

Localized morphological brain differences between English-speaking Caucasians and Chinese-speaking Asians: new evidence of anatomical plasticity

P. Kochunov, P. Fox^{CA}, J. Lancaster, L. H. Tan,¹ K. Amunts,² K. Zilles,^{2,3} J. Mazziotta⁴ and J. H. Gao

Research Imaging Center, University of Texas Health Science Center at San Antonio, 7703 Floyd Curl Drive, San Antonio, TX 78284, USA; ¹Joint Laboratories for Language and Cognitive Neuroscience, The University of Hong Kong, Hong Kong; ²Institute of Medicine, Research Center Juelich, Juelich; ³C&O Vogt Brain Research Institute, Heinrich Heine University, Dusseldorf, Germany; ⁴Brain Mapping Center, Department of Neurology, UCLA School of Medicine, Los Angeles, CA, USA

^{CA}Corresponding author: kochunov@uthscsa.edu

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Deformation field morphometry was applied to magnetic resonance images to detect differences in brain shape between English-speaking Caucasians and Chinese-speaking Asians. Anatomical differences between these two groups were limited to gyri in the frontal, temporal and parietal lobes, which are known (through functional imaging studies) to differentiate Chinese speakers from English speakers. We interpret these anatomical differences as

evidence of neural plasticity shaped by the process of language acquisition during childhood. While anatomical plasticity due to manual skill acquisition (e.g. in musicians) has been established, to our knowledge this is the first report of a brain anatomical difference attributable to a learned cognitive strategy. *NeuroReport* 14:961–964 © 2003 Lippincott Williams & Wilkins.

Keywords: Chinese language; Deformation field morphometry; Plasticity

INTRODUCTION

There is growing evidence that both functional and anatomical plasticity are inherent properties of the human brain. Functional plasticity refers to the dynamic changes in functional organization of a system that are driven by an adaptation to a novel stimulation or acquisition of a new motor skill. Functional plasticity has been observed in somatosensory, auditory, visual and motor systems and is believed to be a basic property of mammalian CNS. Cortical anatomical plasticity supposedly arises when the experienced needs influence the processes that sculpt gross anatomical features of a human cortex. It is well known that genetic factors influence the cortical anatomy, for example, men's brains are larger and more asymmetrical, on average, than women's brains [1]. Handedness is also associated with large-scale, lobar asymmetries [2–5]. Differences in brain cortical anatomy attributable to differences in experiences, anatomical plasticity, however, are less well established. Differences in the depth of the central sulcus are associated with handedness, which may reflect greater use of one hand than the other [2,4,5] but dissociating the genetic component of this effect from the practice effect remains problematic. Perhaps the clearest dissociation due to a practice effect has been presented by Amunts and colleagues [3], who showed that professional keyboard

players who started training early in their life have larger and more symmetrical primary motor cortex. In the present work, we describe brain anatomical differences associated with systematic differences in cognitive strategy.

Differences in neural-system implementation of Asian and Western languages have long been suspected. It was suggested that the differences would be from both the use of tone to connote meaning and from the use of logographic symbols in Asian but not Western modern languages. Early studies, chiefly using visual hemifield procedures, suggested reversed cerebral dominance e.g. more right-hemispheric language processing in Asians than Westerners [6]. However, this reversed dominance theory has not been subsequently confirmed by modern functional imaging methods. Functional imaging has demonstrated other differences in brain activation patterns between native speakers of Mandarin Chinese and native speakers of English [7–13]. The left middle frontal gyrus (MFG), including Brodmann area (BA) 9, is strongly activated in native Chinese speakers during a variety of linguistic tasks, but is not activated or is weakly activated in native English speakers performing the same tasks [7–13]. The cognitive operation involved in Chinese language is suspected to be related to visual spatial working memory, because it requires processing of logographs, which would be more

demanding of this function. However, the same pattern difference was observed for auditory tasks, which would argue for a pervasive strategy difference in linguistic processing between the two groups. In the present study, we sought anatomical concomitants of this learned difference in cognitive strategy, using high-resolution, 3D anatomical MRI and a powerful, newly developed, deformation field morphometry (DFM) analysis method [14].

MATERIALS AND METHODS

Subjects: All subjects were selected from a large cohort (1500 persons) of young (18–40 years of age), healthy normal volunteers whose brains were anatomically imaged using high-resolution $1 \times 1 \times 1$ mm, T1-weighted, 3D, gradient recalled echo MRI sequence at the University of Texas Health Science Center for the purpose of contributing to a probabilistic atlas of the human brain [15]. All persons in the atlas cohort were confirmed to be healthy by medical history, neurological and medical physical examinations and computerized cognitive testing. From this cohort, 20 right-handed Chinese-speaking asian (CA) men were identified. All CA men were born in mainland China, were native speakers of Chinese, and were enrolled in or had completed college. Seven of the CA subjects had previously participated in functional imaging studies which confirmed a typical Asian language activation pattern [9–12]. The CA men had an average age of 28.2 ± 4.5 years (range 22–40 years). English-speaking caucasian (EC) men were chosen to be matched for age, handedness and educational level. All EC men were born in the USA, were native speakers of English, spoke no other language, and were enrolled in or had completed college. The EC men had an average age of 30.2 ± 5.3 years (range 24–40 years.) For both groups, handedness was ascertained by a computerized handedness battery (NeuroCog Software, http://www.loni.ucla.edu/ICBM/ICBM_ResSoftware.html). This is a fully computerized neurocognitive assessment software application, which incorporates both the Edinburgh laterality and Reitan handedness scales. All selected subjects were characterized as strongly lateralized on the right side.

Pre-processing: Subjects' 3D T1-weighted images were automatically skull stripped using BET and FAST programs distributed as a part of FSL package (<http://www.fmrib.ox.ac.uk/fsl/>). The automated brain extraction tool (BET) was used to perform gross deskulling. BET uses the CSF layer between pia and arachnoid matter to guide its processing. Next, WM/GM/CSF segmentation was performed using FAST. This step refined the outer GM border by removing the subarachnoid CSF structures. The extracted brain image was clipped at the level of the brain stem. All brain images were globally spatially normalized to the Talairach template to remove global differences in brain shape. Midline alignment was manually verified and corrected by two experienced neuroanatomists and all images were resliced to an isometric spacing of 0.85 mm.

DFM analysis: The DFM method is detailed in [14]. It is based on a fast 3D warping algorithm [16] and the concept

of group representative brain [17]. This method was validated by measuring the interhemispheric asymmetries in twenty, healthy, right-handed caucasian males in whom it reliably detected all common interhemispheric asymmetries [14]. The processing strategy included the intra-group and inter-group comparisons [14]. The intra-group comparison serves as a null-test hypothesis to establish level of statistical significance. The inter-group test yields a regional distribution of probabilities of inter-group differences relative to intra-group variability.

RESULTS

The brain surface differences between the CA and EC groups are shown in Fig. 1. The DFM analysis identified four regions as having a statistically significant ($p < 0.05$) difference between groups, three in the left hemisphere and one in the right hemisphere (Fig. 1, Table 1). In the left frontal lobe, the middle frontal gyrus (MFG), including BA 9, 46 and 10, was determined to be larger in the CA than in the EC population. In the left temporal lobe, the region that corresponds to the anterior portion of the inferior middle temporal gyrus, including the rostral part of BA 21, was also larger in the CA group. In the left parietal lobe, the superior parietal lobule, including BA 7, was smaller in the CA group, while the corresponding area on the right was larger in CA group. The average brain surface difference for regions with $p < 0.05$ between CA and EC groups was in the order of 2 mm (Table 1).

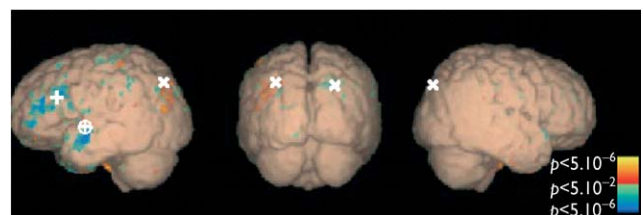


Fig. 1. The 3D renderings of statistically significant ($p < 0.05$) anatomical difference areas, between CA and EC subject, are overlaid on the surface of the CA representative image. The green/blue color indicates that this area was bigger and red/yellow indicates that this area is smaller. White signs show centroids of the area of functional difference discovered in the language studies. BA 9/46 (+) and bilateral BA7/40 (x), were activated during all language-related tasks in CA populations. BA 21 (⊗) was active during processing of Chinese logographs.

Table 1. The fractions of statistically significant lobar surface and average displacement is shown for CA to EC comparison.

	Left lobe		Right lobe	
	% fraction	Average displacement (mm)	% fraction	Average displacement (mm)
Frontal	16.2	1.9	3.8	2.1
Parietal	14.2	1.8	8.1	2.0
Occipital	5.1	2.1	4.8	2.2
Temporal	14.6	2.3	5.3	2.4

DISCUSSION

Areas of functional difference between CA and EC groups have been identified by a rapidly growing body of imaging studies [9–13]. Not all regions reported as having functional differences were seen to have anatomical differences. Each of the areas of anatomical difference, however, has been selectively implicated in Chinese (but not English/European) language processing by one or more studies. Further, the areas detected as being anatomically different between the groups have shown robust and highly reproducible functional differences.

The left MFG, including parts of BA 9, 46 and 10, was found to be more active in CA than EC in a large body of literature [9–13]. The left MFG contained the strongest activations induced by Chinese language tasks and had the greatest functional difference between groups [11,12]. Although the exact functional roles for these areas are not yet well known, the left MFG is thought to coordinate the rather complex allocation of cognitive resources needed for Chinese language processing [12]. The most anterior part of this gyrus (BA 10) is thought to be involved in the fine-grained analysis of the visual-spatial aspects of Chinese character strokes, but is also recruited by Chinese homophone and meaning-judgment paradigms [12].

The anterior portion of left middle temporal gyrus is selectively activated by Chinese-language tasks [11,12]. Both studies reported high activity during semantic and homophone judgments. As with the middle frontal gyrus, the functional role of left middle temporal gyrus is not yet well understood. Classically this region was thought to participate in short-term verbal memory, verbal fluency and word generation [18]. This region has been shown to play a significant role in the processing of sounds with complex spectral and temporal properties [19,20]. The Chinese language is both more structurally complex and more auditory complex than English/European languages (using pitch as well as phonology to convey meaning). Thus, either functional attribution may explain the greater demand on this region by the Chinese language.

Superior parietal lobule activations, including BA 7, have been less reliable at discriminating between CA and EC groups, particularly regarding laterality. Bilateral CA-specific activations have been reported in several studies [7–12]. A left unilateral CA-specific superior parietal lobule effect was also reported [12]. Our detected anatomical differences included the right superior parietal region, which was larger in CA than EC, and the left superior parietal region, which was smaller in CA than EC. The variability in the laterality of the functional differences can almost certainly be attributed to differences in the activation tasks employed. Freedom from reliance on functional tasks is an important advantage of using anatomical imaging to find correlates of population differences in cognitive strategy. The role of the parietal cortex in Chinese-language processing is not yet known.

We interpret these between-group (CA *vs* EC) focal anatomical differences in brain areas known to be differentially activated by Chinese- and English-language tasks as evidence of anatomical plasticity, rather than being due to a genetic difference between groups. That is, we hypothesize that orthographic, phonological and possibly semantic characteristics of the structure of Mandarin Chinese leads

to substantially different cognitive strategy demands than does English (and other Western languages). The differences in language-task activation patterns between CA and EC populations are evidence for these cognitive strategy differences. As language is learned very early in childhood and then used extensively throughout childhood, these brain areas develop during a period of extensive language exercise. That is, form is shaped by function.

While our findings are novel in being the first report of an acquired anatomical difference due to early learning of a cognitive strategy, there is both microscopic and macroscopic evidence in support of the concept that anatomical changes of this magnitude (2–3 mm) can be driven by childhood experiences. At the microscopic scale, Landing and colleagues [21] reported that the thickness of human neocortical layers in BA 4, 17, 18, 19, 21, 36, and 37 varied significantly during early development from birth to 72 months. Childhood development causes waves of thinning and thickening with an average period of 1.7 years. The thickness changes were on the order of 1–2 mm and were mostly attributable to changes in the thickness of layer III, which is responsible for long-distance, inter-area communication by association and callosal fiber systems. Landing and colleagues attributed the observed changes to the development of new cognitive and motor skills, as there was strong correlation between cortical thickness changes and the onset of new, age-specific behaviors. For example, the thickness of layer III in BA 21 increased from 0.5 to 1.2 mm between the ages of 24 and 60 months, overlapping the onset of the ability to discriminate complex object by shape.

Macroscopic changes attributable to adaptation-driven anatomical plasticity have also been reported. Multiple investigations of differential left/right (L/R) asymmetries of the primary motor cortex (PMC; BA 4) in left- *vs* right-handed persons have been reported. The central sulcus, for example, is deeper in the dominant hemisphere [2,4,5]. This finding, however, might be attributable to genetics rather than plasticity, as handedness is strongly influenced by genetics. More convincing evidence for a practice-based asymmetry was provided by Amunts and colleagues [3], who compared the size and symmetry of the PMC in right-handed, highly skilled musicians to that of right-handed, non-musician controls. Macrostructural differences were found, with musicians having larger and more symmetric PMC than controls. Importantly, the age of commencement of musical training (as early as age 36 months) was significantly correlated with the magnitude of the macroscopic difference, while duration of musical training and the age at which the subject was imaged were not. Although this strongly implies that macroscopic changes were induced by skills acquired at a young age, the hypothesis of genetic predetermination of a musician's exceptional skills cannot be completely ruled out.

Recent discoveries in developmental linguistics indicate that language processing begins in early infancy and that nascent language abilities such as phonemic recognition and production of basic sounds are not geographically or ethnically specific, but are shaped by native-language exposure [22–24]. In the context of the present study, this argues that the neural structures supporting language processing are particularly apt for studies of anatomical

plasticity. Even orthographic exposure (learning letters and characters) begins in preschool, at ages comparable to the earliest stages of musical training and, therefore, should be amenable to plastic changes. Further, while it may be argued that persons become musicians because of a genetically determined predisposition, this cannot be argued for language, which is acquired by all normal persons. Finally, while the musician studies demonstrate brain changes associated with learning and practicing a specific skill (music), the present study advances this line of research by showing differences between populations which have the same basic ability (language) but differ in the neural system strategy (which regions are used) by which language is executed.

The inter-group anatomical differences reported here are regional, being restricted to specific gyri and hemispheres. No inter-group differences were found at the level of the whole-brain or the level of the cerebral hemispheres nor the lobar level, within hemisphere. This is consistent with prior reports finding no differences in cerebral asymmetries between Chinese and European Caucasian populations [25]. The regional specificity of the detected anatomical differences, at the gyral level and restricted to regions in which functional activation patterns differ between these language groups, is a further argument against the effect being genetic in origin. This argument is further supported by the fact that neither subject group was from a genetically restricted population. The EC group included persons with ancestors from numerous European countries. The CA group included persons from different regions within China. To help affirmatively answer the question of genetic influence, one needs to perform a longitudinal study of regional cerebral changes linked with developmental variables across the two populations. We intend to investigate this further when anatomical data for EC and CA children becomes available within the ICBM collaboration.

In the present study, previously reported population differences in brain functional organization were discovered to have anatomical concomitants using a deformation field morphometry (DFM) technique. DFM provides an objective, fully automated and unbiased way to perform anatomical analysis of regional brain-surface differences between populations. Because DFM analysis is performed on anatomical images, it is not influenced by the cognitive state at the time of imaging, making the technique robust and versatile. Thus a single anatomical image (per subject) can be used to search for anatomical differences anywhere in the brain. Functional studies (detecting task-induced regional activations), on the other hand, can only be used to compare regions recruited by the specific task. This means that the number of brain regions investigated per study is quite limited. Functional studies also require great care to

ensure comparability of the functional challenges across populations. Collectively, these considerations suggest that identification of inter-group differences in cognitive strategies should be addressed first at the anatomical level. Once anatomical differences are identified, functional studies can be carried out to determine the functions performed by those regions.

CONCLUSIONS

Anatomical differences in language-related brain regions between natively English-speaking Caucasian (EC) and natively Chinese-speaking Asians (CA) were clearly identified. As these anatomical differences are in brain regions recently established by functional imaging to be differentially activated in these two populations, we interpret our findings as anatomical plasticity driven by differences in the systems-level organization of linguistic functions attributable to native language. To our knowledge, this is the first report of a brain anatomical difference attributable to learned cognitive strategy.

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