NeuroImage **13,** 646–653 (2001)
doi:10.1006/nimg.2000.0738, available online at http://www.idealibrary.com on IDEAL®

A Cross-Linguistic PET Study of Tone Perception in Mandarin Chinese and English Speakers

Denise Klein, Robert J. Zatorre, Brenda Milner, and Viviane Zhao

Cognitive Neuroscience Unit, Montreal Neurological Institute, McGill University,
3801 University Street, Montreal, H3A 2B4, Quebec, Canada

Received October 4, 2000

PET was used in a cross-linguistic study to determine whether neural mechanisms subserving pitch perception differ as a function of linguistic relevance. We compared tone perception in 12 native Mandarin speakers, who use tonal patterns to distinguish lexical meaning, with that of 12 native speakers of a nontone language, English. Subjects were scanned under two conditions: a silent resting baseline and a tonal task involving discrimination of pitch patterns in Mandarin words. Both groups showed common regions of CBF increase, but only Mandarin speakers showed additional activation in frontal, parietal, and parieto-occipital regions of the left hemisphere; this latter finding indicates that language experience may influence brain circuitry in the processing of auditory cues. In contrast, only the English group showed activity in the right inferior frontal cortex, consistent with a right-hemispheric role in pitch perception.

Key Words: **language; PET; lexical tone; speech perception.**

INTRODUCTION

Sounds produced by the human voice vary along multiple dimensions. Languages use these dimensions in different ways to distinguish utterances. In particular, there are wide differences from one language to another in the use of "suprasegmental," or prosodic, features, such as variations in fundamental frequency, amplitude, and duration, which are not a function of intrinsic characteristics of phonetic segments. Tonal differences are perceived principally as differences in pitch, although intensity and duration also provide important secondary auditory cues for the identification of specific tones (Karlgren, 1962). Lexical stress and lexical tone are the two principal methods by which languages use prosodic features to distinguish one word from another. In tone languages, a lexically distinctive function is served by the fundamental frequency level or contour realized on a syllable; that is, differences in fundamental frequency over strings of otherwise identical phonemes distinguish different words in the lexicon from one another. Several investigations have taken advantage of this feature to dissociate linguistic from nonlinguistic processing by requiring judgements of pitch changes in two groups of subjects: speakers of a tonal language and individuals who do not know the language in question. This manipulation affords an opportunity for distinguishing different behavioral and neural activity patterns related to tone discrimination in linguistic and nonlinguistic contexts.

On the behavioral level, several studies have manipulated differences in lexical relevance of suprasegmental information (intonation, contour, or stress patterns) and have compared the results for speakers of a tone language with those of a nontone language. Using dichotic listening, Van Lancker and Fromkin (1973) found that pitch discrimination tends to be lateralized to the left hemisphere when the pitch differences are processed linguistically. Lee and Nusbaum's experiments (1993) using a speeded classification task also suggest an interaction between the structure of the signal and the processing strategies of the listener. In contrast, studies by Repp and Lin (1990) and Cutler and Chen (1997) have found that listeners with no knowledge of tone exhibit essentially the same discrimination performance as that of native listeners, lending support for the notion that acoustic characteristics of the stimulus govern these judgements, rather than linguistic knowledge.

More recently, a positron emission tomography (PET) study addressed the issue of lexical relevance by comparing pitch processing of Thai syllables by Thai speakers with that of English speakers. Only the Thai subjects showed activation in the left frontal cortex (Gandour *et al.*, 1998), suggesting preferential activation of specialized speech centers in the left hemisphere when these stimuli are processed linguistically. As an extension to this study, Gandour *et al.* (2000) added a control group of listeners from another tone language (Chinese). Activation in the left frontal re-

1053-8119/01 $35.00

gion was observed only for the Thai group, when Thai, Chinese, and English speakers were compared on a Thai discrimination-judgement task. In contrast, significant activation was observed in the region of the anterior insula for the English and Chinese groups, but not the Thai (Gandour *et al.*, 2000). These findings are consistent with evidence from lesion studies of patients who are speakers of tone languages and who are left-hemisphere dominant for speech (Naeser and Chan, 1980; Gandour and Dardarananda, 1983; Packard, 1986). Interestingly, Gandour *et al.* (1998) failed to observe activity in the right frontal region for the nontone speakers, a finding that contrasts with earlier behavioral work with patients (Zatorre and Samson, 1991) and with PET studies (Zatorre *et al.*, 1992, 1994) that show a robust role for the right frontal cortex in tasks requiring pitch processing of complex auditory stimuli in nonlinguistic contexts.

The goal of the present study was to investigate further how different brain regions are activated as a function of changes in linguistic context. We used PET to compare the patterns of CBF change between native Mandarin- and English-speaking volunteers when performing same-different judgements of tone in Mandarin word pairs. In the Mandarin-Chinese speakers, by virtue of their language experience, we predicted that the linguistic system would be engaged automatically by the tonal stimuli, and that this would most likely result in recruitment of left-hemisphere regions, even though the task itself does not necessarily require lexical access because it can be performed purely on the basis of acoustic information. Conversely, we expected nonspeakers of Chinese to perform tasks of tonal judgement without access to linguistic processes, and, therefore, that their pitch-contour discrimination would involve right-hemisphere processes (Zatorre *et al.*, 1992).

MATERIALS AND METHODS

Subjects

In one group, the subjects were 12 native speakers of Mandarin Chinese (6 male; 6 female), who were born in China and came to Canada after the age of 10 years, and who had become proficient in English in adolescence. In a second group, the 12 subjects (6 male; 6 female) were native speakers of English who had no knowledge of Mandarin or any other tonal language. All subjects were right-handed university students who were in good health, under no medication, and with no history of neurological disorder. The subjects gave informed consent to undergo PET scanning, which was performed according to institution-reviewed medico-ethical guidelines.

Stimuli

Chinese (Mandarin) has four lexical tones (Chao, 1968), traditionally labeled Tones 1, 2, 3, and 4: for example, /ma^1/'mother';/ma^2/'hemp';/ma^3/'horse';/ma^4/ 'scold'. Tones 1–4 can be described phonetically as high-level, high-rising, low-dipping, and high-falling, respectively. There is also a neutral tone whose pitch pattern is contextually conditioned. The primary acoustic correlate of Chinese tones is voice-fundamental frequency (Howie, 1976).

Two word lists were constructed, consisting of 50 pairs of monosyllabic Mandarin words, half of which had the same tone (e.g., /t'ou^2/) and half of which were different in tone (e.g., /fei^2/ /fei^1/). The word lists were matched on the various consonant and vowel sounds available in Mandarin Chinese. Nouns, verbs, and modifiers were chosen, but no pronouns or articles were included. Because Chinese words are usually not spoken alone, but in the context of at least one other word, all the words chosen were distinctive in meaning, so that the subject was able to disambiguate the word. Across the four tone categories, there was an approximately equal distribution of exemplars for both the "same" and "different" stimulus sets. In developing the "different" stimulus set, an attempt was made to ensure that all possible pairings of tones occurred at least twice. All the word pairs in the "different" stimulus set are minimal pairs for tone (see Fig. 1 for a representative spectrogram of a stimulus pair that differed in their intonation patterns). The tones were recorded by a female native speaker of Mandarin in a sound-proof audiovisual room.

Procedure

The baseline condition was silence; subjects were instructed to relax with eyes closed and no overt response was required. In the tone condition, subjects were required to make discrimination judgements of two Mandarin words. They were asked to judge whether or not the two syllables in each pair were identical and then to respond as quickly and accurately as possible, by pressing one of two buttons on a mouse. The experiment included a practice session followed by the experimental session. The order of scans was counterbalanced, as was the key-press response on the mouse. All stimuli were presented binaurally in pairs on each trial via foam insert-earphones (EARTONE 3A) at a level of ~78 dBA and were delivered at a rate of one trial every 4.2 s. Subjects kept their eyes closed for the duration of the scan.

PET Scanning

This experiment formed part of a larger study that is reported elsewhere (Klein *et al.*, 1999). For this part of the study, a total of four scans were performed for each

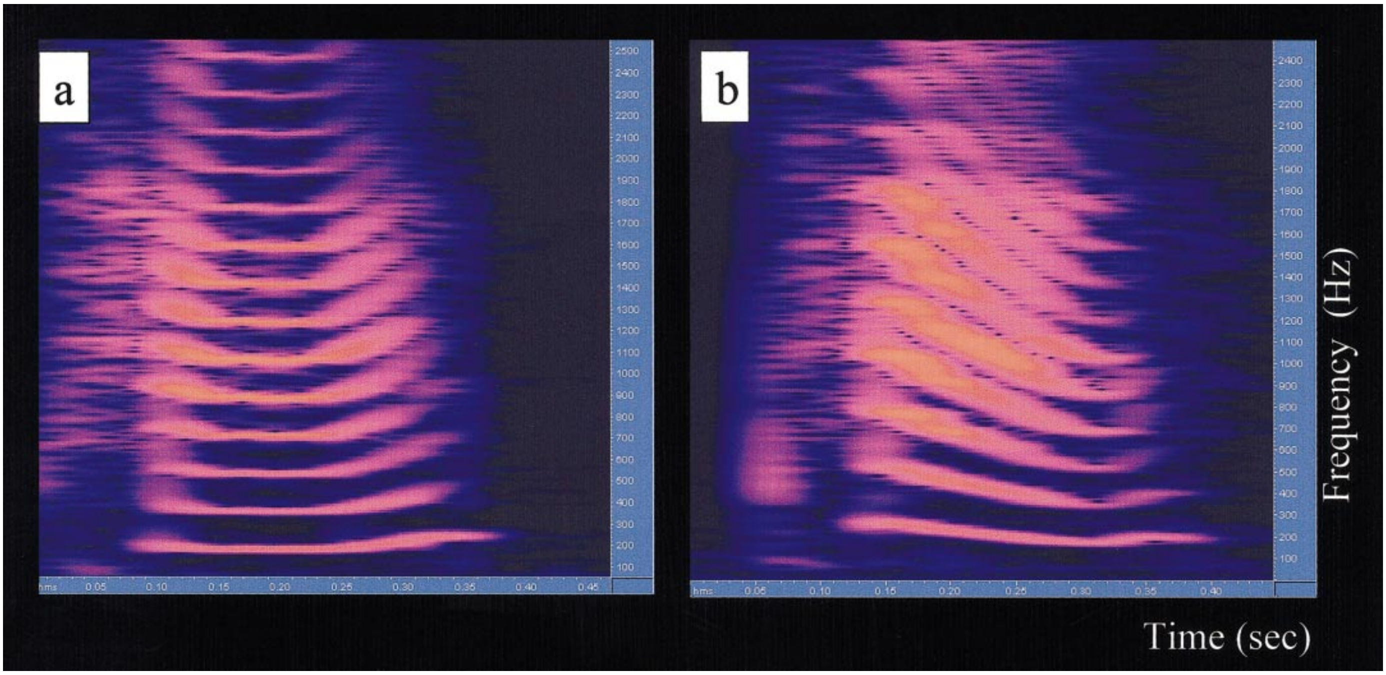

FIG. 1. Narrow-band spectrograms showing an example of the stimuli that differed in their intonation patterns. Both have the same phonemes /pa/ but the left panel (a) corresponds to the Mandarin word "climb" with the rising tone /pa^2/ and the right panel (b) corresponds to the word "afraid" with a falling tone /pa^4/. The x-axis shows time (length of word 0.5 s); the y-axis shows frequency (0–2500 Hz).

subject (two conditions each scanned twice). The scanning session was counterbalanced, such that scans were either presented in a block at the beginning or at the end of the session. Instructions were given before each scan, and 10 practice trials were given prior to bolus injection. PET scans were obtained with a Siemens Exact HR+ tomograph operating in three-dimensional acquisition mode. The distribution of CBF was measured during each 60-s scan using the H_2O^{15} water bolus method (Raichle *et al.*, 1983). T1-weighted structural MRI scans (160 1-mm-thick slices) were also obtained for each subject with a 1.5T Phillips ACS system to provide anatomical detail. CBF images were reconstructed using a 14-mm Hanning filter, normalized for differences in global CBF, and coregistered with the individual MRI data (Evans *et al.*, 1992). Each matched MRI/PET data set was then linearly resampled into the standardized stereotaxic coordinate system of Talairach and Tournoux (1988) via an automated feature-matching algorithm (Collins *et al.*, 1994).

Statistical Analyses

PET images were averaged across subjects for each condition, and the mean-change image-volume was obtained for each comparison; this volume was converted to a t statistic map, and the significance of focal CBF changes was assessed by a method based on three-dimensional Gaussian random-field theory (Worsley *et al.*, 1992). Values equal to, or exceeding, a criterion of $t = 3.5$. were deemed statistically significant ($P < 0.002$; two-tailed, uncorrected). Correcting for multiple comparisons, a t value of 3.53 yields a false-positive rate of 0.58 in 182 resolution elements (dimensions of $14 \times 14 \times 14$ mm), corresponding approximately to the volume of gray matter scanned. Where activity had been observed on the basis of the initial analyses against the baseline scan, the threshold was lowered in Table 2 to $t = 3.0$ to show peaks that approached significance.

RESULTS

Behavioral Data

Behavioral data for both accuracy and latency were analyzed with two-tailed t tests. Reaction times did not differ significantly across the two language groups (mean latency: Mandarin = 1880.6 ms; English = 1948.0 ms.) ($t = 1.1$ (22), $P = 0.3$). The English-speakers were significantly less accurate (mean accuracy = 93%) at making judgements than the native speakers of Mandarin (mean accuracy = 98%) ($t = 3.4$ (22), $P = 0.003$), but performance for both groups was good.

PET Scanning: CBF Changes

Tables 1 and 2 present the stereotaxic coordinates of all significant CBF changes observed from the subtractions. Figure 2 shows some of the more pertinent CBF changes associated with performance of these tasks.

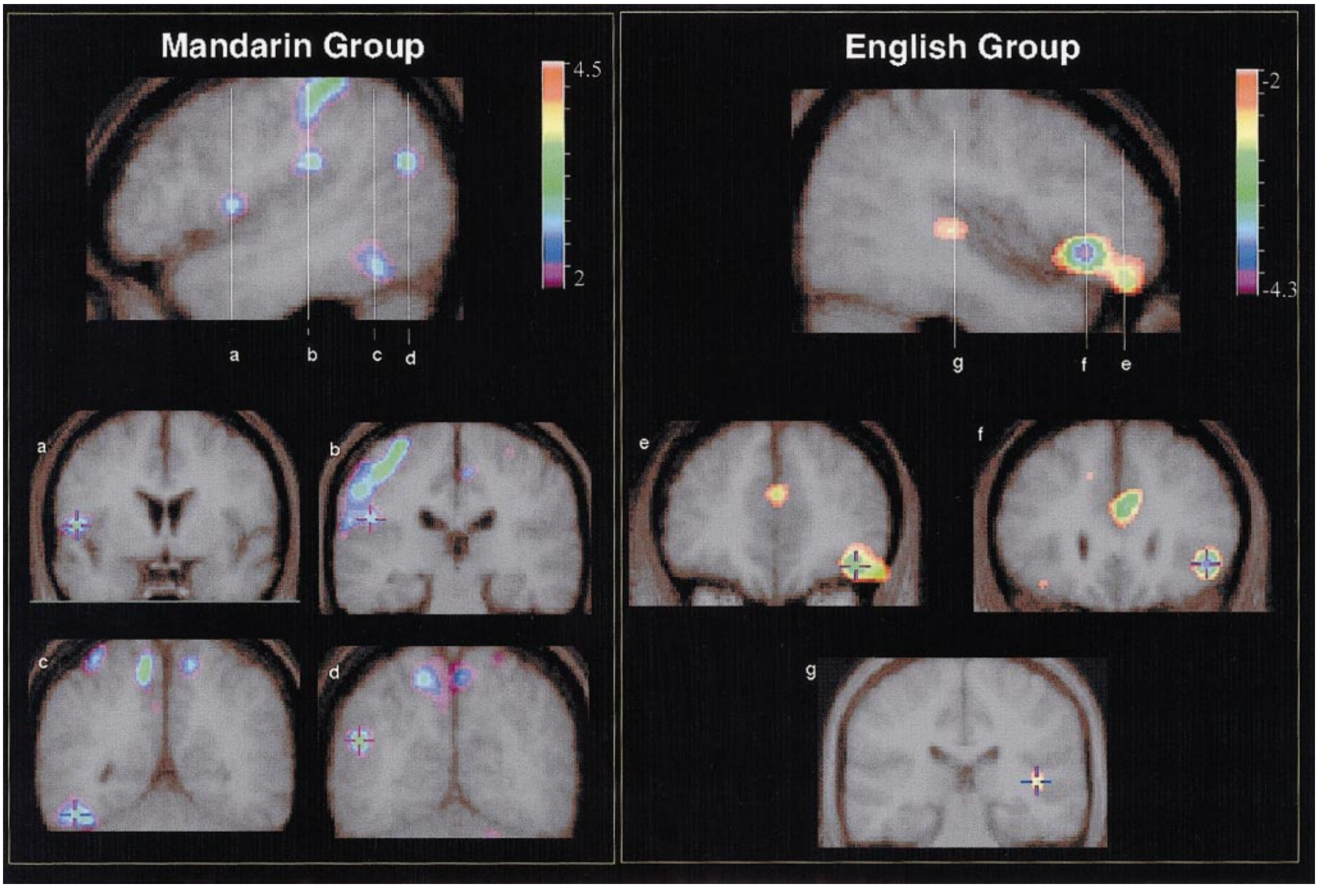

FIG. 2. Averaged PET images obtained from direct comparison of tone discrimination across the two language groups (Chinese Mandarin minus English). The left panel shows the significant CBF increases for the Mandarin Chinese group relative to the English group. The vertical lines through the sagittal section indicate the point of intersection for each of the corresponding coronal sections. Several peaks in Table 2 are visible in the figure. Left panel [Images a–d: Chinese > English]: (a) precentral gyrus (Peak 3); (b) inferior parietal lobule (Peak 5) and postcentral gyrus (Peak 4); (c) lateral occipitotemporal (Peak 10); (d) superior parietal lobule (Peak 9) and middle occipital gyrus (Peak 11). In contrast, the right panel shows the CBF decreases [Images e–g: English > Chinese]: (e) right inferior frontal gyrus (Peak 12); anterior orbitofrontal gyrus (Peak 13); (f) cingulate region (Peak 15); and (g) the right superior temporal gyrus (Peak 16). The range of *t* values for the PET data is coded by the color scale shown at the upper right of each panel. The subject's left is on the left side in all coronal sections.

Tone discrimination relative to silent baseline. A comparison of the tone discrimination to the resting baseline yielded several CBF increases that were common across the English and Mandarin groups. Bilateral CBF increases were observed along the superior temporal gyrus (Foci 3, 14, 16), in the lateral cerebellum (Foci 7, 18) and in the thalamus (Foci 8, 20). In addition, CBF increases were observed in the right inferior parietal lobule (Focus 17) and in the left medial frontal (Focus 1) and postcentral gyri (Focus 5) in similar locations in both groups.

Several CBF increases were observed only for the Mandarin group. In the left hemisphere; these were in the superior temporal gyrus (Focus 4); and the superior parietal lobule (Focus 6); a CBF change was also observed in the midline cerebellum (Focus 19).

In contrast, several CBF increases were observed only for the English group. In the right hemisphere, these were in the superior temporal gyrus (Focus 15); and in the frontal cortex, where peaks were seen in the anterior orbitofrontal (Foci 10,11); middle frontal (Focus 12); and inferior frontal (Focus 13) regions, respectively. In the left hemisphere, a peak in the insula was observed (Focus 2).

Direct comparison of the two language groups. To determine the presence of statistically significant differences between the groups, an analysis of variance was performed comparing the two subtractions directly to one another [(i.e., Tone discrimination minus Silent baseline for the Mandarin Chinese group) - (Tone discrimination minus Silent baseline for the English language group)]. Table 2 and Fig. 2 display the CBF changes that were specific to each group.

CBF changes observed only for the Mandarin Chinese group were all in the left hemisphere: in the ventromedial orbital frontal cortex (Focus 1); frontopolar cortex (Focus 2); pre- and postcentral gyri (Foci 3,4);

TABLE 1

Tone Discrimination Minus Silent Baseline: Mandarin Chinese and English

	Group							
	Mandarin				English			
Blood flow changes	*x*	*y*	*z*	*t* value	*x*	*y*	*z*	*t* value
Left hemisphere								
Frontal								
1. medial frontal gyrus	−7	1	54	5.5	−5	−2	57	5.10
2. insula					−36	18	3	3.77
Temporal								
3. superior temporal gyrus	−59	−26	12	9.91	−56	−19	8	10.08
4. superior temporal gyrus	−52	−4	2	8.10				
Parietal								
5. postcentral gyrus	−42	−30	54	9.84	−42	−23	59	7.20
6. superior parietal lobule	−35	−52	62	4.78				
Cerebellum								
7. lateral	−29	−59	−22	5.73	−28	−59	−23	4.28
Thalamus								
8. thalamus	−3	−19	−3	3.65	−8	−19	8	4.79
9. thalamus					−7	−19	5	4.5
Right hemisphere								
Frontal								
10. anterior orbitofrontal gyrus					31	46	−12	4.97
11. anterior orbitofrontal gyrus					35	49	−8	4.97
12. middle frontal gyrus					36	32	20	3.92
13. inferior frontal gyrus					35	20	11	4.41
Temporal								
14. superior temporal gyrus	59	−23	6	9.93	59	−30	11	11.96
15. superior temporal gyrus					58	−9	2	10.04
16. superior temporal gyrus	54	6	−6	5.81	48	10	−8	7.69
Parietal								
17. inferior parietal lobule	47	−47	50	4.23	43	−49	54	4.00
Cerebellum								
18. cerebellum (lateral)	21	−59	−21	6.27	20	−52	−21	5.94
19. cerebellum (vermis)	5	−62	−14	5.14				
Thalamus								
20. thalamus	8	−26	−2	3.76	4	−13	6	4.35

in the inferior and superior parietal cortex (Foci 5–9); and in the lateral occipitotemporal and middle occipital gyri (Foci 10, 11).

By contrast, for the English group, the only CBF changes observed relative to the Mandarin Chinese group were in the right hemisphere: in the right ventrolateral frontal cortex (Focus 12); anterior orbitofrontal gyrus (Focus 13); lateral orbital gyrus (Focus 14); in the cingulate region (Focus 15); and in the superior temporal gyrus (Focus 16).

DISCUSSION

Comparison of the tone task to a resting baseline revealed several sites of activation that were common to the two groups. The most prominent activity was located bilaterally along the superior temporal gyrus and is most probably related to the initial cortical stages for processing complex auditory stimuli, irrespective of whether the stimuli are perceived as speech or nonspeech. Other common regions activated were the cerebellum and thalamus, implicating these regions in cognitive and motor components shared by both groups. Similar findings have been reported by Gandour *et al.* (1998) and by others (Zatorre *et al.*, 1992, 1994, 1996) in studies involving complex auditory tasks that also required a motor response.

However, the most notable findings from this comparison of tone relative to the baseline are the hemispheric differences between CBF activations for the two groups, with left-hemisphere sites being activated for the Mandarin group, and right-hemisphere sites for the English speakers, despite the two subject groups having to process acoustically equivalent stimuli. This differential outcome of the CBF increases for the Chinese and English groups was most clearly revealed by the direct comparison of subtractions across groups. Only the Mandarin speakers showed additional activation in certain left-hemisphere sites, in line with the prediction that pitch processing in a linguistic context

TABLE 2

Tone Discrimination: Chinese Minus English

	x	*y*	*z*	*t* value
Blood flow changes CBF: Chinese > English				
Left hemisphere				
Frontal				
1. ventromedial frontal cortex	−1	39	−21	4.44
2. fronto-polar cortex	−9	61	−6	3.50
3. precentral gyrus	−51	1	6	3.14
Parietal				
4. postcentral gyrus	−40	−31	51	3.68
5. inferior parietal lobule	−47	−30	24	3.02
6. inferior parietal lobule	−54	−23	38	3.15
7. superior parietal lobule	−10	−57	56	3.52
8. superior parietal lobule	−43	−40	60	3.39
9. superior parietal lobule	−17	−74	54	3.36
Occipitoparietal junction				
10. lateral occipitotemporal gyrus	−40	−56	−18	3.00
11. middle occipital gyrus	−44	−66	24	3.24
Blood flow changes CBF: English > Chinese				
Right hemisphere				
Frontal				
12. ventrolateral frontal cortex	43	27	−5	4.27
13. anterior orbitofrontal cortex	35	42	−14	3.63
14. lateral orbital gyrus	46	42	−17	3.12
15. cingulate region	3	34	20	4.07
Temporal				
16. superior temporal gyrus	43	−28	5	3.04

will preferentially activate specialized regions of the left hemisphere. In this study, natural speech stimuli constituted real words for the Mandarin listeners, but nonwords for the English listeners, and the PET findings reflect this difference. This left lateralization most probably results from phonological, lexical, and semantic processing implicitly activated by the word stimuli (Price *et al.*, 1996). This is consistent with studies showing impaired lexical tone judgements in left-hemisphere damaged patients who speak a tone language (Eng *et al.*, 1996; Gandour and Dardarananda, 1983; Naeser and Chan, 1980; Yiu and Fok, 1995). Nevertheless, because of the absence of a nonlinguistic control condition in this study, we cannot exclude the possibility that the differences observed between groups may have been due to a general difference in strategy for the processing of pitch change following language experience.

Although we observed recruitment of several regions in the left hemisphere (including precentral areas) when Mandarin-speaking subjects were making tone judgements, it is worth noting that we did not observe activity in the left frontal cortex, as was previously seen in Thai subjects when they made judgements of Thai lexical tones (Gandour *et al.*, 1998). Gandour *et al.* postulated that phonological processing is required for the tone task by virtue of the fact that pitch patterns are associated with lexical tones in Thai. In an extension of this study (Gandour *et al.*, 2000), these authors compared the CBF patterns of Thai, Chinese and English speakers on a task requiring discrimination judgements of Thai words; they found that, when comparing tone to pitch, only the Thai group, for whom the tones were lexically distinctive, showed activation in the left frontal cortex (near Brodmann's area 44/6).

It is unclear how to interpret the seemingly divergent findings between our study and those of Gandour *et al.* (1998, 2000). In a different context, Zatorre *et al.* (1996) have argued that those studies that have found left frontal premotor activation have, for the most part, required the subjects to dissect the speech sound into its constituent elements. On this view, it is possible that articulatory recoding, as indexed by the activation in the left frontal cortex (area 44/6), would only be necessary if phonetic identification formed part of the task. Support for this idea comes from a recent fMRI study by Burton *et al.* (2000). These authors suggest that the involvement of left frontal areas in phonological processes arises when the subject must perform a task that requires overt segmentation of the phonetic units of the stimulus (e.g., dip-ten), but not when the phonetic judgement does not require overt segmentation (e.g., dip-tip). Overt phonetic segmentation might still occur in tone discrimination, but in the present study where the tone items comprised minimal pairs for tone, it seems not to have been obligatory.

Other factors such as task difficulty may also contribute to differences in outcome between our study and that of Gandour *et al.* (1998, 2000). In their tone discrimination studies, the performance scores were low, even for the Thai subjects, who were using their native language. The fact that the task was difficult even for native speakers of Thai may be related to the speeded-response timing of Gandour *et al.*'s task (2-s response interval), whereas in our study, the response rate required was slower (4-s response interval). Moreover, in our study, all subjects, both Mandarin Chinese and English, were able to execute the task with high accuracy and speed, even though the nontone speakers were less accurate than the tone-language speakers.

In notable contrast to the Mandarin group, several significant CBF increases in the right hemisphere were observed in the English group: specifically in the right frontal region, in the cingulate, and in the superior temporal region. The tendency for greater right-sided activation in frontal and temporal regions in the nonnative speakers is concordant with previous findings for pitch processing (Zatorre *et al.*, 1992, 1994), supporting the idea of functional specialization within the right cerebral hemisphere for tone perception. The patterns of CBF changes observed in the nontone language speakers provide support for the hypothesis that perceptual analysis and judgement of tonal pitch information preferentially involve neural systems within the right frontal cortex. However, it also appears that the operations involved in these tasks make demands upon a widely distributed system. The right prefrontal cortex may contribute to many distinct functions (Pardo *et al.*, 1991), but in this experiment its activation was specific to the pitch condition. This adds support for the idea that this region may form part of a distributed network involved in maintenance of pitch information in auditory working memory (Marin and Perry, 1999), an idea supported by anatomical data (Chavis and Pandya, 1976) and by the finding that focal lesions to either the right superior temporal gyrus or the right frontal lobe result in deficits in retention of pitch (Colombo *et al.*, 1990; Zatorre and Samson, 1991).

In conclusion, the cross-linguistic contrast between the tone and nontonal speaker groups gave rise to two important and complementary findings. In the Mandarin Chinese group, activity was confined to the left hemisphere. It is unclear whether these left-sided activations are specifically related to the processing of tone, or more generally to the linguistic system, because radiation limitations in this experiment precluded the inclusion of additional conditions (such as a nonspeech condition); but in the Mandarin Chinese group, we did not observe right frontal activity, suggesting that different regions were called into play when these subjects were making judgements based on tone. In contrast, for the English group, the activation foci were in the right prefrontal cortex, supporting the prediction that pitch processing in the absence of access to linguistic information would involve right-hemispheric mechanisms. The lateralization effect is apparently language-specific because the tones are meaningful only to the Mandarin speakers.

It is this differential outcome for the two groups that provides support for the view that linguistically relevant properties of complex auditory stimuli are critical in determining which neural mechanisms are engaged in the perception of speech prosody (see Gandour *et al.*, 1998, 2000). Our findings also support the view (e.g., Gandour *et al.*, 2000) that auditory parameters of the speech signal are not solely encoded in higher cortical areas as a function of their complex acoustic properties. Instead, their representation, and thus further access to domain-specific regions, are driven by top-down processes according to their linguistic function in a particular language (Gandour *et al.*, 2000). Thus, speech perception may be viewed as emerging from an interaction between stimulus-driven perceptual processes and experience-dependent top-down mechanisms.

ACKNOWLEDGMENTS

We thank the technical staff of the McConnell Brain Imaging Unit and of the Medical Cyclotron Unit for their invaluable assistance and S. Milot for his technical expertise. We also thank Ling Wong, Lauren Dade, Patrick Bermudez, Joelle Crane, and Regina Visca for their technical help. Supported by grants from the Canadian Institutes of Health Research (MT2624, MT11541, SP-30) and by the McDonnell-Pew Program in Cognitive Neuroscience.

REFERENCES

Burton, M. W., Small, S. L., and Blumstein, S. E. 2000. The role of segmentation in phonological processing: An fMRI investigation. *J. Cogn. Neurosci.* **12:** 679–690.

Chao, Y. R. 1968. *A Grammar of Spoken Chinese.* Univ. California Press, Berkeley, CA.

Chavis, D., and Pandya, D. N. 1976. Further observations on corticofrontal pathways in the rhesus monkey. *Brain Res.* **117:** 369–386.

Collins, D. L., Neelin, P., Peters, T. M., and Evans, A. C. 1994. Automatic 3D intersubject registration of MR data in standardized Talairach space. *J. Comput. Assist. Tomogr.* **18:** 192–205.

Colombo, M., D'Amato, M. R., Rodman, H. R., and Gross, C. G. 1990. Auditory association cortex lesions impair auditory short-term memory in monkeys. *Science* **247:** 336–338.

Cutler, A., and Chen, H-C. 1997. Lexical tone in Cantonese spoken-word processing. *Percept. Psychophys.* **59:** 165–179.

Eng, N., Obler, L., Harris, K., and Abramson, A. 1996. Tone perception deficits in Chinese-speaking Broca's aphasics. *Aphasiology* **10:** 649–656.

Evans, A. C., Marrett, S., Neelin, P., Collins, L., Worsley, K., Dai, W., Milot, S., Meyer, E., and Bub, D. 1992. Anatomical mapping of functional activation in stereotactic space. *Neuroimage* **1:** 43–53.

Gandour, J., and Dardarananda, R. 1983. Identification of tonal contrasts in Thai aphasic patients. *Brain Language* **18:** 94–114.

Gandour, J., Wong, D., and Hutchins, G. 1998. Pitch processing in the human brain is influenced by language experience. *NeuroReport* **9:** 2115–2119.

Gandour, J., Wong, D., Hsieh, L., Weinzapfel, B., and Hutchins, G. D. 2000. A cross-linguistic PET study of tone perception. *J. Cogn. Neurosci.* **12:** 207–222.

Howie, J. 1976. *Acoustical Studies of Mandarin Vowels and Tones.* Cambridge Univ. Press, New York.

Karlgren, B. 1962. *Sound and Symbol in Chinese.* Hong Kong Univ. Press, Hong Kong.

Klein, D., Milner, B., Zatorre, R. J., Zhao, V., and Nikelski, J. 1999. Cerebral organization in bilinguals: A PET study of Chinese-English verb generation. *NeuroReport* **10:** 2841–2846.

Lee, L., and Nusbaum, H. C. 1993. Processing interactions between segmental and suprasegmental information in native speakers of English and Mandarin Chinese. *Percept. Psychophys.* **53:** 157–165.

Marin, O. S. M., and Perry, D. W. 1999. Neurological aspects of music perception and performance. In *The Psychology of Music* (Deutsch, D., Ed.), pp. 653–724. Academic Press, San Diego.

Naeser, M. A., and Chan, S. W. 1980. Case study of a Chinese aphasic with the Boston Diagnostic Aphasia exam. *Neuropsychologia* **18:** 389–410.

Packard, J. 1986. Tone production deficits in nonfluent aphasic Chinese speech. *Brain Language* **29:** 212–223.

Pardo, J. V., Fox, P. T., and Raichle, M. E. 1991. Localization of a human system for sustained attention by positron emission tomography. *Nature* **238:** 44–45.

Price, C. J., Wise, R. J., and Frackowiak, R. S. 1996. Demonstrating the implicit processing of visually presented words and pseudowords. *Cerebral Cortex* **6:** 62–70.

Raichle, M. E., Martin, W. R. W., Herscovitch, P., Mintun, M. A., and Markham, J. 1983. Brain blood flow measured with intravenous H_2O^{15}. II. Implementation and validation. *J. Nuclear Med.* **24:** 790–798.

Repp, B. H., and Lin, H. 1990. Integration of segmental and tonal information in speech perception: A cross-linguistic study. *J. Phonet.* **18:** 481–495.

Talairach, J., and Tournoux, P. 1988. *Co-Planar Stereotaxic Atlas of the Human Brain.* Thieme, New York.

Van Lancker, D., and Fromkin, V. 1973. Hemispheric specialization for pitch and tone: Evidence from Thai. *J. Phonet.* **1:** 101–109.

Worsley, K. J., Evans, A. C., Marrett, S., and Neelin, P. 1992. A three-dimensional statistical analysis for CBF activation studies in human brain. *J. Cereb. Blood Flow Metab.* **12:** 900–918.

Yiu, E., and Fok, A. 1995. Lexical tone disruption in Cantonese aphasic speakers. *Clin. Linguistics Phonetics* **9:** 79–92.

Zatorre, R. J., and Samson, S. 1991. Role of the right temporal neocortex in retention of pitch in auditory short-term memory. *Brain* **114:** 2403–2417.

Zatorre, R. J., Evans, A. C., Meyer, E., and Gjedde, A. 1992. Lateralization of phonetic and pitch discrimination in speech processing. *Science* **256:** 846–849.

Zatorre, R. J., Evans, A. C., and Meyer, E. 1994. Neural mechanisms underlying melodic perception and memory for pitch. *J. Neurosci.* **14:** 1908–1919.

Zatorre, R. J., Meyer, E., Gjedde, A., and Evans, A. 1996. PET studies of phonetic processing of speech: Review, replication and re-analysis. *Cerebral Cortex* **6:** 21–30.