Positional and surface area asymmetry of the human cerebral cortex

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A B S T R A C T

Previous studies of cortical asymmetry have relied mainly on voxel-based morphometry (VBM), or manual segmentation of regions of interest. This study uses fully automated, surface-based techniques to analyse position and surface area asymmetry for the mid-surfaces of 112 right-handed subjects' cortical hemispheres from a cohort of young adults. Native space measurements of local surface area asymmetry and vertex position asymmetry were calculated from surfaces registered to a previously validated hemisphere-unbiased surface-based template. Our analysis confirms previously identified hemispheric asymmetries (Yakovlevian torque, frontal and occipital petalia) in enhanced detail. It does not support previous findings of gender/ asymmetry interactions or rightward planum parietale areal increase. It reveals several new findings, including a striking leftward increase in surface area of the supramarginal gyrus (peak effect 18%), compared with a smaller areal increase in the left Heschl's gyrus and planum temporale region (peak effect 8%). A second finding was rightward increase in surface area (peak effect 10%) in a band around the medial junction between the occipital lobe, and parietal and temporal lobes. By clearly separating out the effects of structural translocation and surface area change from those of thickness and curvature, this study resolves the confound of these variables inherent in VBM studies.

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Introduction

Hemispheric functional and structural asymmetries are well known features of the human brain. It has been proposed that they reflect evolutionary, hereditary, developmental, experiential, and pathological factors and have frequently been associated with language lateralization (Geschwind and Levitsky, 1968; Price, 2000; Toga and Thompson, 2003). Functional lateralization of language and other cognitive functions, such as visuospatial processes, has been argued to be more efficient as it avoids competition between hemispheres for the control of motor responses and could theoretically speed up processing by allowing transfer of information between closely knit focal areas located in the same hemisphere rather than through inter-hemispheric connection fibers (Witelson, 1985). Others have argued that the left hemisphere's specialization over language is related to its dominance for the fine movement of the right hand (Kimura, 1973), while other models suggest that functional and structural lateralization of auditory cortices is related to differences in the way acoustical features relevant for speech and other sounds are processed (Zatorre et al., 2002).

The most conspicuous features of brain hemispheric structural asymmetry are the relative protrusions of the right frontal and left occipital lobes that are so pronounced as to leave an inner impression in the skull (known as petalia). An associated finding is an often wider right than left frontal lobe and the reverse pattern for the occipital lobe (LeMay, 1976). These geometric distortions, which are also frequently associated with an extension of the right occipital and left frontal lobes across the inter-hemispheric midline and to a shift of structures surrounding the Sylvian fissure, are together referred to as the Yakovlevian anticlockwise torque (LeMay, 1976; Yakovlev and Rakic, 1966). Another well-established hemispheric asymmetry includes the trajectory of the Sylvian fissure which, at its posterior limit, curves upwards more anteriorly on the right than on the left hemisphere (Geschwind and Levitsky, 1968). The planum temporale (PT), a region in the posterior dorsal surface of the superior temporal gyrus that is thought to be relevant for the processing of speech has been reported to be larger on the left side by many investigators (e.g. Geschwind and Levitsky, 1968; Steinmetz, 1996). The volume of Heschl's gyrus has also been reported to be greater on the left side (Penhune et al., 1996); furthermore the degree of HG asymmetry across individuals predicts...
to some extent both functional activation patterns (Warrier et al., 2009) and behavioral ability to learn novel speech sounds (Golestani and Zatorre, 2004; Wong et al., 2008). Conversely, the planum parietale (PP), the posterior wall of the posterior ascending ramus of the Sylvian fissure has been shown to be larger in the right hemisphere (Gannon et al., 2005; Jancke et al., 1994).

Other previously observed asymmetries include the anterior cingulate cortex (ACC) and the central sulcus (CS). The volume of the right ACC has been shown to be larger than the left (Pujol et al., 2002), and there is evidence of significant sulcal pattern asymmetries in this region (Paus et al., 1996). Hutsler et al. (1998) manually segmented the cingulate and post-central gyrus in mesh representations of the left and right hemispheres of ten right-handed subjects. Although the results did not reach statistical significance, the size of the cingulate gyrus showed a right greater than left tendency and the post-central gyrus showed a left greater than right tendency. Cykowski et al. (2008) used an automated, approach to study the sulcal depth of the central sulcus (CS) and demonstrated that the superior CS in men, and the midpoint of the CS in women had leftward asymmetry. Other MR morphometry studies used manual segmentation to explore CS depth asymmetry (e.g. Amunts et al., 2000; Amunts et al., 1996; Davatzikos and Bryan, 2002), and reported handedness effects that showed the dominant hemisphere to be deeper than the non-dominant.

Both structural and functional inter-hemispheric brain asymmetries have frequently been reported to be influenced, among other factors, by gender and handedness. Several studies suggest that the male brain is more functionally lateralized (Lake and Bryden, 1976; Shawritz et al., 1995; Toga and Thompson, 2003). While greater functional lateralization of visual processing skills in males is a relatively consistent finding (e.g. Bourne, 2005; Johnson et al., 2002; Rasmjou et al., 1999), the functional lateralization of language perception reported by Shaywitz et al. (1995) is less consistently found and remains controversial (e.g. Hund-Georgiadis et al., 2002; Obleser et al., 2001). In the structural realm, the asymmetry of the PT, while controversial, is reported to be greater for males (Good et al., 2001). Gender specificity was not consistently found in the case of the asymmetry of the PP, which has been reported to be larger in the right hemisphere (Gannon et al., 2005; Jancke et al., 1994). Whatever the underlying cause or causes responsible for gender-related asymmetries, they are thought to reflect the known gender differences in motor and visuospatial skills, linguistic performance, and vulnerability to deficits following focal cerebral lesions (Kimura, 2000).

In the past, the most commonly used method for the assessment of asymmetry in magnetic resonance imaging (MRI) studies has been manual segmentation (e.g. Founds et al., 1999); a method that is time consuming and limited to a priori determined regions of interest. Further, in the absence of standardized methods of measurement, there has been considerable uncertainty regarding the exact anatomic definitions of the posterior border of the PT (Steinmetz et al., 1989; Westbury et al., 1999). The method used in these earlier studies (the ‘knife-cut’ rule) has exhibited good inter-rater reliability within individual research groups, but large variability between different research groups, suggesting that the method is poorly defined operationally (Westbury et al., 1999). New, precise, and more reliable technical standards of identifying the anatomic borders of the PT (Westbury et al., 1999), and computer-assisted measurement (Kim et al., 2000; Barta and Dazzan, 2003) promise to improve the uniformity of results in these MRI studies.

Recently, several groups have applied automatic techniques to analyse morphological asymmetries in the human brain. Watkins et al. (2001) and Good et al. (2001) used VBM to analyse asymmetries of grey matter density. As both papers concede, when the registration strategy employed is low-dimensional (normalizing only gradual low-frequency distortions in brain shape), VBM cannot disambiguate grey matter density asymmetries caused by systemic local (high-frequency) structural translocations from those caused by biologically-based changes in the size of corresponding anatomical structures. More recently, Luders et al. (2006) analysed the asymmetry in cortical thickness computed from gray matter tissue maps of 60 subjects and aligned using a surface-based registration strategy. Intriguingly, they show diffuse and widespread cortical thickness asymmetries.

In this study, we employed fully automated processing and analysis of MRI data that allowed for the direct study of positional and area asymmetry of the cortical mid-surface on a whole-brain vertex-based corticometric basis, complementing and extending existing techniques of cortical thickness analysis, VBM, and manual segmentation. Several recent publications (Barta et al., 1997; Chance et al., 2008; Harasty et al., 2003) have underlined the utility of surface area as a measure of cortical morphometry since it relates directly to mini-column number and spacing (Chance et al., 2008). We apply our methods to a normative adult cohort and examine the effects of gender and brain size on patterns of asymmetry. As inter-hemispheric brain asymmetries have functional correlates, a good characterization of these asymmetries promises to further our understanding of normal and pathological brain function. The following well-established and frequently demonstrated findings with likely corollary impacts on cortical area or positional asymmetries were expected here and served as a proof of principle of the current methods:

(i) Yakovlevian torque and frontal and occipital petalia.
(ii) Perisylvian asymmetry including the positional asymmetry of its posterior limit as well as planum temporale asymmetry

Materials and methods

Data acquisition

This study uses a subset of the International Consortium for Brain Mapping (ICBM) dataset of magnetic resonance images (MRIs) that has been described elsewhere (Watkins et al., 2001). In brief, the subjects were 112 unselected normal, right-handed volunteers (68 males and 44 females), ranging in age from 18 to 44 years (mean 24.82, SD 4.81). Each subject gave written informed consent; the Research Ethics Committee of the Montreal Neurological Institute and Hospital approved the study. Subjects were scanned using a Phillips Gyroscan 1.5 T superconducting magnet system. T1-weighted images were generated from a 3D fast field echo sequence with 140–160 slices at 1 mm isotropic resolution, with a TR of 18 ms, a TE of 0 ms, and a flip angle of 30°.

Processing of MRI data

All MR images were submitted to the CIVET pipeline (version 1.1.7) (http://wiki.bic.mcgill.ca/index.php/CIVET) developed at the MRI for fully automated structural image analysis (Ad-Dab’bagh et al., 2006; Zijdenbos et al., 2002), The main pipeline processing steps: i) linearly register native MR images to standardized MNI–Talairach space based on the ICBM152 data set (Collins et al., 1994; Mazzotta et al., 1995, 2001; Talairach and Tournoux, 1988). ii) Correct for intensity non-uniformity artifacts using N3 (Sled et al., 1998). iii) Classify the image into white matter (WM), gray matter (GM), cerebrospinal fluid (CSF) and background using a neural net classifier (INSECT) (Zijdenbos et al., 1998). iv) Compute partial volume tissue fractions and an enhanced CSF skeleton (Kim et al., 2005). v) Fit images with a deformable mesh model to extract 2-dimensional inner (WM/GM interface) and outer (pial) cortical surfaces for each hemisphere using the 3rd edition of the CLASP algorithm (Kabani et al., 2001; Kim et al., 2005; MacDonald et al., 2000). vi) Generate cortical mid-surfaces by taking mid-points of the linked inner and outer surfaces. vii) Non-linearly align these hemisphere mid-surfaces with SURFTRACC.
follows the surface manifold and thus respects anatomical boundaries. Diffusion smoothing, unlike the volumetric blurring used in VBM, a 40 mm FWHM surface-based blurring kernel (Chung et al., 2001). Measurements of cerebral volume, vertex position asymmetry and surface area asymmetry are then calculated.

Hemisphere mid-surfaces were used for positional and surface-area asymmetry calculation because they provide a relatively unbiased representation of sulcal vs gyral regions (Im et al., 2008; Van Essen et al., 2006).

Cerebral volume
Cerebral volume was calculated for each subject as the sum of volume enclosed by the subject’s two native-scaled outer (pial) cortical hemisphere surfaces, excluding both the brainstem and cerebellum.

Vertex position asymmetry
Surface registration shifts the vertices of each subject hemisphere across its surface into correspondence with the vertices of the registration template (Lyttelton et al., 2007). Since the identical hemisphere-unbiased template is used for the registration of both left and right hemispheres, a correspondence is generated between the vertices of the left and right subject hemispheres. The coordinates of each subject’s rescaled registered right hemisphere vertices were reflected through the Talairach plane X = 0 (“flipped”), and vector-subtracted from the subject’s rescaled registered left hemisphere coordinates to yield native scale positional asymmetry vectors for every subject at every vertex on the iterative template. Thus, for each vertex of each subject, the asymmetry vector records the displacement between the subject’s left and flipped right aligned native-scaled hemispheres.

Surface area asymmetry
Cortical surface area was measured by calculating the area of each triangle of each subject’s rescaled mid-surface hemispheres, and assigning a third of this area to each of its three vertices (i.e. the area assigned to any vertex is one third of the total area of all triangular facets adjoining it). Each subject’s mid-surface area measurements were smoothed with respect to the registration model geometry using a 40 mm FWHM surface-based blurring kernel (Chung et al., 2001). Diffusion smoothing, unlike the volumetric blurring used in VBM, follows the surface manifold and thus respects anatomical boundaries.

Subject asymmetry was calculated for each vertex of the mesh as the log-transformed ratio of left over right smoothed surface area. Thus, for each vertex of each subject, the asymmetry value at each vertex represents the log ratio of the left to right surface areas in a local weighted ROI defined by the smoothing kernel. Surface area asymmetry results were not overly sensitive to the size of smoothing kernel or choice of mid-surface. Separate datasets were generated using a 20 mm smoothing kernel, and also using the inner (WM/GM) surfaces, with both alternative datasets producing very similar results to those reported.

Statistical analysis
Statistical analyses were implemented using SurfStat, a statistical toolbox based on Random Field Theory (RFT) (Worsley et al., 1996, 2004) created for MATLAB 7 (The MathWorks, Inc.) by Dr. Keith Worsley (http://www.math.mcgill.ca/keith/surfstat/) at the MNI. Each subject’s native-scaled surface area (univariate), and positional (3-vector), asymmetry measurements were regressed against their cerebral volume and gender using the following linear model:

\[ Y = b_0 + b_1 CV + b_2 G + \varepsilon \]

where \( Y \) was either the univariate surface area asymmetry or the multivariate vertex position asymmetry, CV was cerebral volume, G was the subject’s gender, and \( \varepsilon \) was the error term. Testing a null hypothesis for the coefficient of interest in the model above leads to a surface map \( T \) that is either a t-statistic (in the case where \( Y \) is univariate) or a Hotelling’s \( T^2 \) (in the case where \( Y \) is multivariate). The RFT approach is based on modelling such a map \( T \) as a smooth random field and providing a suitable approximation for the distribution of its maximum, \( T_{\text{max}} \). RFT provides a decision threshold \( t_\alpha \), corrected for multiple comparisons, and such that the probability of \( T_{\text{max}} \) exceeding \( t_\alpha \) be less or equal to \( \alpha \) (usually \( \alpha = 0.05 \)). Significant regions are detected at those vertices for which \( T \) exceeds \( t_\alpha \). The resulting map \( T \) is a standard random field. The value \( t_\alpha \) was computed from standard RFT (Cao and Worsley, 1999; Worsley, 1994), using the Matlab code “stat_threshold”, provided in http://www.math.mcgill.ca/keith/surfstat/.

Results
Surface area analysis
The results of the surface area asymmetry analysis are shown in Fig. 2. The effect map has been masked to show only significant areas of positive asymmetry.
vertices using random field theory with alpha set to 0.05. Non-significant vertices were set to zero. Leftward asymmetry is focused in the supramarginal gyrus (SMG), much of the superior temporal plane (including Heschl's gyrus and the PT), anterior portions of the superior temporal gyrus and sulcus, and posterior portions of the orbital frontal cortex (OFC). Rightward asymmetry is prominent in a band running around the anterior occipital lobe, in the cingulated, and around the gyrus rectus. No significant local cerebral volume or gender effects were detected.

Vertex position analysis

Fig. 3 shows a thresholded effect map of the significant vertex displacement between the left and right hemispheres (RFT thresholded, alpha 0.05, non-significant vertices set to zero). The map is dominated by the displacement of the posterior ascending ramus of the Sylvian fissure (PAR), which is anteriorly translocated in the right hemisphere. Arrows indicate the direction of the displacements. Smaller but significant displacements shift the right frontal pole (gyrus rectus) and left occipital pole laterally towards the opposing hemisphere.

Fig. 2. Thresholded surface area asymmetry effect map (RFT threshold α = 0.05). Leftward asymmetry is focused in the supramarginal gyrus, planum temporale, anterior lateral temporal lobe, and lateral orbital frontal cortex. Rightward asymmetry is prominent in a band running around the anterior occipital lobe, in the cingulated, and around the gyrus rectus.

Fig. 3. Average left hemisphere coloured with millimetre displacement to average right hemisphere (RFT threshold α = 0.05). Lines show movement to right hemisphere location. The most dominant effect is the anterior–posterior translocation of the ascending portion of the temporal gyrus. Patilia shift is also present as demonstrated clearly in the movie in supplementary materials.
hemisphere. These movements are more easily visualized in the accompanying movie in supplementary materials. No significant local cerebral volume or gender effects were detected.

Fig. 4 shows the significance of vertex displacement asymmetry (RFT threshold \( \alpha = 0.05 \)). Although much of the cortex shows significant asymmetry, the significance hotspot occurs in the planum temporale, consistent with the focus of previous research in this area.

Discussion

The use of a fully automated surface analysis of cortical morphology in a large population of normal subjects has generated a series of findings that both confirm and refute previous reports based on manual analysis in smaller populations. Moreover, some novel findings have arisen.

Proof of principle and confirmed findings

Vertex displacement analysis served to visualize and quantify hemispheric displacements in the vicinity of the PT as well as frontal and occipital displacement effects associated with the well-documented Yakovlevian torque (LeMay, 1976; Yakovlev and Rakic, 1966). Our analysis supports previously reported rightward areal increase for the dorsal portion of the ACC (Pujol et al., 2002) and confirms the presence of significant leftward areal asymmetries in the superior temporal plane (Steinmetz, 1996). These leftward areal asymmetries encompass much of the region containing primary and secondary auditory cortices, including Heschl's gyrus (HG), consistent with prior findings of volumetric asymmetries in this vicinity (Penhune et al., 1996, 2003, Wong et al., 2008). Asymmetries have also been reported in the MR longitudinal relaxation rate, suggesting greater myelin content in the left than the right HG (Sigalovsky et al., 2006). These macrostructural asymmetries may be related to microstructural differences in columnar organization; in particular, cell columns in the left auditory cortex are more widely spaced (Seldon, 1981a; Chance et al., 2006), and have wider spacing of intrinsic connections (Galuske et al., 2000) than those on the right, all of which would be consistent with the surface area asymmetries we observed.

Unconfirmed findings

Our results do not support previous reports of a rightward PP areal asymmetry (Gannon et al., 2005; Jancke et al., 1994). This probably derives from the fact that the cortical surfaces of the PT and PP are contiguous and lack clearly defined landmarks that separate them. It is plausible that the overall asymmetry in the region surrounding the posterior parts of the Sylvian fissure (SF) is better accounted for by a simultaneous leftward posterior displacement and areal expansion, as illustrated in Fig. 5. This dynamic would lead to both a comparatively shorter (anterior-posterior axis) PT on the right, and an apparently longer right PAR, due to its anterior translocation. This finding is also consistent with the fact that the position of Heschl's sulcus is more posterior on the left than on the right (Penhune et al., 1996). The posterior shift on the left causes a less acute angle between the floor of the SF and the PAR, leading to an underestimation of the PAR on the
left when manual segmentation is attempted. Hence the expansion of the PT on the left comes at the expense of the PAR, and by extension the PP (Fig. 5). This explanation is consistent with other existing research that explains the observed PT asymmetry. Steinmetz et al., (1989) found that while the PT was larger on the left side, asymmetry decreased or disappeared when the posterior descending ramus of the SF was included in the calculation of PT size (producing what these authors referred to as 'PT+'). Supporting this notion of a spurious asymmetry based on subjective region labelling, Jancke et al., (1994) and Westbury et al. (1999) found that the sum of PT and PAR was not asymmetric even when each component was asymmetric when measured separately.

It has been documented that asymmetry in the superior temporal plane exists at least as early as birth and may change very little throughout development (Witelson and Pallie 1973; Galaburda et al., 1987), suggesting that recruitment of cortical columns, rather than post-natal synaptogenesis and pruning, may be more important in the determination of the relative sizes of these structures. One possibility might be that the left PT recruits more cortical columns posteriorly. This would drive the floor of the SF to expand backwards, leading to a downward and backward shift of the PAR. If this stretches the contiguous PP and inferior surface of the SMG, the surface for the entire area would technically expand, even if there were a reduction in the height of the PAR. This interpretation also explains our finding of a leftward asymmetry of the surface area of the SMG.

A controversial finding that was not supported was that of gender differences in asymmetry around the PT and PP (Jancke et al., 1994). It is difficult to disambiguate gender effects from those simply related to cerebral volume because, in general, cerebral volume is greater for men than women. As discussed by (Im et al., 2008), our methodology first extracts morphometric measurements in native space, and then includes both cerebral volume and gender as covariates in subsequent analysis. In that whole-brain analysis, neither local surface area asymmetry nor positional asymmetry was related to subject’s cerebral volume or gender. The absence of significant cerebral volume effects deserves attention. It is understandable in the case of surface area, since, in calculating local percent surface area asymmetry, bilateral changes in absolute local surface area are normalised. In the case of positional asymmetry however, we would predict that the magnitude of asymmetry should increase for larger cortices. Although this effect was not large enough to be significant at the vertex level, it was significant at an aggregate level. When the magnitude of each subject’s vertex displacements are averaged across all 40K vertices, larger brains correlate with greater average displacement magnitude, in accordance with our prediction (Fig. 6).

Our study did not support previous reported asymmetry in the depth of the central sulcus (Amunts et al., 2000; Amunts et al., 1996; Cykowski et al., 2008; Davatzikos and Bryan, 2002). This may be explained by the methodological differences between the studies. The metric they used was sulcal depth, rather than surface area. It is possible to have an increase in depth without increase in area if the width of the sulcus were correspondingly reduced. Secondly, these authors explored gender and handedness interactions whereas we did not. It is also worth noting that any exploratory whole-brain analysis will have less statistical power than a hypothesis driven ROI approach, due to the increased number of multiple comparisons.

![Fig. 6. Relationship between the average magnitude of vertex asymmetry displacement and cerebral volume. For every 100 cm³ increase in cerebral volume, the average distance between corresponding nodes on the left and flipped right hemispheres increase by 0.29 mm (p<0.01).](image)

![Fig. 7. Asymmetry of the medial parieto-occipito-temporal junction. On the left expanded detail view from Fig. 2 showing the rightward surface area asymmetry in this region. In the middle is a schematic showing how sulcal deepening could produce this effect. On the right is the effect map for depth-potential asymmetry (Boucher et al., 2009). The blue regions indicate that the right hemisphere surface is displaced outward relative to the left. The red regions indicate the converse. The deepening of the parieto-occipital fissure and calcarine sulcus coupled with the heightening of surrounding gyri can explain the rightward increase area in this region.](image)
Novel findings

The most striking result from our study is the leftward areal expansion in the SMG, as compared to its smaller counterpart in the PT (Fig. 2). This smaller leftward asymmetry in PT area coincides with an extremely significant posterior shift of the PT, as shown in Fig. 4. The significance of this posterior shift is explained by the low surface variability in this region. This may partly explain why the PT is a focus of asymmetry research, since the lower surface variability makes the asymmetry readily identifiable. Given the relative symmetry of the pre-central and post-central gyri and the posterior translocation of the posterior ascending ramus of the Sylvian fissure in the left hemisphere, the leftward expansion in surface area around the SMG is predictable.

The SMG contains several distinct cytoarchitectonic areas, the largest being area PF, as described originally by von Economo and Koskinas (1925) and updated by Caspers et al. (2006). This region closely matches the spatial location of our observed asymmetry in SMG area. No statistically significant asymmetry in cytoarchitectural volume has been reported for the SMG (Caspers et al., 2008; Eidelberg and Galaburda, 1984). However, Caspers et al. (2008) did report a non-significant 15% leftward asymmetry in PF volume. The magnitude of this volume asymmetry closely matches that of our observed asymmetry in SMG surface area (leftward 18%). It is possible that that their result did not reach significance because of (a) different samples: the histological studies had low sample sizes (N = 8,10) compared with ours (N = 112), (b) different boundary definitions: tight correspondence would require that histological boundaries align closely with gross cortical morphology (class two variability (Rade-maker et al., 1993)); and (c) methodological variance: the histological analysis techniques used in (Caspers et al., 2008) provide a unique insight into cortical microstructure but the extensive processing needed could add variability. Despite the lack of statistical significance of the Caspers result, it is encouraging that similar trends are observed in volume and area asymmetry in the SMG region while using such different techniques.

Given the substantial contribution of the SMG to language functions as part of Wernicke’s area (Demonet et al., 1992), it is plausible that the SMG requires a greater surface area on the left in right-handed individuals, in the same manner as the PT. Whether the increase in surface area surrounding the left SMG is directly related to left-dominant language processing, and/or is simply an epiphenomenon of the reorganisation of structures around the posterior Sylvian fissure remains to be established.

Another novel finding is the increase in surface area in the parieto-occipital fissure in the right hemisphere (Fig. 2). Given that Yaklovian torque twists the left occipital pole across the midline, squeezing the right occipital lobe anteriorly, this result seems at first glance counterintuitive. However, a significant deepening of the junction between the occipito-parietal fissure and the calcarine sulcus in the right hemisphere can explain this finding (Fig. 7). This structural asymmetry in visual association cortices might be related to a functional asymmetry in visuospatial processing (Hellige, 1996; Irving-Bell et al., 1999; Sack et al., 2002). For instance, it has been reported that lesions in the right association cortices are more likely to produce anosognosia syndromes (Ramachandran, 1995). It is plausible that rightward increase in surface area relates to the rightward functional dominance in this region. Another contribution to this asymmetry might be mechanical in origin. The leftward expansion of the structures surrounding the Sylvian fissure and the posterior shift of the lateral parietal and occipital lobes squeeze the right occipital lobe anteriorly, perhaps necessitating structural reorganisation of the right occipital and parietal lobes. It is noteworthy that Van Essen’s tension-based theory of morphogenesis which proposes that mechanical tension, working against internally generated hydrostatic pressure, could potentially explain the cortical folding patterns and associated hemispheric differences in surface area found here (Van Essen, 1997).

Finally, our results reveal a systematic asymmetry in surface area in the orbital–frontal cortex (OFC), a region involved in complex viscerosomatic, emotional salience and reward-related cognitive systems (Rolls, 2000; Whittle et al., 2008). While some studies have shown evidence of functional lateralization (see Whittle et al., 2008), the functional significance of anatomical asymmetry of the OFC remains unclear. We report two specific forms of OFC surface area asymmetry. First, a medial rightward surface area expansion of the gyrus rectus, which is consistent with the reported rightward volumetric asymmetry of the gyrus rectus (Nakamura et al., 2008). Second, a lateral leftward expansion of the posterior orbital gyrus. The normal and asymmetric sulcal pattern variation in the OFC, which determines the shape of the medial, lateral, anterior and posterior orbital frontal gyri, but not the gyrus rectus, may in part explain this robust finding (Chiavaras and Petrides, 2000; Nakamura et al., 2007).

Methodological issues

The main advantage of explicit modelling of the cortical manifold is that group-dependent or longitudinal changes in cortical thickness, cortical surface area, gyration index and structural translations can be separately evaluated. A detailed understanding of which shape attributes account for the anatomical differences found in any given study might lead to different hypotheses of underlying biological mechanisms. Surface analysis techniques thus extend VBM by separating different components that contribute to bulk changes in overall gray matter distribution. For example, the pattern of leftward SMG surface-area asymmetry reported here is absent in the (Luders et al., 2006) analysis of cortical thickness, it is a result of a change in the number or spacing of cortical columns (Chance et al., 2008), rather than a change in density of dendritic arborisation or the extent of pruning.

Differences are also to be expected between our results and those produced by manual segmentation of cortical regions of interest for the same reason that it is impossible to separately decompose volumes of regions of interest into measures of mean cortical thickness and total surface area.

Conclusion

We have presented a novel corticometric methodology and applied it to the analysis of cortical asymmetry of position and surface area. Our results confirm the previously documented effects of Yaklovian torque and petalia shift, leftward areal increase in the superior temporal plane and rightward areal increase in the dorsal ACC. Our results do not support the reported rightward PP asymmetry, but rather explain these effects on the basis of positional shifts. We did not find any gender asymmetry interaction. We report several novel findings, including increased leftward areal expansion focused on the SMG, and rightward areal expansion in a band around the junction between the occipital lobe, and parietal and temporal lobes. Our technique complements and extends existing methodology, and provides specific advantages, particularly in the disambiguation of underlying causes of statistically significant cortical changes.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.neuroimage.2009.03.063.

References


