Prediction of Human Intelligence using Morphometric Characteristics of Cerebral Cortex

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Abstract-A number of studies from imaging data have reported neuroanatomical correlates of intelligence. However, studies related to intelligence assessing all possible aspects of cortical structure have been little addressed. We examined the relationship between human intelligence and morphometric characteristics of cortical surface such as gray matter volume, surface area, thickness, convolution, and sulcal depth with 79 young people (Age range: 17-27, Male/Female: 39/39). All cortical measures were calculated each lobe region and hemisphere in native space. Our study also addressed to predict the human intelligence using the morphometric characteristics correlated to intelligence quotient (IO). We applied partial least squares to analyze complex information obtained from different structural properties of the cerebral cortex. We found that there were no significant relationships between each cortical measurement and IQ while considering age, gender and intracranial volume (ICV). When we examined the same regression model excluding ICV, some cortical measurements were associated with IQ frequently in frontal and temporal lobe. It might conclude that human intelligence is significantly correlated with the cortical complexity coming from brain size, rather than cortical shape itself. The combination of various cortical measurements explained 52.57% of IQ. The results showed that they were more useful for prediction of human intelligence than alone. Our findings may suggest that makes it

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Index Terms—Prediction, human intelligence, characteristics of cerebral cortex, Partial least square regression, MRI

I. INTRODUCTION

Previous studies have reported neuroanatomical correlates of intelligence with various cerebral characteristics, such as the size of the brain, the volumes of subcortical and cerebellar regions, the thickness of the corpus callosum, the amount of intracranial tissue and the thickness of the cortex as well as the cortical convolution as a degree of the cortical folding [1-4]. As three-dimensional surface based methods were advanced, cortical measures have been used for studies of correlations between intelligence and cortical thickness in local variations [4-6] and of relationships between intelligence and cortical convolution [2]. Although the positive associations with intelligence and brain morphology are revealed by cortical thickness and convolution measurements, these single measurements are not sufficient to reflect various aspects of cortical shape. Our previous study investigated the variation of the fractal dimension (FD) through analysis of cortical thickness, sulcal depth, and folding area, which reflected the cortical complexity [7]. The results show a negative correlation between cortical thickness and FD in particular region, which means that a thick cerebral cortex had a less complex cortical structure than a thin cortex [7]. It is important to provide more information about cortical characteristics with several measurements than a single measurement because that can suggest more detailed biological and neuro-developmental implications [7]. However, studies related to intelligence assessing all possible aspects of cortical structure have been little addressed. Recent study reported a neurometric intelligence quotient (IQ) model to predict intelligence prospectively from brain structure and function [8]. It showed that brain images can be used to predict complex behaviors and traits. But Choi YY et al. mentioned that few anatomical studies have strongly implicated specific areas in g [9-10].

In this study, we examined the relationship between intelligence and gray matter volume, cortical surface area, cortical thickness, cortical convolution, and sulcal depth in the sulcal region, respectively. We hypothesized that greater intelligence had more complex brains. Our study also addressed to predict the human intelligence using morphometric characteristics of cortical surface correlated to IQ. Our second hypothesis was that the combination of various cortical measurements would provide to be more useful for prediction of human intelligence than alone. We applied partial least squares regression (PLSR) for prediction of human intelligence to analyze complex information obtained from different structural properties of the cortical surface. Our findings may suggest that makes it possible to predict human intelligence by cortical structures.

II. MATERIALS AND METHODS

A. MRI data Acquisition

Seventy eight healthy young Korean subjects were scanned at the Neuroscience Research Institute (NRI, Gachon University, Korea) with demographic data including age (39 men and 39 women; ages range of 17 - 27 years; mean \pm standard deviation [SD]: 22.7 \pm 1.9 years). At NRI, contiguous 0.9mm axial MPRAGE images were acquired with a 1.5T MR scanner (Magnetom Avanto, Siemens) with TR=1160 ms; TE=4.3 ms; flip=15°; FOV=224 mm; matrix=512x512 ; and number of slices = 192. Two images were acquired and averaged for each subject.

B. Participants

All participants underwent both the Korean version of the Wechsler Adult Intelligence Scale Revised (WAIS). The WAIS is a standard intelligence quotient (IQ) test that incorporates 11 subtests on diverse cognitive abilities: Information, Comprehension, Vocabulary, Similarities, Block Design, Object Assembly, Picture Completion, Digit Span, Arithmetic, Digit Symbol, and Picture Arrangement [11-12]. Verbal IQ (VIQ) and Performance IQ (PIQ) are the subtests of WAIS Verbal Comprehension subtests, and Perceptual Organization subsets, respectively. The intelligence quotient scores were FSIQ (mean \pm standard deviation [SD]: 120.8 \pm 13.0), VIQ (mean \pm standard deviation [SD]: 117.2 \pm 12.1).

C. Data Preprocessing

T1 native images were normalized to a standardized stereotaxic space using a linear transformation and corrected for intensity nonuniformity [13-14]. Then they were classified into white matter, gray matter, cerebrospinal fluid, and background using an advanced neural-net classifier [15]. The hemispherical surfaces of the inner and outer cortex were automatically extracted, consisting of 40,962 vertices using CIVET pipeline [16-17]. It has been performed for automatic surface parcellation of lobar regions using a surface registration algorithm efficiently and our previous studies extracted the lobar regional cortical thickness [18] and other cortical measurements [19].

D. Cortical Measurements

Brain size Intracranial volume (ICV) has been used by many researchers as an estimate for brain size [19-24]. ICV is defined as the total volume of gray matter, white matter, and cerebrospinal fluid.

| | TABLE I |
|-----|-------------------------------------|
| (A) | CORRELATION EFFECTS IN THE CORTICAL |
| | Fato |

| MEASUREMENTS WITH FSIQ | | | | | | | | | |
|------------------------|---|--------|--------|--------|--------|--------|--|--|--|
| | | Н | F | Т | Р | 0 | | | |
| Vol | L | 0.37* | 0.37* | 0.38* | 0.27* | 0.18 | | | |
| | R | 0.37* | 0.41* | 0.43* | 0.20 | 0.16 | | | |
| Area | L | 0.36* | 0.36* | 0.33* | 0.25* | 0.13 | | | |
| | R | 0.33* | 0.37* | 0.37* | 0.19 | 0.08 | | | |
| Thick | L | 0.26* | 0.21 | 0.37* | 0.17 | 0.14 | | | |
| | R | 0.30* | 0.30* | 0.44* | 0.14 | 0.19 | | | |
| Depth | L | 0.31* | 0.26* | 0.17 | 0.23* | 0.04 | | | |
| | R | 0.29* | 0.38* | 0.27* | -0.02 | 0.12 | | | |
| Curv. | L | -0.42* | -0.39* | -0.13 | -0.29* | -0.36* | | | |
| | R | -0.35* | -0.37* | -0.24* | -0.15 | -0.30* | | | |
| GI | L | 0.11 | 0.09 | 0.06 | 0.08 | 0.04 | | | |
| | R | 0.21 | 0.21 | 0.17 | 0.05 | 0.12 | | | |
| FD | L | -0.01 | 0.06 | 0.03 | -0.08 | -0.03 | | | |
| | R | 0.02 | 0.09 | 0.13 | 0.03 | -0.16 | | | |

Note that the values are Pearson's coefficients *P value < 0.05 (2-tailed).

V Hemisphere: H, Frontal lobe: F, Temporal lobe: T, Parietal lobe: P, Occipital lobe: O

Vol.: sum of cortical volume, Area: sum of mid-surface area, Thick.: average of cortical thickness, Depth: sum of sulcal depth, Curv.: average of absolute mean curvature, GI: gyrification index, FD: fractal dimension

| | MEASUREMENTS WITH BRAIN SIZE (ICV) | | | | | | | |
|-----------|------------------------------------|-------------|-------------|-------------|---------------|--------|--|--|
| | | Н | F | Т | Р | 0 | | |
| Vol | L | 0.93* | 0.86* | 0.88* | 0.74* | 0.68* | | |
| | R | 0.93* | 0.90* | 0.86* | 0.76* | 0.70* | | |
| Area | L | 0.90* | 0.77* | 0.84* | 0.65* | 0.56* | | |
| | R | 0.91* | 0.81* | 0.82* | 0.72* | 0.56* | | |
| Thick | L | 0.63* | 0.61* | 0.65* | 0.46* | 0.49* | | |
| | R | 0.65* | 0.66* | 0.66* | 0.44* | 0.52* | | |
| Depth | L | 0.41* | 0.35* | 0.37* | 0.24* | 0.02 | | |
| | R | 0.35* | 0.43* | 0.19 | 0.19 | 0.01 | | |
| Curv. | L | -0.68* | -0.60* | -0.42 | -0.55* | -0.39* | | |
| | R | -0.62* | -0.66* | -0.34* | -0.50* | -0.30* | | |
| GI | L | -0.02 | 0.05 | -0.09 | -0.00 | -0.03 | | |
| | R | 0.03 | 0.12 | -0.05 | 0.04 | -0.03 | | |
| FD | L | 0.19 | 0.23* | 0.14 | 0.19 | -0.09 | | |
| | R | 0.07 | 0.22 | 0.10 | 0.02 | -0.18 | | |
| Note that | the val | ues are Pea | rson's coet | ficients *P | value < 0.0 | 05 | | |

(B) CORRELATION EFFECTS IN THE CORTICAL MEASUREMENTS WITH BRAIN SIZE (ICV

(2-tailed).

Cortical Surface Area It has been used as an overall degree of folding [25-26]. We calculated the surface area of middle cortical surface, which was the straightforward sum of the areas of the triangles making up the surface model in each hemisphere and lobar region [7, 19].

Cortical Thickness It was defined as the Euclidean distance between the counterpart vertices of the inner and outer cortical surfaces [27]. We used averaged value of the thickness in each hemisphere and lobar region [19].

Cortical volume It was measured to reflect the lobar volume directly. We masked the extracted inner and outer cortical surfaces to original images (T1 MRI) in native space and then isolated the voxels of the cerebral cortex that were located between inner and outer surfaces [19]. The cortical volume was calculated by measuring the volume of the voxels in each hemisphere and lobar region.

Sulcal Depth It has been used as an important aspect of cortical shape. First, sulcal depth map was calculated using Euclidean distance from each vertex in the middle cortical surface to the nearest voxel on the cerebral hull volume [19, 28]. We defined sulcal regions if the depth is greater than a

3mm threshold and hull regions were defined if the depth is lower than a 3 mm threshold from the sulcal depth map [19, 28]. And, we calculated the sulcal depth on vertex of middle cortical surface using geodesic distance in order to reflect the true depth of cortical shape and then summed at vertex of each hemisphere and lobar region.

Absolute Mean Curvature It has been widely used for the measure of mean curvature on the cortical surface model to quantify the complexity of cortical folding [2, 19, 26, 29-32]. Mean curvature was measured on the middle cortical surface after 10 iterations of smoothing, preserving the original folding pattern [7]. Absolute mean curvature was computed at the vertices that lied within sulcal regions on the middle cortical surface and then averaged in each hemisphere and lobar region.

E. Statistical Analysis

Pearson's correlation test was performed to examine the relationships between each cortical measurement and FSIQ score and to select the variables significantly related to intelligence. The result was reported in Table I (A). Additionally, we performed a complementary statistical analysis between cortical measurements and ICV for the brain size effect (see Table I (B)).

Partial least square regression (PLSR) is an extension of the multiple linear regression analysis [33]. The purpose of the statistical analysis is to predict human intelligence from the selected cortical measurements and to describe their common structure in R [34]. Altogether, 36 variables were used to make up X matrix for PLSA analysis (33 cortical measurements significantly related to IQ, age, gender and ICV). Cross-validation commonly used to determine the optical number of components to take into account variances of X in partial least square regressions. Data were omitted once and only once. The number of components was selected



Fig. 1 Cross-validated RMSEP curves

This plot shows the estimated RMSEPs as functions of the number of components. Twenty four components seem to be enough. This gives an RMSEP of 13.59 (adj. CV 13.56)

for explained variances of X in the cross-validated root mean squared error of prediction (RMSEP) curves. The validation results showed the estimated RMSEP as functions of the number of components (Fig. 1 Cross-validated RMSEP curves for the X variables).





Fig. 2 The figure shows the cross-validated prediction of IQ with 24 components versus measured actual IQ. (r = 0.73)

III. RESULTS

We examined the relationship of each cortical measurement and FSIQ. The results are shown in Table I (A). Almost cortical measurements were significantly associated with FSIQ except for GI, FD (p<0.05). FSIQ was positively relevant to cortical volume and surface area in each hemisphere, frontal, temporal lobe, and only left parietal lobe. Cortical thickness was associated with FSIQ in each hemisphere and temporal lobe, and right frontal lobe. Sulcal depth was correlated to FSIQ in each hemisphere, frontal nd right temporal lobe. Absolute mean curvature in the sulcal region was detected the correlation to FSIQ in each hemisphere, frontal, occipital lobe, left parietal and right temporal lobe.

We selected 24 components to predict FSIQ because it seems to be enough (see Fig.1). This gives an RMSEP of 13.24 (adj. CV: 13.21), which is close to the RMSEP of the 78 data (8.90) and is explained X variance of 100%. This showed the cross-validated prediction of IQ with 24 components versus measured IQ (see Fig.2). We have chosen an aspect ratio of 1, and to draw a target line. The points follow the target line, and there is no indication of a curvature or other anomalies. A fitted model explained FSIQ of 52.57% (adj. R square: 51.94%). The results showed significant positive correlations between predicted and actual FSIQ (r=0.73).

IV. DISCUSSION

Our findings showed that more than 50% of human intelligence can be predicted by morphometric characteristics of complicated cortical structure. To our best knowledge, only a study reported that prediction model of intelligence quotient (IQ) explained 50% of variance in IQ using structural and functional magnetic resonance imaging [8]. In this study, the combination of volumetric measurements (for example, cortical volume, thickness) and shape complexity measurements (for example, surface area, sulcal depth, absolute mean curvature) gave the best result in prediction of human intelligence. In other words, PLSR was used to build 24 components as the best predictor of human intelligence. It is important to search the model that explains as much as possible of the covariance between various cortical measurements and FSIQ. The model with 24 components explained 100 % of variance in various cortical measurements and 52.57% of variance in FSIQ.

Intriguingly, we observed that intelligence had the significant relationship to all measures in the left parietal lobe except for cortical thickness (see Table I (A)). Previously, we reported that thick cerebral cortex had a less complex cortical structure than a thin cortex from the result showing a negative correlation between cortical thickness and FD [7]. Based on the findings, the outcomes seem to agree with the previous our study that the more intelligent individuals may have the more complex folding in left parietal lobe, for example, deeply and frequently convolution of gyral shape during thinning of cortical thickness. Although our result did not reveal the negative correlation with cortical thickness because of lobe unit limitation as a global measure, this seems to be consistent with other previous studies, which showed a negative correlation between cortical thickness and intelligence in the lateral parietal cortex [8]. However, the exact underlying mechanisms remain to be established.

We expected that there were would be a significant relationship between shape complexity measures (for example, FD, GI) and intelligence, because we hypothesized that greater intelligence would have the more complicated cortical shape according to highly cortical folding. Contrary to the expected, intelligence had nothing to do with FD as cortical complexity, a same measure [35] that quantifies the spatial frequency of sulcal and gyral convolutions and fissuration of the brain surface as well as GI. Although the complexity, which was measured by FD, in the previous study had a significant relationship with the full-scale intelligence quotient (IQ) in right hemisphere and education in both hemispheres, the discrepancies in findings that may be associate with the differences in FD method and the image preprocessing [7]. However, it is possible that FD as a single global value to estimate the cortical complexity may make the differences of other findings, which observed only partly positive correlations between local cortical convolution and intelligence [2]. GI also may be the same reason because the variations in cortical folding are regional. As alternative hypothesis, various cortical measurements related to intelligence would be mainly influenced by the brain size effect. We additionally performed a complementary statistical analysis between cortical measurements and ICV to examine the brain size effect (see Table I (B)). On the other hand, correlation was not observed between the brain size

and FD as well as GI. Although it is well known that the relationship between GI and brain size within human have not shown any significant correlation, Toro et al. showed that increase in prefrontal folding with brain size using a local measure of cortical folding, supporting that may be a consequence of the increased brain size [36-37]. It is likely that the observed relationship between human intelligence and cortical measurements might underscore the relevance of increased neuronal numbers according to the result of a larger brain, supporting our previous study indicating that human cortices are not simply scaled versions of one another [19]. In other words, neuroanatomical correlations of intelligence may be not simply present due to complicated cortical shape itself. However, it may be not revealed in lobe unit measures due to the existing locally specific regions related to the intelligence. Thus, the precise nature of this neuroanatomical correlation underlying architecture remains to be established and required further investigation.

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