Title: *Brain mapping of Chinese speech prosody*

Short Title: *Chinese prosody*

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Color figures = 5; Tables = 5

Introduction

Speech prosody refers to melodic or suprasegmental features of an utterance (e.g., pitch) that may signal a variety of linguistic and paralinguistic functions (Lehiste, 1996). Over the last quarter century, increasing attention has been focused on the roles of the left (LH) and right (RH) cerebral hemispheres in the processing of prosodic information. Evidence has been steadily accumulating in the dichotic listening (Shipley-Brown, Dingwall, Berlin, Yeni-Komshian, & Gordon-Salant, 1988), lesion deficit (Baum & Pell, 1999) and brain imaging (Meyer, Alter, & Friederici, 2003; Plante, Creusere, & Sabin, 2002) literature implicating the RH in the perception of prosodic units assigned to phrase- and sentence-level structures. Dichotic listening (Wang, Jongman, & Sereno, 2001) and lesion deficit (Gandour, 1998a, 1998b; Wong, 2002) data from *tone languages* point to LH and RH lateralization, respectively, for tonal and affective information. This article presents an overview of research findings from positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) studies on the perception of Chinese speech prosody (see Buckner & Logan, 2001; Rugg, 1999, for tutorials on haemodynamic methods of brain imaging).

Background and significance

The underlying basis for hemispheric asymmetry of speech perception is controversial (see Ivry & Robertson, 1998; Poeppel, 2003; Zatorre & Belin, 2001; Zatorre, Belin, & Penhune, 2002, for recent reviews). One view is that the LH is specialized for speech as opposed to other complex auditory signals. A contrary view is that speech is processed in either the LH or RH depending on the particular spectral and/or temporal nature of the acoustic cue(s). A compromise view is that hemispheric specialization reflects an interaction between higher-order language functions and lower-level acoustic cues. One auditory cue of relevance to speech prosody is pitch. It is well established that pitch of non-speech signals is mediated by the RH. It is also well known that variations in pitch may signal phonological contrasts at both the syllable (tone) and sentence (intonation) levels of representation. The question arises then as to which hemisphere mediates pitch processing in a speech context.

Mandarin Chinese employs pitch variations at the syllable level to contrast four lexical tones: e.g., ma^1 'mother', ma^2 'hemp', ma^3 'horse', ma^4 'scold' (Howie, 1976), plus variations in pitch at the sentence level to contrast an unmarked question intonation with its corresponding statement (Shen, 1990). It is well-known that prosodic features may be assigned to different hierarchical levels of representation or prosodic frames. It is also true that the temporal domain usually covaries with the prosodic frame. Syllable-based tones are manifested on a time scale of 200-350 ms, whereas sentence-based intonation patterns are realized typically on a time scale of seconds. Comparisons of syllable-level to sentence-level prosody permit us to evaluate the interaction of linguistic and temporal factors in prosody processing. Chinese syllables consist of three sub-syllabic units: onsets, rhymes, and tones. Onsets and rhymes are segmental; tones are suprasegmental. Comparisons of tones to consonants and rhymes may lead to the identification of a specialized neural circuitry for sub-syllabic suprasegmental units.

Our experimental approach involves crucially the use of tone and non-tone languages, speech and non-speech stimuli, and hierarchical levels of linguistic units.

The cross-linguistic design enables us to tease apart language-specific effects on brain processing. If brain activity is due primarily to functional properties of the stimulus, we expect brain activity of native and non-native speakers to vary depending on language-specific functions of acoustic cues in their respective languages. By using non-speech homologues to natural speech stimuli, we remove segmental and semantic information from the auditory signal. What remains is suprasegmental information divorced of verbal content. Such stimuli are useful for determining whether or not prosodic processing is speech-specific, in addition to providing a window into prelexical stages of processing.

PET/fMRI results

Tone. We first investigated the influence of language experience on the perception of segmental (consonants (C), rhymes (R)) and suprasegmental (tones (T)) information in Chinese (Hsieh, Gandour, Wong, & Hutchins, 2001; cf. Klein, Zatorre, Milner, & Zhao, 2001). Subjects judged C, R, and T in Chinese monosyllables [speech] or low-pass filtered versions of the same stimuli [non-speech] (Table 1). Comparisons of language group maps of speech and non-speech (pitch (P)) tasks relative to passive listening show that left inferior frontal gyrus (IFG) regions are activated for Chinese listeners across tasks; right IFG areas for English listeners on the P task (Figure 1).

Chinese listeners are able to extract tonal information associated with the Chinese tones via left IFG regions in both speech and non-speech stimuli. Conversely, English listeners exhibit activation in right IFG areas. Pitch processing is lateralized to the LH only when the pitch patterns are phonologically significant to the listener; otherwise, to the RH. These findings suggest that LH mechanisms mediate processing of linguistic information irrespective of acoustic cues or type of phonological unit (i.e., segmental or suprasegmental).

[Insert Table 1 and Figure 1 about here]

Whether a particular auditory/acoustic cue serves a phonological function in a listener's native language dictates laterality. No activation occurs in left frontal regions for English listeners on either the T or P task because they were judging auditory features of Chinese tones that are not phonologically significant in the English language. Similarly, when judging Thai tones, Chinese listeners fail to show activation of LH regions (Gandour et al., 2000; Gandour et al., 2002).

The optimal test for phonetic extraction requires that *non-minimal* pairs be compared directly to *minimal* pairs (see Burton, 2001, for review; Burton, Small, & Blumstein, 2000). Paired speech stimuli that are distinguished by two or more differences in their phonemic composition may constitute a non-minimal pair for tone (e.g., *shao*^{2} vs. *fang*^{4}). Subjects must separate the tone from the whole syllable in order to make a same-different judgment. Minimal pairs are distinguished by only a difference in tone (e.g., *shao*^{2} vs. *shao*^{4}).

We compared the extraction of Chinese C, R, and T in minimal vs. non-minimal pairs (Gandour et al., under review). Subjects were asked to selectively attend to targeted sub-syllabic components and make same-different judgments (Table 2). Direct between-group comparisons in both minimal and non-minimal pairs reveal increased activation for the Chinese group in predominantly left-sided frontal, parietal, and temporal regions. Within-group comparisons of non-minimal and minimal pairs show that frontal and parietal activity varies for each sub-syllabic component. The Chinese group shows bilateral activation of the anterior MFG for $R_{non\text{-}minimal}$ minus $R_{minimal}$ and $T_{non\text{-}minimal}$ minus $T_{minimal}$ only (Figure 2). In temporal order, consonants occur before rhymes or tones, whereas rhymes and tones occur concurrently. Perhaps, more attentional resources are recruited in non-minimal pairs to extract phonetic information from units (R, T) that occur simultaneously than for units that are presented sequentially (C).

[Insert Table 2 and Figure 2 about here]

Bilateral posterior IFG activity is seen in $T_{non\text{-}minimal}$ minus $T_{minimal}$. This unique effect for tonal processing is likely due to an increase in subvocal rehearsal due to late arrival of tonal information (Cutler & Chen, 1997). Rhymes induce greater activation in the left posterior MFG for the Chinese group when compared to C and T in non-minimal pairs. Rhymes appear to be pivotal for integrating tonal information with the Mandarin syllable (Ye & Connine, 1999).

The activation of this network in processing non-minimal pairs shows that phonetic segmentation varies as a function of the sub-syllabic unit (C, R, T) in relation to both task demands (e.g., attention, memory) and syllable structure. The fact that the rhyme elicits greater activation in the left posterior MFG than either C or T indicates that not all phonological units are treated alike with respect to phonetic segmentation.

In an attempt to fractionate mediational components that may be involved in phonetic extraction, we compared tonal matching to a control condition in which whole syllables are matched to one another (Li et al., submitted). A list of three Chinese monosyllables followed by a monosyllabic *probe* made up a sequence for each trial. Subjects were asked to ignore the first two items in the syllable list and make a matching judgment on the last item in comparison to the probe according to the task - tone or syllable (Table 3). The only difference between conditions is the focus of attention, either to a subpart of the syllable or to the whole syllable itself. A peak focus of activation in the left inferior frontal sulcus near its junction with the inferior precentral sulcus is observed when subjects are required to compare lexical tones while ignoring other phonetic components of a syllable (Figure 3). Activity in this region has been reported in studies of segmental phonemes (Burton, 2001) and attentional (Shaywitz et al., 2001) processing. It may reflect selective attention to internal attributes of target items during encoding, though this region is also activated when subjects are asked to focus on syllables that occur in specific serial positions in a list (Gelfand & Bookheimer, 2003). The left SPL activity may reflect voluntary orienting attention (cf. Brass & von Cramon, 2002, visual modality). The pre-SMA is activated when subjects are required to guide their sequence of processes by pre-cued instruction (Crosson et al., 2001).

[Insert Table 3 and Figure 3 about here]

No significant brain activity is observed in ventral aspects of the IFG or the inferior parietal lobule (IPL). The former has been implicated in articulatory rehearsal, the latter in phonological storage (Jonides et al., 1998). This finding is expected because our tone- and syllable-matching tasks were designed to impose similar demands on rehearsal and storage. Phonetic extraction of sub-syllabic lexical tones involves an attention-modulated, executive function that is differentially sensitive to internal dimensions of a whole stimulus.

Intonation. A key question is whether the observed laterality effects in tone perception are due to level of linguistic structure or size of temporal domain or both.

Chinese tones are manifested at the syllable level, intonation at the sentence level. This opposition between syllable-based and sentence-based prosody maximizes the difference in time scales for linguistically-relevant pitch processing. We hypothesized that Chinese listeners would be predominantly right lateralized in their perception of intonation because of the longer temporal integration windows.

Indeed, prosodic functions at the syllable level (*local*) engage LH mechanisms predominantly; prosodic functions at the sentence level (*global*) additionally recruit RH mechanisms (Gandour et al., 2003). When asked to compare lexical tones in paired sentences (Table 4), Chinese listeners show frontoparietal activation in the LH (Figure 4), whereas bilateral frontoparietal activity is observed when they are asked to compare intonation in the same sentences. In a direct comparison of tone and intonation, the latter is found to engage only RH mechanisms in frontotemporal regions. These results suggest that temporal integration windows at post-perceptual stages of processing may be defined relative to the hierarchical level of the prosodic unit.

However, the target prosodic unit that listeners selectively attended to and the temporal domain of selective attention were coterminous. Both tone and intonation were presented in sentences consisting of 3 syllables. In the case of tone, only the sentence-final syllable was the target of attention. In the case of intonation, all three syllables comprised the target. This potential confound leaves open the possibility that the temporal domain of selective attention, instead of the hierarchical level of the prosodic frame, is the principal driving force in hemispheric lateralization of speech prosody.

Differential patterns of brain activity are language-dependent. Chinese listeners show activation confined to LH regions when processing lexical tone, but activation extending bilaterally when processing intonation. In contrast, English listeners show bilateral activation when processing tone, predominantly right-sided activation when processing intonation.

[Insert Table 4 and Figure 4 about here]

Emotion. Because of similarities in their acoustic profiles, intonation and emotion permit us to assess the extent to which hemispheric lateralization of speech prosody depends on functional instead of acoustical properties. Subjects were asked to perform discrimination judgments of intonation (I: statement, question) and emotion (E: happy, angry, sad) presented in semantically-neutral Chinese sentences (Table 5). When comparing intonation relative to emotion (I vs. E), the Chinese group demonstrated prefrontal activation bilaterally; parietal activation in the LH only (Figure 5). The reverse comparison (E vs. I), on the other hand, revealed that activation occurred in anterior and posterior prefrontal regions of the RH only. These findings show that some aspects of perceptual processing of emotion are dissociable from intonation, and moreover, that they are mediated by the RH.

[Insert Table 5 and Figure 5 about here]

Conclusions

In summary, we may conclude that: functionally relevant properties of complex auditory stimuli are critical in determining hemispheric lateralization of speech prosody; linguistic information signaled by prosodic cues is lateralized differentially to either the LH and/or RH as a function of the level of the prosodic unit; phonetic extraction of prosodic information recruits a widely distributed network in frontal, temporal, and parietal regions of the LH; selective attention to syllable-internal suprasegmental information is mediated by a subregion in left posterior dorsal prefrontal cortex in tandem with the SPL; and the RH plays a crucial role in assessing the emotional significance of prosodic cues.

Directions for future research

Many questions remain to be answered in this rapidly growing subfield of cognitive neuroscience. Studies are likely to be directed to isolating the neural substrates of mediational components. Other aspects of Chinese speech prosody (e.g., sentence-level focus) invite comparisons to the mapping of comparable phenomena in non-tone languages. Chinese is optimal for studying the interaction of segmental and suprasegmental features and their neural correlates in speech perception. It also provides a window for investigating whether lateralization of prosody is driven by the hierarchical level of the prosodic unit or the size of the temporal domain. Developmental questions will lead to studies of how speech prosody processing varies in bilingual brains as a function of age of acquisition and level of proficiency (cf. Sereno et al., this volume).

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Table 1 PET paradigm

Condition	Stimulus	Example	Response
Consonant	Chinese monosyllables[b]	mu^4 ti^3 she^2 liu^1 ma^4	same
		ni^3 ke^4 bao^3 fo^2 di^3	different
		gou^1 bi^4 xiu^1 shou^3 gou^4	same
Vowel	Chinese monosyllables[b]	mu^4 ti^3 she^2 liu^1 ma^4	different
		ni^3 ke^4 bao^3 fo^2 di^3	same
		gou^1 bi^4 xiu^1 shou^3 gou^4	same
Tone	Chinese monosyllables[b]	mu^4 ti^3 she^2 liu^1 ma^4	same
		ni^3 ke^4 bao^3 fo^2 di^3	same
		gou^1 bi^4 xiu^1 shou^3 gou^4	different
Pitch	Filtered monosyllables[a]	---^{4} ---^{3} ---^{2} ---^{1} ---^{4}	same
		---^{3} ---^{4} ---^{3} ---^{2} ---^{3}	same
		---^{1} ---^{4} ---^{1} ---^{3} ---^{4}	different

Note. Chinese monosyllables are presented in *pinyin* orthography ([1] = tone 1, [2] = tone 2, [3] = tone 3, [4] = tone 4). Correct responses are shown in parentheses (L = left mouse button; R = right mouse button). [a] = nonspeech condition; [b] = speech condition

Table 2 Sample minimal and non-minimal pair triplets

	Minimal Pair	Response	Non-minimal Pair	Response
Consonant	**ch**ai^4 heng^2 **ch**ai^4	same	**ch**ai^4 heng^2 **ch**a^1	same
	mang^1 you^2 **f**ang^1	different	**m**ang^1 you^2 **r**en^4	different
Rhyme	b**o**^{2} liu^4 b**o**^{2}	same	b**o**^{2} liu^4 p**o**^{3}	same
	r**ong**^{2} lei^4 r**eng**^{2}	different	r**ong**^{2} lei^4 d**eng**^{3}	different
Tone	huo^2 pian^4 huo^2	same	huo^2 pian^4 ke^2	same
	shao^2 dong^1 shao^4	different	shao^2 dong^1 fang^4	different

Note: Bold = target, subsyllabic unit.

Table 3 Sample auditory stimuli for tone and syllable matching.

Phonetic Unit	Syllable List			Probe	Match
Tone	rou^2	bei^3	$duo^{\mathbf{4}}$	$na^{\mathbf{4}}$	yes
	bo^2	ka^3	$tu^{\mathbf{1}}$	$meng^{\mathbf{4}}$	no
Syllable	rou^2	bei^3	$\mathbf{duo^4}$	$\mathbf{na^4}$	no
	bo^2	ka^3	$\mathbf{tu^1}$	$\mathbf{tu^1}$	yes

Note. Chinese syllables are written in *pinyin* transcription.

Target phonetic units are in bold type. Tones are indicated in superscript.

Table 4 fMRI paradigm

Condition	Stimuli	Example		Response
All Pitch	Hums	□^{4} □^{4} □^{4}.	□^{4} □^{4} □^{4}?	different
		□^{2} □^{4} □^{2}?	□^{2} □^{4} □^{2}?	same
		□^{1} □^{2} □^{4}?	□^{1} □^{2} □^{4}.	different
		□^{3} □^{2} □^{4}.	□^{3} □^{2} □^{4}.	same
Final Pitch	Chinese	nuo^4 la^4 bu^4.	nuo^4 la^4 bu^4?	same
(Tone)		pao^2 nu^4 lai^2?	pao^2 nu^4 lai^1?	different
		cao^1 li^2 zai^4?	cao^1 li^2 zai^4.	same
		ta^3 pei^2 gai^4.	ta^3 pei^2 gai^2.	different
All Pitch	Chinese	nuo^4 la^4 bu^4.	nuo^4 la^4 bu^4?	different
(Intonation)		pao^2 nu^4 lai^2?	pao^2 nu^4 lai^1?	same
		cao^1 li^2 zai^4?	cao^1 li^2 zai^4.	different
		ta^3 pei^2 gai^4.	ta^3 pei^2 gai^2.	same

Table 5 fMRI paradigm for Chinese speech discrimination

Conditions	Sentence pairs within trials				English gloss	Response
Intonation	ta^1 zai^4 jia^1	(A/S)	ta^1 zai^4 jia^1	(A/Q)	He’s at home	Different
	ta^1 lai^2 wan^2	(A/S)	ta^1 lai^2 wan^2	(H/S)	He’s visiting	Same
	xia^4 yu^3 le	(H/Q)	xia^4 yu^3 le	(H/S)	It’s raining	Different
Emotion	ta^1 zai^4 jia^1	(A/S)	ta^1 zai^4 jia^1	(A/Q)	He’s at home	Same
	ta^1 lai^2 wan^2	(A/S)	ta^1 lai^2 wan^2	(H/S)	He’s visiting	Different
	xia^4 yu^3 le	(H/Q)	xia^4 yu^3 le	(H/S)	It’s raining	Same

Note. (Emotion / Intonation): A = angry; H = happy; S = sad / S = statement; Q = question.

Figure Captions

Figure 1. Averaged PET activation maps of Chinese (left) and English (right) groups for the tone (top panel) and pitch (bottom panel) tasks superimposed on Talairach-transformed anatomic images. T = tone; P = pitch. Stereotaxic coordinates are in mm (Talairach & Tournoux, 1988). F3o = inferior frontal gyrus/pars opercularis; PRG = precentral gyrus/premotor cortex; F3t = inferior frontal gyrus/pars triangularis; FO = frontal operculum; INS = insula; FP = frontal pole. Activation foci are observed in the left inferior frontal gyrus of Chinese subjects in both the tone and pitch tasks relative to passive listening. In the pitch task, activation patterns in the left and right frontal lobes are complementary between language groups. [Adapted from *Brain and Language*, **76**, p. 238, 2001, with permission from Elsevier]

Figure 2. Averaged fMRI activation maps obtained from comparison of $\text{tone}_{\text{non-minimal}}$ vs. $\text{tone}_{\text{minimal}}$ discrimination judgments within the Chinese (top panel) and English (bottom panel) language groups. L = left; R = right; IFG = inferior frontal gyrus; MFG = middle frontal gyrus; IPL = inferior parietal lobule. Both panels show activation foci in anterior and posterior regions of the frontal lobe. However, the posterior foci are centered in the inferior frontal gyrus in the Chinese group, the middle frontal gyrus in the English group. The top and bottom panels, respectively, show predominantly left-sided and bilateral activation in the parietal lobe.

Figure 3. Averaged fMRI activation map obtained from a direct comparison of tone vs. syllable discrimination judgments for a group of 12 native speakers of Chinese. IFS = inferior frontal sulcus; SMA = supplementary motor area;

SPL = superior parietal lobule. This horizontal section shows brain activity in dorsal aspects of the frontal and parietal lobes in the LH.

Figure 4. Averaged fMRI activation maps for the Chinese and English language groups obtained by comparing discrimination judgments of Chinese intonation and tone (I vs. T). I = intonation; T = tone; STG = superior temporal gyrus; STS = superior temporal sulcus. A series of sagittal sections for the right hemisphere shows a frontal and temporal activation in the Chinese group only. [Adapted from *Brain and Language*, **84**, p. 331, 2003, with permission from Elsevier]

Figure 5. Averaged fMRI activation maps obtained from direct comparison of intonation (top panel) and emotion (bottom panel) judgments relative to each other between the two language groups (Chinese minus English). I = intonation; E = emotion. The top panel shows activation foci bilaterally in frontal regions and in the left inferior parietal lobule. In contrast, the bottom panel shows activation in right frontal areas only. [Adapted from *Human Brain Mapping*, **18(3)**, p. 155, 2003, with permission from Wiley-Liss]

Figure 1

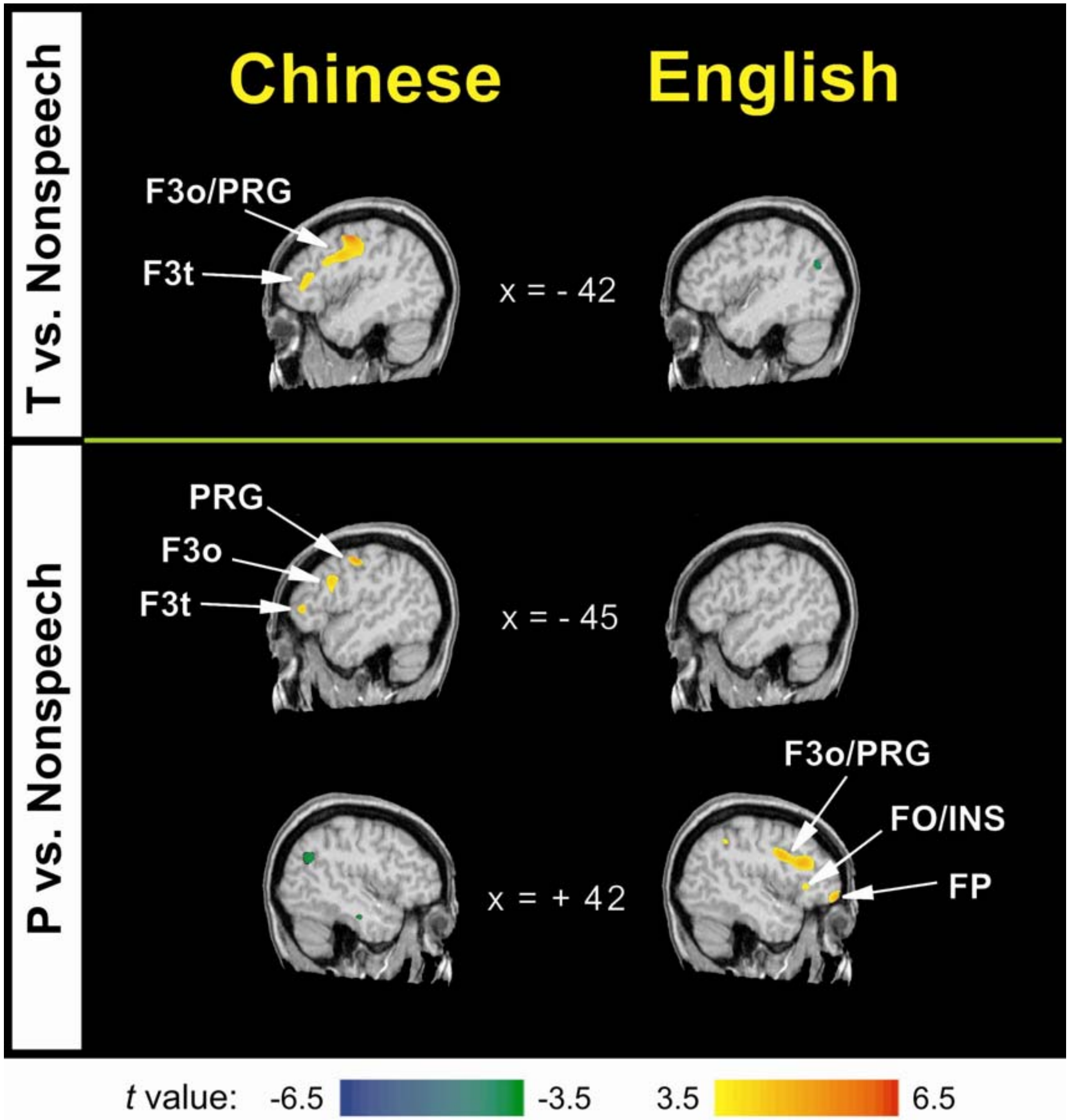
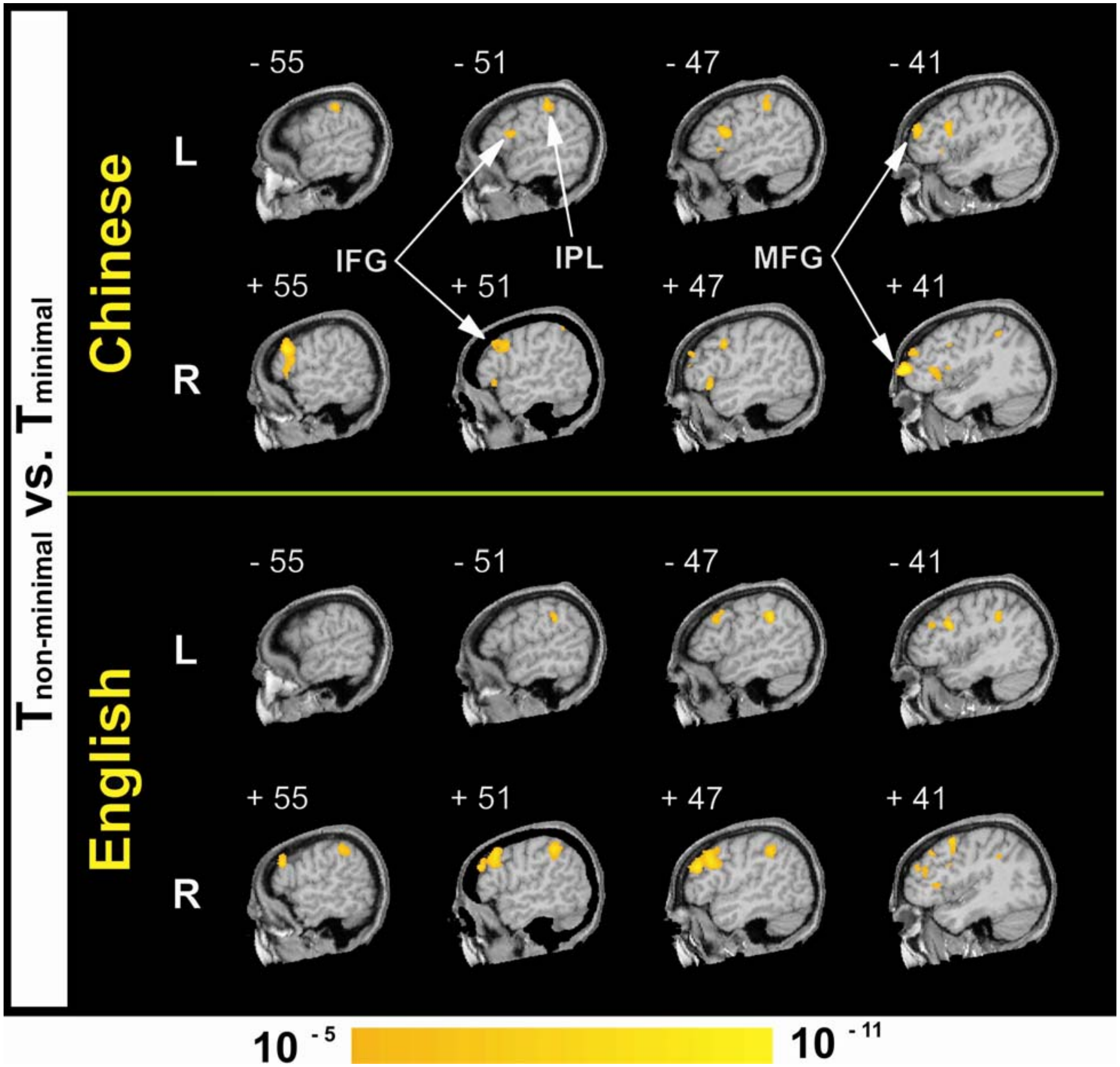

Chinese
English
T vs. Nonspeech
F3o/PRG
F3t
x = - 42
P vs. Nonspeech
PRG
F3o
F3t
x = - 45
F3o/PRG
FO/INS
FP
x = + 42
t value: -6.5 -3.5 3.5 6.5

Figure 2



T non-minimal vs. T minimal
Chinese
English
L
R
L
R
- 55
- 51
- 47
- 41
+ 55
+ 51
+ 47
+ 41
IFG
IPL
MFG
- 55
- 51
- 47
- 41
+ 55
+ 51
+ 47
+ 41
10 -5
10 -11

Figure 3

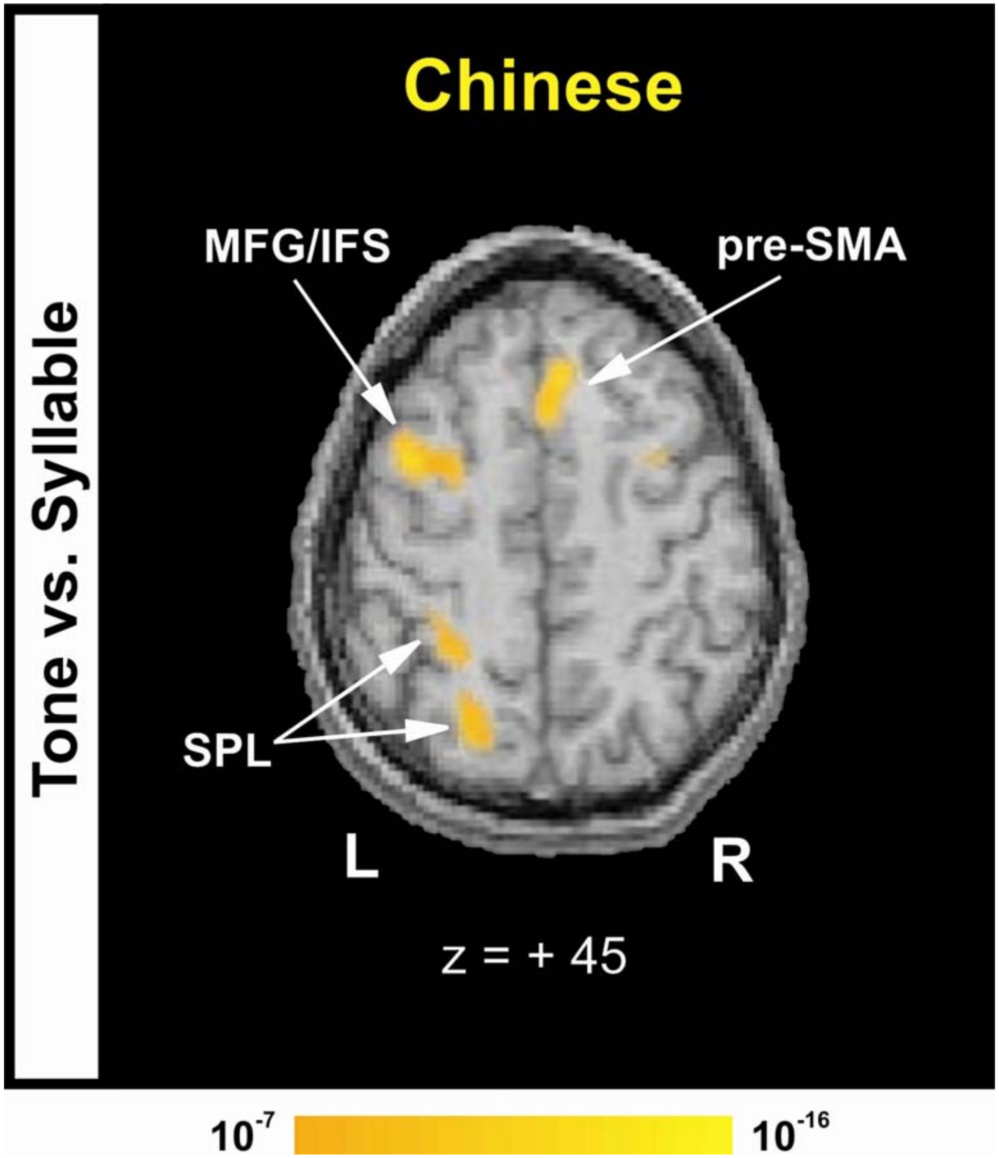


Figure 4

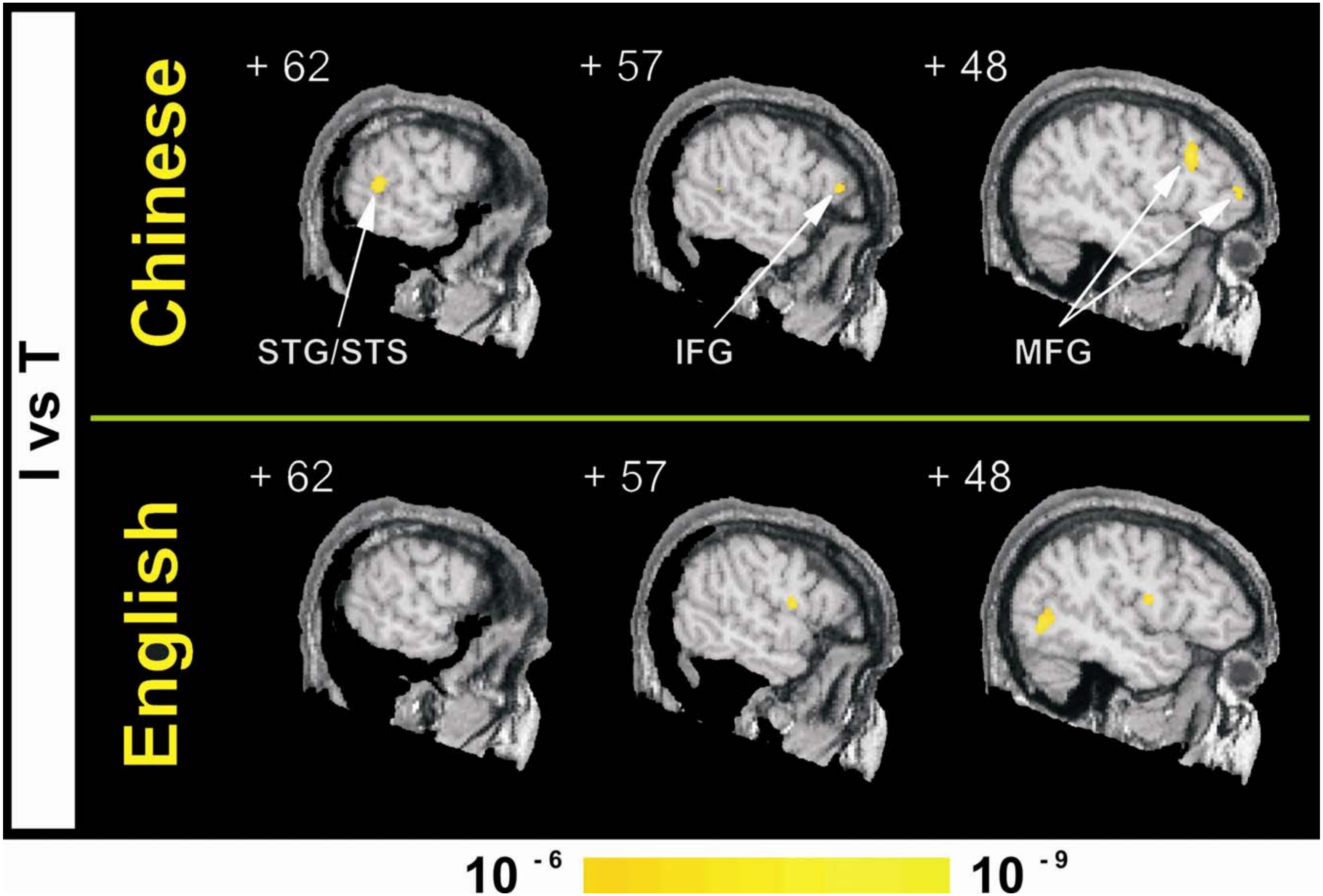
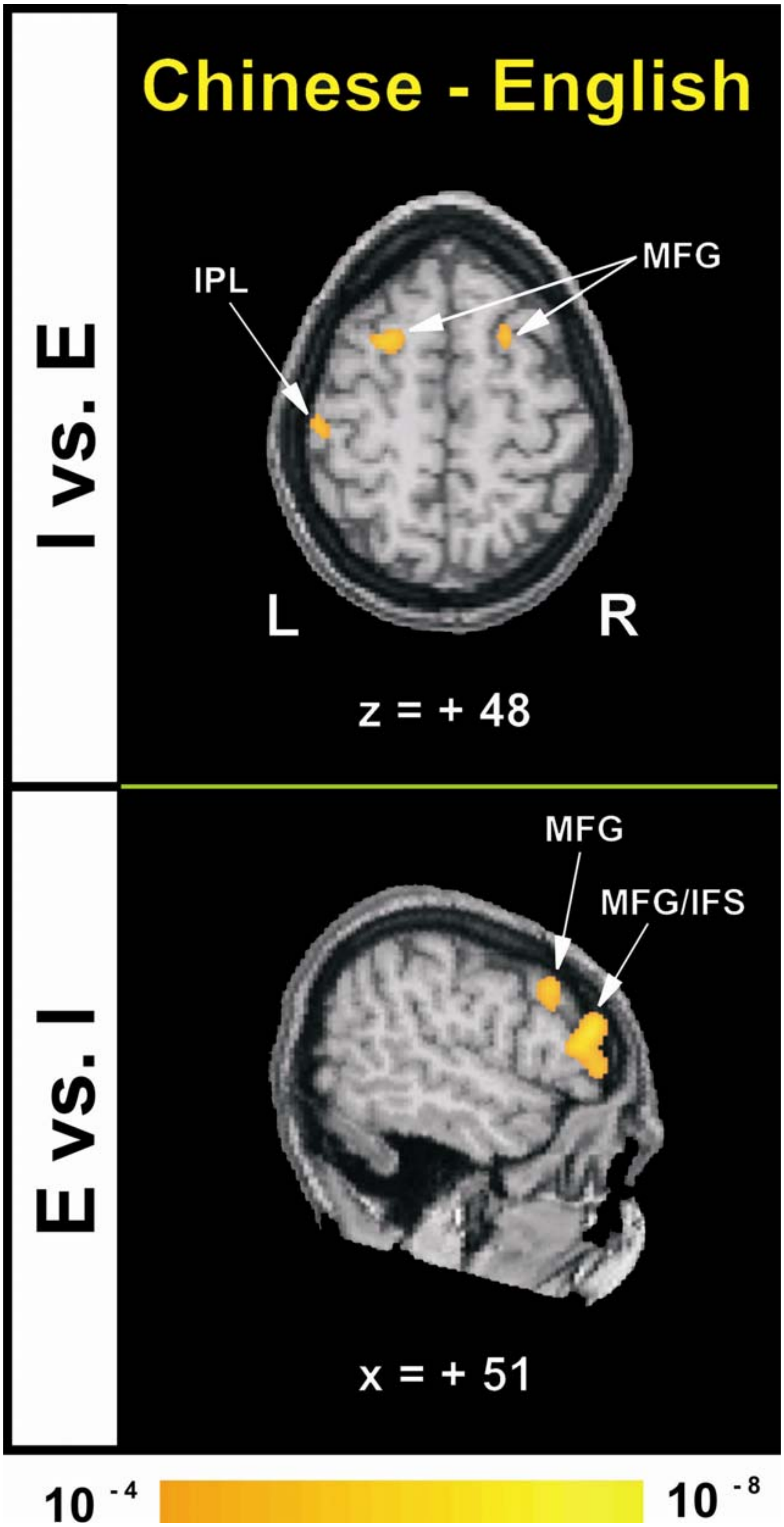


Figure 5



Chinese - English
I vs. E
IPL
MFG
L
R
z = + 48
E vs. I
MFG
MFG/IFS
x = + 51
10 -4
10 -8