. An alternative explanation is that the activation of anterior cingulate gyrus may be attributed to the participants' preparation, planning, and anticipation of the cognitive task rather than task-related processing itself (Murtha et al., 1996). Further evidence is needed to support this point of view. The posterior cingulate gyrus

has generally been found to be related to verbal and auditory memory (Valenstein et al., 1987; Rudge and Warrington, 1991), whose role in the tasks of the current study is not clear.

Compared to the tone-change condition, the vowel-change condition elicited greater activation in the left middle frontal gyrus, left middle temporal gyrus, and left anterior cingulate gyrus for the pinyin-naming task (see Table 4). The left middle frontal gyrus has been found to be activated always together with left inferior frontal gyrus in language production studies (Petersen et al., 1988; Price et al., 1994). Both are deemed to play a role in phonological encoding (Indefrey and Levelt, 2000; Levelt and Indefrey, 2001). It appears that the left middle frontal gyrus and the left middle temporal gyrus play an especially important role in vowel production. The activation of the anterior cingulate is likely due to its role in the attention system (Posner and Petersen, 1990), because the vowel-change condition was more demanding than the tone-change condition according to participants' report.

In the character-naming task, the left middle temporal gyrus and left hippocampal gyrus were activated more in the tone-change condition than in the vowel-change condition (see Table 4). The left middle temporal gyrus (BA37) is believed to be important for word-level comprehension, especially as the ties between the concepts and corresponding lexical representations (Dronkers et al., 2004). Like posterior cingulated gyrus discussed above, for the pinyin-naming task, the hippocampal gyrus is also related to verbal and auditory memory (Milner, 1974). This consistent finding of greater activation of areas (but different areas for the pinyin and character) for verbal/auditory memory requires further research.

Compared to the tone-change condition, the vowel-change condition elicited greater activation in the left precentral gyrus, an area related to speech articulation. This is probably due to the fact that vowel change requires more coordination of mouth, larynx, and tongue than does tone change.

Our findings of neural dissociation between Chinese tone and vowel processing in particular brain areas provided additional evidence for the psycholinguistic phonological encoding models based on European languages (Dell, 1988; Levelt, 1992; Levelt et al., 1999). As is the case for European languages, suprasegment and segment in Chinese may be represented relatively independently. Such dissociation has been extended to other language components. For example, Siok et al. (2003) found that Chinese syllables and phonemes are represented in distinct brain areas. They found that left middle frontal cortex contributes to syllabic processing, whereas the left inferior prefrontal gyrus contributes to sub-syllabic phonemic processing and phonological segmentation. Gandour et al. (2003), however, found that the patterns of activation in left prefrontal cortex vary depending on sub-syllabic segmental (consonants and rhymes) and suprasegmental (tones) units. Rhymes extraction induces greater activation in the left posterior MFG when compared to consonants and tones, no matter phonological segmentation is needed or not.

It should be pointed out that, although both pinyin- and character-naming tasks yielded converging evidence of neural dissociation between vowel and tone processing, the specific regions of dissociations varied between the two tasks. One possible explanation lies in the different linguistic contexts provided by pinyin and characters. For example, pinyin has clear separation between consonants and vowels (in fact, only vowels were used in the present study) and clear tone symbols, whereas Chinese characters have neither. Future research is needed to examine the interaction between linguistic contexts and neural dissociation between segmental and suprasegmental processing.

Conclusion

In summary, this study found that, although tone and vowel production activated similar brain regions such as the bilateral inferior frontal gyrus, insula, and precentral gyrus, neural dissociation was found for the two conditions, especially in the right inferior frontal gyrus. The right inferior frontal gyrus was found to play an important role in tone production.

Acknowledgment

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