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The relationship between the presence of sulcal pits and intelligence in human brains

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ABSTRACT

Sulcal pits are hypothesized to form early during development and be under tighter genetic control than other regions of the cortex. We investigated the relationship between the presence of sulcal pits and intellectual ability, estimated with the full-scale, verbal, and performance intelligence quotient (IQ), in the brains of 78 healthy young adults. We automatically extracted sulcal pits from magnetic resonance images and developed a method for their automatic labeling. The difference in the number of sulcal pits between high and average IQ groups for each labeled region was statistically analyzed. We found that in the high verbal IQ group a sulcal pit was more frequently present in the left posterior inferior frontal sulcus (70% in the high IQ group vs. 40% in the average IQ group) and the right posterior inferior temporal sulcus (70% vs. 43%), which have been reported to be regions of language function. Greater mean curvature of the deep sulcal areas in these regions was shown for the high verbal IQ group. This provides the complementary morphological information about the presence of more sulcal pits. These findings suggest that factors influencing verbal intelligence may emerge in the language areas early during cortical development and may be under tight genetic control.

Introduction

Structural neuroimaging analyses have reported significant associations between general intellectual ability and brain structure in humans. Human intelligence has been correlated with several cerebral characteristics, such as brain size, global and regional volume of gray and white matter, and the thickness of the cortex and corpus callosum (Choi et al., 2008; Haier et al., 2004; Luders et al., 2007; McDaniel, 2005; Narr et al., 2007; Posthuma et al., 2002; Shaw et al., 2006). In addition to volumetric characteristics, cortical sulcal shape is considered another important neuroimaging marker of brain function. With respect to intellectual ability, our previous study examined the relationship between global cortical complexity, which was measured by fractal dimension, and the full-scale intelligence quotient (IQ) (Im et al., 2006). Another study extended our previous finding, showing significant positive correlations between intelligence and local cortical complexity based on the calculation of mean curvature in the left temporo-occipital lobe and posterior cingulate gyrus (Luders et al., 2008).

To understand the complex sulcal pattern, its development and the large intersubject variability, a new sulcal feature, called the *sulcal pit*, has recently been introduced (Lohmann et al., 2008). Sulcal pits are defined as the deepest local regions of sulci, and are thought to be the first cortical folds that occur during radial growth of the cerebral cortex and the process of gyrogenesis. Their formation might be more influenced by genetic than environmental factors because they show relatively invariant spatial distribution, which may be due to a human-specific predetermined protomap of functional areas and spatial immobility during development (Hasnain et al., 2001, 2006; Im et al., 2010; Lohmann et al., 1999, 2008; Rakic, 1988; Regis et al., 2005). We examined the hemispheric asymmetry of sulcal pits and showed the higher frequency and smaller spatial variance of sulcal pits in the left superior temporal regions which are part of Wernicke's area. It may be related to the lateralization of language function to the left hemisphere (Im et al., 2010). This suggests that the formation of sulcal pits in some specific functional areas could be associated with increased intellectual and cognitive performance. In other words, brain function and sulcal pits might be related, and their relationship could provide novel insights into factors governing human intelligence and brain structure.

In this study, to examine the relationship between the presence of the sulcal pits and intellectual ability estimated with IQ scores from healthy individuals, we statistically analyzed the difference in the frequency of sulcal pits (the number or percentage of sulcal pits present) between high and average IQ groups from magnetic resonance imaging (MRI) data. For automatic regional analysis, we developed a novel method for automatically defining anatomical labels of sulcal pits located in corresponding sulcal regions across

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subjects. Furthermore, we analyzed cortical thickness and curvature in statistically significant regions to provide complementary morphological information related to our findings.

Material and methods

Data acquisition

Protocols were approved by the relevant institutional review boards (Seoul National University, Catholic University of Korea), and written informed consent was obtained from participants. Volunteers were recruited through advertisements and screened to cover the entire range of intelligence except the potentially retarded range. We administered a reliable and valid intelligence test, the Wechsler Adult Intelligence Scale—Revised test (Wechsler, 1981), to assess psychometric IQ in 78 healthy young adults. The subjects consisted of 39 men and 39 women, and their ages ranged from 17.6 to 27 years (mean ± standard deviation [SD]: 22.7 ± 1.9 years). We measured the full-scale IQ from 11 subtests on the following diverse cognitive abilities: information, comprehension, vocabulary, similarities, block design, object assembly, picture completion, digit span, arithmetic, digit symbol, and picture arrangement. Full-scale IQ scores ranged from 83 to 143 (mean ± SD: 120.8 ± 13). We also measured verbal and performance IQ. Verbal IQ results ranged from 88 to 148 (mean ± SD: 120.2 ± 13.8), and performance IQ results ranged from 79 to 140 (mean ± SD: 117.2 ± 12.1). Subjects were scanned for MRI data at the Neuroscience Research Institute (Gachon University, Korea). Contiguous 0.9 mm axial MPRAGE images were acquired with a 1.5 T MR scanner (Magnetom Avanto, Siemens) with TR = 1160 ms; TE = 4.3 ms; flip = 15°; FOV = 224 mm; matrix = 512 × 512; and number of slices = 192 (the x, y, z dimensions of the reconstructed voxel: 0.44 × 0.44 × 0.90 [mm]). Two images were acquired and averaged for each subject.

Image processing and cortical surface extraction

The native images were normalized to a standardized stereotaxic space using a linear transformation and corrected for intensity nonuniformity (Collins et al., 1994; Sled et al., 1998). Then, images were classified into white matter, gray matter, cerebrospinal fluid, and background using an advanced neural net classifier (Zijdenbos et al., 1996). The hemispherical surfaces of the inner (gray/white matter boundary) and outer (gray matter/cerebrospinal fluid boundary) cortex were automatically extracted, consisting of 40,962 vertices (Kim et al., 2005; MacDonald et al., 2000). We used the inner cortical surface to extract the sulcal pits.

Extraction of sulcal pits on the cortical surface

A sulcal pit is the deepest local point in a sulcal catchment basin, and can be identified by using a sulcal depth map on the cortical surface. Sulcal depth maps were generated by measuring the 3D Euclidean distance from each vertex in the cortical surface to the nearest voxel on the cerebral hull (Im et al., 2008a, 2010). We used a watershed algorithm based on a depth map to extract sulcal pits on triangular meshes. To prevent overextraction of the pits, we first reduced noisy depth variations by surface-based diffusion smoothing with a full-width half-maximum (FWHM) value of 10 mm (Chung et al., 2003). Then we performed segment merging in the watershed algorithm using the area of the catchment basin, the distance between the sulcal pits, and the ridge height. If one of the areas of two or more catchment basins was smaller than a threshold (30 mm^2) when they met at a ridge point, the smaller catchment basin below the threshold was merged into the adjacent catchment basin with the deepest pit and its sulcal pit removed. If the distance between two pits was less than a 15 mm threshold, the shallower pit was also merged into the deeper one. Finally, merging was executed when the ridge was lower than a threshold of 2.5 mm. We explained methodological procedures in more detail and showed that the smoothing and merging thresholds cooperate well in detecting appropriate sulcal pits in our previous study (Im et al., 2010).

Cortical thickness

The inner and outer surfaces had the same number of vertices, and there was a close correspondence between the counterpart vertices of the inner and outer cortical surfaces. The cortical thickness was defined as the Euclidean distance between these linked vertices (Lerch and Evans, 2005).

Absolute mean curvature

We measured the mean curvature for each vertex on a discrete surface model of the inner cortex (Meyer et al., 2002). The sign of the mean curvature was negative on an inwardly folded region and positive on an outwardly folded region. Because mean curvature is susceptible to noise features and small geometric changes of shape, we smoothed the cortical surface model geometrically. The smoothing algorithm changed the 3-D position of each vertex toward the barycenter of its first neighbors as one step (Im et al., 2008a,b; Toro and Burnod, 2003). Mean curvature was measured on the surface after 10 iterations of smoothing. It was validated in our previous study that 10 iterations of smoothing is appropriate for reducing noise features, but preserving the original folding pattern (Im et al., 2008b). The absolute value of the mean curvature was used to characterize cortical folding in regions of sulcal pits.

Automatic labeling of sulcal pits

In our previous study, a group map of sulcal pits was constructed by transforming 148 individual maps to a surface group template (Im et al., 2010). We defined clusters from the distribution of the pits and classified each pit with reference to 48 anatomical labels on the group template. Here, we present a procedure for the automatic labeling of sulcal pits using previously labeled data as a training set. We matched variable sulcal folding patterns to the surface group template with a 2D surface-based registration (Lyttelton et al., 2007; Robbins et al., 2004). Given spatial alignment, we can use the spatial distribution of a previously labeled sulcal pit as prior information on the template space. In addition, inherent geometric information of the sulcal pit can be a feature for computing the probability of its label. We used the depth of a sulcal pit as a geometric feature. Assigning label (W) to each sulcal pit (S) from its geometric feature (F) and prior information can be understood as a general Bayesian formulation.

$$P(W|F) \propto P(F|W)P(W)$$
$$S = (s_1, s_2, s_3, \ldots, s_m):\ \text{a set of sulcal pits}$$
$$W = (w_1, w_2, w_3, \ldots, w_m):\ \text{a labeling of } S$$
$$F = (f_1, f_2, f_3, \ldots, f_m):\ \text{an observed geometric feature on } S.$$

We computed the maximum *a posteriori* estimate of the label. Each sulcal pit s_i was labeled with w_i that maximized the conditional posterior probability, given the product of the probability of observing the geometry f_i with the prior probability at the location of s_i on the template.

$$arg\ max_{w_i \in \Lambda} P(w_i|f_i) \propto arg\ max_{w_i \in \Lambda} P(f_i|w_i)P(w_i)$$
$$\Lambda:\ \text{a set of 48 labels},\ w_i \in \Lambda.$$

The prior probability of the label was estimated to be the frequency of labeled sulcal pits occurring at each location on the template space. To make a smooth probability map of sulcal pits, the pits were Gaussian blurred with a surface-based diffusion smoothing