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## Neuroanatomical markers of speaking Chinese

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*Neuroanatomical markers of speaking Chinese***Neuroanatomical markers of speaking Chinese**

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5. Chinese;
6. Multilingual.

*Neuroanatomical markers of speaking Chinese***Abstract**

The aim of this study was to identify regional structural differences in the brains of native speakers of a tonal language (Chinese) compared to non-tonal (European) language speakers. Our expectation was that there would be differences in regions implicated in pitch perception and production. We therefore compared structural brain images in three groups of participants: 31 who were native Chinese speakers; 7 who were native English speakers who had learnt Chinese in adulthood and 21 European multilinguals who did not speak Chinese. The results identified two brain regions in the vicinity of the right anterior temporal lobe and the left insula where speakers of Chinese had significantly greater gray and white matter density compared with those who did not speak Chinese. Importantly the effects were found in both native Chinese speakers and European subjects who learnt Chinese as a non-native language, illustrating that they were language related and not ethnicity effects. On the basis of prior studies, we suggest that the locations of these gray and white matter changes in speakers of a tonal language are consistent with a role in linking the pitch of words to their meaning.

*Neuroanatomical markers of speaking Chinese***Introduction**

Natural languages share common properties. They use words, syntax and prosody to communicate meanings. It is therefore reasonable to suppose that the neural regions that process lexical meaning, syntax and prosody in one language do so in another. However, there are also differences between languages that are likely to have consequences on brain structure and function. Identifying these consequences is important on both theoretical and practical grounds in order to understand how the language network adapts to distinct requirements and to predict the effects of regional damage. A strong contrast is between tonal languages (e.g. Chinese) that use pitch to signal differences in word meaning and non-tonal languages (e.g. European languages) that do not. We asked two questions: What regional structural differences exist in the brain of native speakers of a tonal language compared to non-tonal language speakers? Prior research provides clues but no definitive answers to this question. Second, if a tonal language is acquired as a non-native language do the same regional brain differences emerge? This question has not been addressed before to our knowledge.

Our study focuses on structural brain differences that reflect the long-term use of a tonal language. To do this we compared brain structure in groups of subjects who do, and do not, speak Chinese. Differences in the local brain tissue composition were extracted using voxel based morphometry (VBM) after eliminating macroscopic differences in brain shape and controlling for ethnicity and number of languages. Prior research indicates that both cognitive and motor abilities can correlate with differences in brain structure e.g., [Gaser and Schlaug 2003; Lee et al. 2007; Maguire et al. 2000; Draganski and May 2008; Mechelli et al. 2004] and so we expected that

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2  
3 there would be structural brain differences between tonal and non-tonal language  
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5 speakers. The advantage of using structural imaging is that, unlike functional imaging,  
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7 the interpretation does not depend on the stimuli, task or ability to perform the task in  
8  
9 the scanner.  
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14  
15 Our expectation was that the brains of Chinese and non-Chinese speakers would differ  
16  
17 in regions implicated in pitch perception and production. In Mandarin, for instance,  
18  
19 there are four different tones that differ in pitch height and the shape of the pitch  
20  
21 contour. To illustrate, the syllable /ma/ means “mother” when spoken in one tone but  
22  
23 a reproach when spoken in another. Understanding and producing speech in a tonal  
24  
25 language such as Chinese requires binding together pitch information with syllabic  
26  
27 information. We expected therefore that structural brain changes should reflect the  
28  
29 ability in tonal language speakers to track the pitch contour of continuous speech and  
30  
31 simultaneously bind it with syllabic information, a skill non-tonal language speakers  
32  
33 do not have. What regions might be involved? Lesion studies [Zatorre and Samson  
34  
35 1991] suggest that regions in the right hemisphere (right temporal and right frontal)  
36  
37 but not in the left hemisphere are important for the retention of pitch information with  
38  
39 the right anterior temporal region especially relevant in judging pitch constancy  
40  
41 [Warrier and Zatorre 2004]. Functional neuroimaging studies also indicate the  
42  
43 importance of right temporal activation in tasks involving pitch processing in normal  
44  
45 subjects e.g., [Warren et al. 2003a; Patterson et al. 2002]. For example, regions anterior  
46  
47 to Heschl’s gyrus (HG) in the right superior temporal cortex have been associated  
48  
49 with voice pitch processing e.g., to identify gender, and the speaker’s affective state,  
50  
51 while voice spectral information is processed in posterior parts of the superior  
52  
53 temporal gyrus (STG) and areas surrounding the planum parietale (PP) bilaterally e.g.  
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*Neuroanatomical markers of speaking Chinese*

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3 to determine a speaker's identity [Lattner et al. 2005]. However, these studies did not  
4  
5 investigate pitch processing in the context of comprehension and production of a tonal  
6  
7 language.  
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9

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11  
12 The importance of the left rather than right hemisphere for discriminating tone for  
13  
14 lexical purposes has been highlighted by studies of Chinese speaking patients with  
15  
16 aprosodia [Hughes et al. 1983], behavioural studies of normal subjects [ e.g., Wang et  
17  
18 al. 2001] and neuroimaging studies [Gandour et al. 2000];[ Gandour et al. 2003]  
19  
20 ;[Hsieh et al. 2001];[Wong et al. , 2004]; { Wang et al.2003}. See Zatorre and  
21  
22 Gandour, 2008 for a recent integrative review of the topic. Neuroimaging studies of  
23  
24 connected speech in Chinese are scarce but there are cross-language studies on  
25  
26 sentence level prosody and tone that report right rather than left lateralized activation.  
27  
28 Tong and colleagues [Tong et al. 2005] found rightward asymmetries in the middle  
29  
30 frontal gyrus (MFG) in both Chinese and English subjects during the discrimination  
31  
32 of sentence-level prosodic phenomena in Mandarin Chinese. Likewise, Gandour et  
33  
34 al. (2004) found right MFG and right superior temporal sulcus (STS) activations in  
35  
36 both Chinese and English subjects processing Mandarin tone and intonation in  
37  
38 syllable utterance pairs. As these effects were common to both Chinese and English  
39  
40 subjects, the authors suggest that pitch processing for lexical meaning is left  
41  
42 lateralized but pitch processing for non-lexical processing i.e. speech prosody  
43  
44 perception is mediated primarily by the right hemisphere. However, the mismatch  
45  
46 negativity (MMN) data from Luo and colleagues [Luo et al. 2006] suggest a slightly  
47  
48 different interpretation. They demonstrated that early auditory processing of a lexical  
49  
50 tone at a preattentive stage is actually lateralized to the right hemisphere in native  
51  
52 Mandarin Chinese speakers. In the same subjects varying the initial consonants of the  
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3 same consonant-vowel structure produced an opposite pattern. Given the distinct  
4  
5 acoustic features between a lexical tone and a consonant, this opposite lateralization  
6  
7 pattern suggests the dependence of right versus left hemisphere mainly on acoustic  
8  
9 cues before speech input is mapped into a semantic representation in the processing  
10  
11 stream. This would suggest that both hemispheres are important for tonal language  
12  
13 identification recruiting both left dominant language systems and right hemisphere  
14  
15 acoustic systems. Further, as Zatorre and Gandour (2008) argue, it is probable that  
16  
17 linguistic status modulates processing at many points before access to word meaning.  
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24 Structural imaging offers an alternative perspective on the brain regions mediating the  
25  
26 processing of a tonal language. To our knowledge there has been one prior structural  
27  
28 study. Kochunov and colleagues [Kochunov et al. 2003] examined brain differences  
29  
30 between English-speaking Caucasians and Chinese-speaking Asians. They identified  
31  
32 global surface differences in brain shape using deformation field morphometry that  
33  
34 they attributed to the acquisition of a tonal language. However, these surface  
35  
36 differences may reflect differences in ethnicity or in the number of languages spoken  
37  
38 by their two groups. Hence we sought to identify whether there were any structural  
39  
40 brain differences between tonal and non-tonal language speakers in brain regions  
41  
42 implicated in pitch perception and production, controlling for ethnicity and number of  
43  
44 languages spoken. If regional gray or white matter density differences were found  
45  
46 only in the native Chinese speakers then the effects could be attributed to ethnicity  
47  
48 alone. However, if regional gray or white matter density was significantly greater in  
49  
50 both native and non-native Chinese speaking groups, then the effect would more  
51  
52 likely be a consequence of speaking a tonal language. Our expectation was that the  
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same regional differences would be evident in native and non-native speakers of Chinese because acquisition would recruit components of a common network.

**Materials and Methods**

The study was approved by the National Hospital and Institute of Neurology's joint medical ethics committee.

*Participants*

Fifty-nine right handed volunteers (between 18-29 years of age), neurologically normal, MRI compatible and proficient in English and Chinese or at least one other language were included. In London, most proficient multilingual speakers acquire English as their second language. Consequently, we had more volunteers who spoke English as their non-native language (n=52) than English as their native language (n=7). Each participant was assigned to one of three groups depending on their ability to speak our target tonal language (Chinese) or not. The first group comprised 21 European multilinguals that never learnt Chinese, another tonal or a pitch accent language. All spoke English as their non-native language and their first languages were German (n = 8), Greek (n = 11), and Portuguese (n = 2). The second group comprised 31 native Chinese multilinguals that learnt English. The third group comprised seven native English multilinguals who were late learners of Chinese, studying Mandarin at the School of Oriental and African Studies in London.

As shown in Table 1, all three multilingual groups were well matched for age and number of languages spoken. As per convention, all subjects completed a language history questionnaire (cf; Li, Sepanski & Zhao, 2006) allowing us to screen the subjects' eligibility to take part in the study. The 7 native English participants all

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2  
3 learnt Chinese through formal university instruction and reported it to be the dominant  
4  
5 foreign language they used at the time of this study. All were full time Masters  
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7 students learning Mandarin at SOAS, University of London. For this course, they had  
8  
9 to read and write Chinese articles and speak Chinese with classmates. Three subjects  
10  
11 had travelled and lived in China for more than 3 months. As a group they had used  
12  
13 Chinese on average for 2 years [range 1-4 years, s.d. 1.1 years]. Their self rating of  
14  
15 proficiency in Chinese was good overall with writing Chinese being their least  
16  
17 proficient skill and speaking Chinese being their most proficient skill.  
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24 All non-native English speaking subjects were residents in the UK and reported  
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26 English to be their dominant language of daily use. All learnt English mainly through  
27  
28 formal classroom instruction (4 Chinese and 4 Europeans also learnt English at home)  
29  
30 and all rated English as their most proficient foreign language. The native Chinese  
31  
32 speakers spoke English for a mean of 13.8 years [range 3-20 years, s.d. 4.6 years]  
33  
34 while the non-Chinese speaking group: mean=15.4 years, range 1-23 years, s.d. 3.8  
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36 years.  
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41 Table 1 about here  
42

*Behavioural Assessments*

43  
44 As an index of English and Chinese fluency at the single word and connected speech  
45  
46 levels, we administered a verbal fluency task and a composite picture description task  
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48 on the same occasion as MRI scanning. The verbal fluency task is a standard clinical  
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50 test for single word production. The composite picture description task is commonly  
51  
52 used to elicit speech at the sentence level. Ten participants from the native Chinese  
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54 group and one participant from the non-native participant group did not complete  
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56 these additional behavioral assessments. The results for the Chinese version of these  
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3 tasks were therefore collected from 21/31 native Chinese speakers and 6/7 non-native  
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5 Chinese speakers. The results from the English versions of these tests were collected  
6  
7 from the same 27 subjects (21 native and 6 non-native Chinese speakers) and also  
8  
9 from the 21 Europeans who did not speak Chinese. Additional assessments of  
10  
11 English vocabulary knowledge and reading abilities (in all English speaking  
12  
13 participants) were assessed with the Lexical Decision Test from the Psycholinguistic  
14  
15 assessment of language processing in aphasia (PALPA)[Kay et al. 2001] and the  
16  
17 English Vocabulary Test[Meara 1992]. This confirmed that the Chinese and European  
18  
19 multilingual participants were also matched for their English language abilities (see  
20  
21 Table 1).  
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29 In the verbal fluency task, participants named as many items as possible within a  
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31 minute beginning with a given phoneme e.g., /s/. Different phonemes were used in the  
32  
33 Chinese and English version of the task (counterbalanced across the native and non-  
34  
35 native speakers of Chinese). The important point to note is that, although there was a  
36  
37 wide range of fluency scores within group, there was no significant group difference  
38  
39 in Chinese fluency (Mann-Whitney  $U = 46.5$ ,  $z < 1$ ) between the native Chinese  
40  
41 speakers (Mean/SD = 8.6/3.8) and the non-native Chinese speakers (Mean/SD =  
42  
43 13.5/10.4). The critical analytic point is that both Chinese speaking groups  
44  
45 demonstrate proficiency in Chinese that is sufficient to warrant our categorical,  
46  
47 between group comparison. We also note that fluency score was not significantly  
48  
49 correlated with the number of languages spoken on either the English fluency tests  
50  
51 ( $r=0.3$ ,  $p=0.1$ ) or Chinese fluency tests ( $r=-0.3$ ,  $p=0.2$ ).  
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3 In the picture description task, participants described a picture for one minute. The  
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5 pictures were taken from the Comprehensive Aphasia Test (CAT:[Swinburn et al.  
6  
7 2005]) and the Boston Diagnostic Aphasia Examination (BDAE: [Goodglass and  
8  
9 Kaplan 1972]). Different pictures were used in the Chinese and English version of the  
10  
11 task (counterbalanced across native and nonnative speakers of Chinese). The picture  
12  
13 descriptions were scored, as per the CAT manual by a native Chinese speaker who  
14  
15 was also fluent in English from an early age. The picture description score covered  
16  
17 both content and manner of expression thereby providing a test for both semantic and  
18  
19 syntactic knowledge. The content measure is the sum of appropriate information  
20  
21 carrying words minus inappropriate information carrying words. To this are added  
22  
23 values for syntactic variety (on a scale of 0 to 6), grammatical well-formedness (on a  
24  
25 scale of 0 to 6) and speed of speech production (on a scale of 0-3). As might be  
26  
27 expected, the overall score was significantly higher (Mann-Whitney  $U = 15.00$ ,  $Z =$   
28  
29  $2.81$ ,  $P < 0.01$ ) for the native Chinese speaking group (Mean/SD = 18.8/5.1) than the  
30  
31 non-native Chinese speaking group (Mean/SD = 13.2/1.9) but as with the verbal  
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33 fluency tasks, the results demonstrated Chinese speech production abilities in both  
34  
35 groups that was sufficient for our categorical comparison with those who did not  
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37 speak any Chinese.  
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*MR data acquisition*

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50 Focal gray and white matter density was estimated on the basis of T1- weighted  
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52 anatomical whole brain images acquired with a Siemens 1.5 T Sonata magnetic  
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54 resonance imaging (MRI) scanner (Siemens Medical Systems, Erlangen, Germany). A  
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56 T1-weighted three-dimensional (3D) MDEFT (modified driven equilibrium Fourier  
57  
58 transform) sequence [Deichmann et al. 2004] was used to acquire 176 sagittal  
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3 partitions with an image matrix of 256×224 yielding a final resolution of 1 mm<sup>3</sup>  
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5 [repetition time (TR)/echo time (TE)/inversion time (TI), 12.24/3.56/ 530 ms]. The  
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7 same scanner parameters and scanner hardware were used for the acquisition of all  
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9 images.  
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*MR data preprocessing*

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17 The structural brain images were preprocessed using Statistical Parametric Mapping  
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19 software (SPM5 Wellcome Trust Centre of Imaging Neuroscience;  
20  
21 <http://www.fil.ion.ucl.ac.uk/spm>) running under Matlab 6.5 (MathWorks, Natick,  
22  
23 MA). The images were segmented into gray and white matter images using the  
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25 unified segmentation algorithm, a generative model that combines tissue  
26  
27 segmentation, bias correction and spatial normalization in the inversion of a single  
28  
29 unified model. Estimating the model parameters (to give a maximum a posteriori  
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31 solution) involves alternating among classification, bias correction and registration  
32  
33 steps. This approach affords better results than serial applications of each component  
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35 because conditional dependencies among the model parameters are modelled  
36  
37 properly; i.e., registration and bias correction help the tissue classification, and the  
38  
39 tissue classification helps the registration and bias correction [Ashburner and Friston  
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41 2005].  
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51 The resulting gray and white matter images were smoothed with an isotropic kernel of  
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53 8 mm at full-width half maximum. Smoothing widths of between 8 to 12 mm are  
54  
55 generally recommended for VBM analyses to ensure that (a) each voxel contains the  
56  
57 average amount of gray or white matter from around the voxel and (b) the data are  
58  
59 normally distributed by the central limit theorem, thus increasing the validity of  
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parametric statistical tests [Mechelli et al. 2005]. After smoothing, each voxel represents the local average amount of gray or white matter in the region, the size of which is defined by the smoothing kernel.

*MR data analysis*

The aim of the statistical analysis was to investigate how the ability to speak a tonal language (Chinese) correlated with local gray and white matter signal intensity. The same analysis was repeated with gray and white matter images.

Images from each of the three participant groups were modelled separately to assess differences in those who did and did not speak Chinese (see Table 1). As we were unable to manipulate number of languages spoken independently of first language, we factored out the number of languages spoken by modelling it as a confounding variable. The effect of age was also modelled as a confounding variable and we excluded the effects of global signal intensity using proportional scaling, so that we could focus the analysis on relative, regional differences in gray or white matter.

Regions with significant differences between Chinese versus non-Chinese speakers were identified using a statistical threshold of  $p < 0.05$  following correction for multiple comparison either across the whole brain or in our bilateral temporal regions of interest determined using a bilateral temporal mask image previously reported [Leff et al. 2008]. This mask image included Heschl's gyrus, planum temporale, the superior temporal gyrus (STG) and superior temporal sulcus (STS). It covered 7009 voxels, equal to 40 resolution elements or resells, and was created by manual segmentation of the bilateral temporal lobes on the single-subject canonical T1 brain

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3 template in MRICro [Rorden and Brett 2000]. We report the effects of each Chinese  
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5 speaking group (native and non-native) relative to the European multilinguals who did  
6  
7 not speak Chinese  
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9

**Results***Structural correlates of speaking Chinese*

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17 Two regions were identified where gray and white matter density was higher in those  
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19 who spoke Chinese than those who did not speak Chinese, see Figure 1. One was in  
20  
21 the right anterior superior temporal gyrus and the underlying right middle longitudinal  
22  
23 fasciculus extending anteriorly from Heschl's gyrus. The other was in the left  
24  
25 posterior region of the insula, just medial to left Heschl's gyrus and the underlying  
26  
27 white matter. The plots in Figure 2 illustrate that, in both areas, there was a  
28  
29 categorical increase in gray and white matter density in Chinese speakers compared to  
30  
31 non-Chinese speakers. There was no significant difference between the native and  
32  
33 non-native Chinese speakers in these regions. Therefore despite our small sample of  
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35 non-native Chinese speakers, there was evidence that gray and white matter in these  
36  
37 non-native Chinese speakers, there was evidence that gray and white matter in these  
38  
39 regions was more similar to the native Chinese speakers than the multilinguals who  
40  
41 did not speak Chinese, following a conservative random effects analysis in auditory  
42  
43 processing areas.  
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51 The replication of these effects across native and non-native Chinese speakers  
52  
53 demonstrates that the results were not driven by differences in ethnicity (see Table 2).  
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55 No other significant gray or white matter effects were revealed in either the bilateral  
56  
57 temporal lobes or across the whole brain. There was no significant difference in the  
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reverse contrast, between European multilinguals > Chinese native and non-native speakers.

**Discussion**

In this structural imaging study we found that gray and white matter density in the right anterior temporal lobe and the left insula was significantly greater in those who spoke Chinese compared to those who did not. Importantly the effects were found in both native Chinese speakers and European subjects who learnt Chinese as a non-native language, illustrating that they were language related and not ethnicity effects. Although our study was not designed to pinpoint the exact level of processing that underlies the structural brain differences, we can nonetheless speculate, on the basis of prior studies, that these structural brain differences may reflect different levels of experience with tone processing.

Previous studies have associated the acquisition of foreign pitch patterns in word identification with greater gray matter volume in left Heschl's gyrus (HG) rather than in the regions identified here [Wong et al. 2008]. Pitch perception is clearly important in perceiving tonal contrasts, and structural differences in left Heschl's gyrus may moderate ease of acquisition especially in the early auditory processing stages as Wong and colleagues note. Nevertheless, Warren and colleagues [Warren et al. 2003b] propose that tracking of acoustic information streams occurs in anterior auditory areas, anterior to HG, whereas the segregation of sound objects (a crucial aspect of auditory scene analysis) depends on posterior areas. When they varied the pitch to produce a melody, they found greater functional activation in regions beyond



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2  
3 HG and PT, specifically in the superior temporal gyrus and planum polare. Their  
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5 results support the view that there is a hierarchy of pitch processing in which the  
6  
7 center of activity moves anterolaterally away from primary auditory cortex as the  
8  
9 processing of melodic sounds proceeds. Tonal language speakers have to  
10  
11 continuously track speech pitch changes, not only at a lexical level but also at a  
12  
13 phrasal level to map the acoustic information onto meaning. Consistent with Warren  
14  
15 et al.'s data [Warren et al. 2003b] our gray and white matter results in tonal language  
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17 speakers point to the importance of temporal brain regions anterior to HG, specifically  
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19 in the right temporal lobe.  
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27 Our structural imaging findings are also consistent with functional imaging studies of  
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29 English speech comprehension which highlight the importance of the anterior superior  
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31 temporal lobe when a suitable acoustic complexity of the speech signal is controlled,  
32  
33 In native English speakers, intelligible speech results in left dominant anterior  
34  
35 temporal lobe activation [Scott et al. 2000] along with activity in the homotopic right  
36  
37 anterior temporal cortices [Spitsyna et al. 2006; Crinion and Price 2005].  
38  
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43 The second brain region where our Chinese speakers showed significantly greater  
44  
45 gray matter density compared with non-Chinese speakers was in a posterior region of  
46  
47 the left insula, just medial to left Heschl's gyrus. The co-ordinates we have identified  
48  
49 from structural data are similar to those shown to be involved in a functional imaging  
50  
51 study of Mandarin speakers discriminating tones in Chinese words [Wong et al 2004],  
52  
53 perceptual processing of utterances that convey information about a speaker's  
54  
55 affective/emotional state by their 'tone' [Dietrich et al. 2008] and when participants  
56  
57 listen to speech with high relative to low degrees of prosodic expression [Hesling et  
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3 al. 2005]. **Underlying this left posterior insula region we also found increased**  
4  
5 **white matter in the left superior longitudinal fasciculus (SLF). Friederici (2009)**  
6  
7 **argues that the SLF is crucial for the ability to process complex sentence**  
8  
9 **structures. However, the functional significance of this pathway is hotly debated.**  
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11 **Differentiation of the SLF from the arcuate fasciculus and their respective**  
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13 **cortical projections (see Glasser and Rilling, 2008 for a meta-analysis) is not**  
14  
15 **easily achieved by the current means of diffusion tensor imaging and**  
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17 **interpretation of their functional roles must, therefore, await further empirical**  
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19 **support. Nevertheless, our gray matter findings are consistent with previous**  
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21 **studies that have associated the left posterior insula with the processing of tone**  
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23 **in speech perception.**  
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32 Our aim was to identify brain regions where there are categorical differences between  
33 subjects who do and do not speak Chinese, irrespective of their ethnicity. We have  
34 identified 2 key regions in the right temporal and left insula cortex. As our Chinese  
35 speaking participants were all proficient in Chinese, we did not have sufficient  
36 variance within group to show a correlation between brain structure (gray/white  
37 matter density) and proficiency in Chinese perception and production tasks. Indeed,  
38 although our sample size of multilingual non-native Chinese speaking group was  
39 small, the fact that we observed structural differences in this group is likely to be a  
40 consequence of homogeneity in their proficiency, how they learnt Chinese and their  
41 daily use of Chinese (they were all on the same full time Masters course). Future  
42 studies are therefore required to investigate how gray and white matter changes within  
43 or between subjects, over the course of learning to speak Chinese. More detailed  
44 behavioral assessments would also help to establish whether the structural brain  
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*Neuroanatomical markers of speaking Chinese*

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3 differences shown in this study are related to speech perception, production or  
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5 comprehension abilities, or more general pitch perception skills. For example,  
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8 investigation of musical abilities may be relevant as previous studies have shown that,  
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10 irrespective of the age of onset of musical training, individuals with a musical abilities  
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12 show a more robust response in the brain stem to differences in lexical pitch [Wong,  
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14 Skoe et al.2007] and, as might be expected, they are also better at perceiving pitch  
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16 patterns in a non-lexical context and are more adept at learning to use pitch patterns  
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18 for lexical purposes [Wong Perrachione & Parrish 2007].  
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24 Finally, we note that previous studies have suggested that typological differences  
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26 between tonal and non-tonal languages are associated with genetic differences in the  
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28 populations that speak them [Dediu and Ladd 2007]. The fact that our group of non-  
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30 native Chinese speakers showed gray and white matter differences relative to other  
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32 European multilinguals in exactly the same regions as native Chinese speakers  
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34 implicates language acquisition as an important source of structural brain differences  
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36 in tonal language speakers too. Of course, we cannot determine from our cross-  
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38 sectional study whether the gray and white matter differences we have identified are  
39  
40 the result of having acquired a tonal language or facilitate the acquisition of a tone  
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42 language. It is possible, but unlikely that the European multilinguals that learnt  
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44 Chinese had differences in these brain regions. Resolution of this issue requires  
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46 further suitably controlled, longitudinal structural studies of the acquisition of Chinese  
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48 in non-native speakers.  
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**Conclusions**

*Neuroanatomical markers of speaking Chinese*

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There are three conclusions that can be validly made from our results at this stage. First, they demonstrate that left insula and right superior temporal, gray and white matter densities are a marker of speaking Chinese in both native and non-native Chinese speakers. Second, they suggest an explanation for a previously reported structural difference between Chinese and non-Chinese speakers (namely, ability to speak a tonal language rather than ethnicity per se). Third, the location of the gray and white matter changes in right superior temporal lobe suggests that in speakers' of a tonal language this region is an important substrate for the crucial link between the pitch of words and their meanings.

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*Neuroanatomical markers of speaking Chinese***Table Legends:****Table 1: Demographic details of the three multilingual groups.**

The table displays mean scores and standard deviations (SD) of the subject groups.

**Table 2: Brain regions with higher gray and white matter in Chinese speakers.**

Location of effects are given in x,y,z co-ordinates in MNI space. Z = Z score; GM = gray matter. WM = white matter

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*Neuroanatomical markers of speaking Chinese***Table 1: Demographic details of the three multilingual groups.**

<b>Group Details</b>	<b>Native Chinese</b>	<b>Europeans</b>	<b>English-Chinese</b>
<b>Number of subjects</b>	31	21	7
<b>Age (years)</b>	22.0 (3.2)	25.5 (2.1)	22.0 (1.9)
<b>Number of Languages</b>	2.9 (1.0)	2.7 (1.0)	3.9 (1.2)
<b>Age of bilingualism</b>	6.1( 3.7)	10.4 (5.1)	11.0 (3.3)
<b>English Verbal Fluency</b>	14.0 (5.4)	12.6 (3.9)	20.3 (6.8)
<b>English Picture Description</b>	29.2(6.4)	36.5 (10.4)	28.1(5.6)
<b>English Lexical Decision</b>	105.4 (8.3)	105.6 (7.0)	111.0 (1.3)
<b>English Vocabulary Test</b>	173.5 (34.1)	181.3 (27.7)	218.0 (11.9)
	Mean (SD)	Mean (SD)	Mean (SD)

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*Neuroanatomical markers of speaking Chinese***Table 2: Brain regions with higher gray and white matter in Chinese speakers.**

Brain Region	Main effect of Speaking Chinese		Native Chinese > European multilinguals		English-Chinese > European multilinguals	
	x y z	Z	x y z	Z	x y z	Z
<b>Right Temporal lobe</b>						
Anterior superior temporal lobe GM	54 14 -18	3.9	52 14 -20	4.7	54 16 -18	2.9
Middle longitudinal fasciculus WM	46 -2 -16	4.4	46 -4 -16	5.1	46 2 -20	3.3
	44 -16 -6	4.0	44 -14 -12	5.2	44 -16 -4	2.8
<b>Left Hemisphere</b>						
Long insula/transverse temporal GM	-36 -16 2	4.1	-34 -16 0	5.5	-38 -16 4	3.4
Superior longitudinal fasciculus WM	-48 -12 16	4.6	-46 -10 16	5.0	-50 -16 18	4.2

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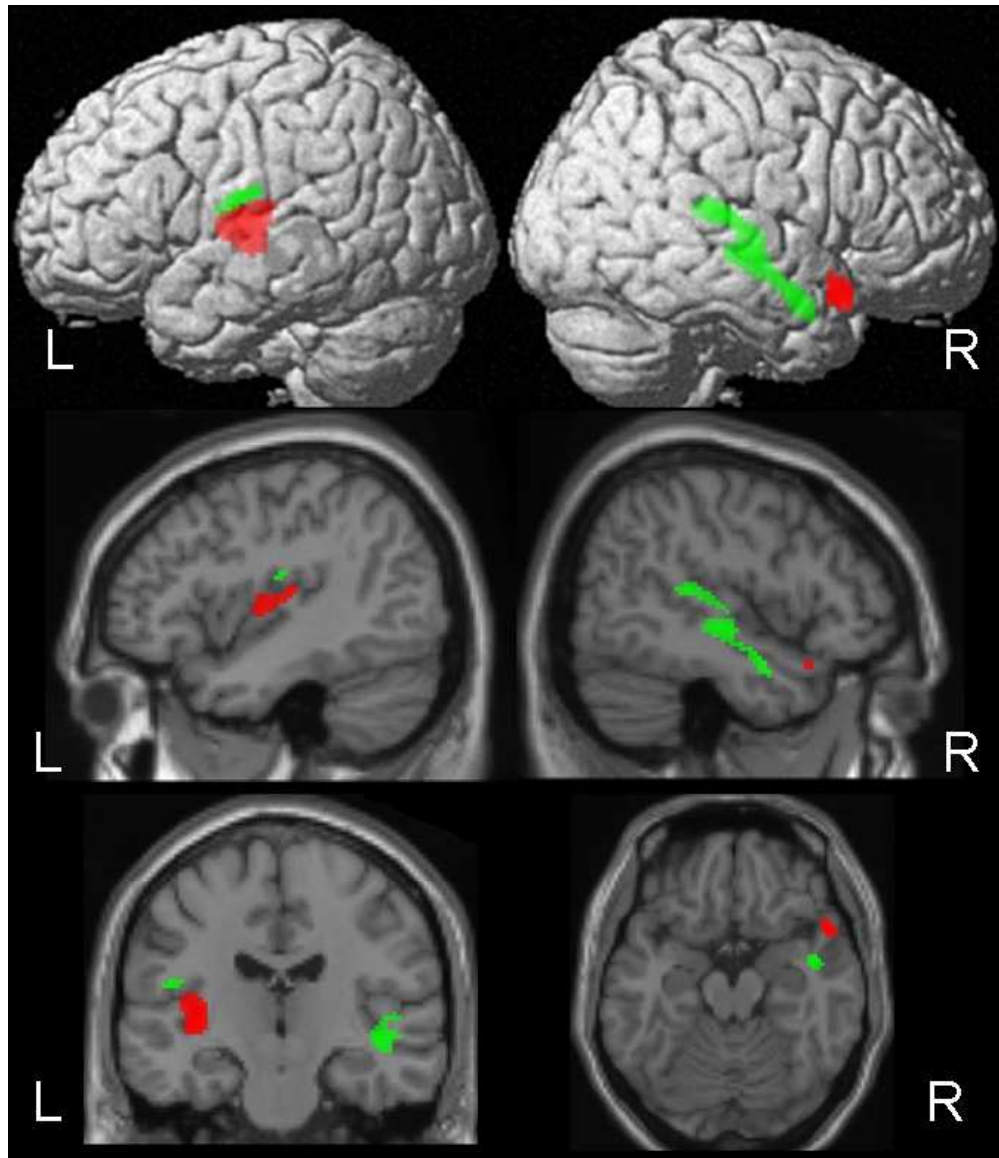


Figure 1: The effect of speaking Chinese.

The top row illustrates increased gray (red) and white (green) matter ( $p < 0.001$ , random effects analyses) for Chinese speakers relative to non-Chinese speakers, surface rendered onto a single-subject brain T1 template. The middle row displays sagittal projections and the third row coronal and axial projections. Details regarding the location and significance of results are given in Tables 2. L= left hemisphere; R= right hemisphere.

114x132mm (150 x 150 DPI)

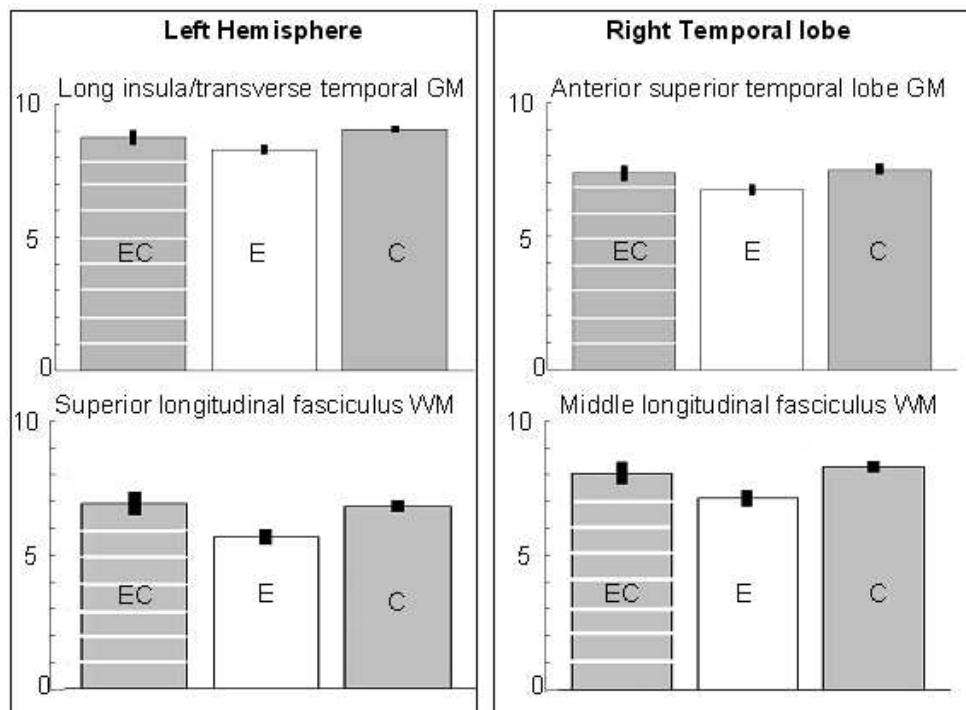


Figure 2: The effect of speaking Chinese.

The plots illustrate gray and white matter density in Europeans who do speak Chinese (EC), Europeans who do not speak Chinese (E) and native Chinese speakers (C) ( $p < 0.001$ , random effects analyses). The left column illustrates increased gray (top) and white (bottom) matter density in the left hemisphere. The right column displays plots of gray (top) and white (bottom) matter density in the right temporal lobe region. X axis – subject groups; Y axis- effect size at peak coordinates of interest. The error bars on the parameter estimates of gray matter correspond to 90% confidence intervals in SPM. Details regarding the location and significance of results are given in Tables 2.

155x119mm (96 x 96 DPI)