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The Relationship Between General Intelligence and Cortical Structure in Healthy Individuals

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Abstract—Considerable work in recent years has examined the relationship between cortical thickness (CT) and general intelligence (IQ) in healthy individuals. It is not known whether specific IQ variables (i.e., perceptual reasoning [PIQ], verbal comprehension IQ [VIQ], and full-scale IQ [FSIQ]) are associated with multiple cortical measures (i.e., CT, cortical volume (CV), cortical surface area (CSA) and cortical gyrification (CG)) within the same individuals. Here we examined the association between these neuroimaging metrics and IQ in 56 healthy adults. At a cluster-forming threshold (CFT) of $p < 0.05$, we observed significant positive relationships between CT and all three IQ variables in regions within the posterior frontal and superior parietal lobes. Regions within the temporal and posterior frontal lobes exhibited positive relationships between CV and two IQ variables (PIQ and FSIQ) and regions within the inferior parietal lobe exhibited positive relationships between CV and PIQ. Additionally, CV was positively associated with VIQ in the left insula and with FSIQ within the inferior frontal gyrus. At a more stringent CFT ($p < 0.01$), the CT–PIQ, CT–VIQ, CT–FSIQ, and CV–PIQ relationships remained significant within the posterior frontal lobe, as did the CV–PIQ relationship within the temporal and inferior parietal lobes. We did not observe statistically significant relationships between IQ and either CSA or CG. Our findings suggest that the neural basis of IQ extends beyond previously observed relationships with fronto-parietal regions. We also conclude that CT and CV may be more useful metrics than CSA or CG in the study of intellectual abilities.

Key words: cortical measures, brain structure–function, intelligence, verbal comprehension, perceptual reasoning, full-scale IQ.

INTRODUCTION

Surface-based structural brain analysis techniques, involving an estimation of morphometric measures such as cortical thickness (CT), cortical volume (CV), cortical surface area (CSA), and cortical gyrification (CG) have expanded our understanding of the impact of various neurodegenerative diseases on brain structure. These measures provide specific indices of several unique aspects of brain structure. These measures also provide insight into the dynamics of brain structure during neurodevelopment (Burgaleta et al., 2014; White et al., 2010), the effects of aging on brain structure (Bajaj et al., 2017; Burgaleta et al., 2014; Hogstrom et al., 2013), and the relationships between brain structure and function (Burgaleta et al., 2014; Gregory et al., 2016). Mathematically, many of these structural measures are interrelated. For example, CV is the product of two, genetically distinct properties: CT and CSA (Winkler et al., 2010). CG positively correlates with both total brain volume and CSA but negatively with CT (Gautam et al., 2015; Hogstrom et al., 2013). Given the complex relationships between these heterogeneous morphometric properties, it is crucial to study the simultaneous relevance of each of these measures to cognition (e.g., their individual and joint relationships with measures of human intellectual ability [IQ)]). For instance, if two structural measures, such as CT and CSA, both have a positive association with cognitive abilities, then CV should also exhibit a positive, and possibly stronger, relationship than either CT or CSA alone.

Fundamentally, despite the fact that some cortical measures (CT, CV, CSA and CG) may covary, these measures reflect different facets of brain structure and could each contribute uniquely to cognitive function. Specifically, CT and CSA are considered highly heritable and genetically independent (Eyler et al., 2011;

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Abbreviations: CFT, cluster-forming threshold; CG, cortical gyrification; CSA, cortical surface area; CT, cortical thickness; CV, cortical volume; FSIQ, full-scale IQ; IQ, intelligence; PIQ, perceptual reasoning; VIQ, verbal comprehension IQ.

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Kremen et al., 2010; Panizzon et al., 2009). Due to their unique regional variation with the timing of prenatal perturbations, these measures are often understood as separate morphometric variables during neurodevelopment, aging, and disease (Eyler et al., 2011; Hogstrom et al., 2013; Panizzon et al., 2009). Moreover, CV is considered distinct from, though mathematically related to, CT and CSA (i.e., due to the non-uniform, integrated influence of CT and CSA) (Gerrits et al., 2016). Further, CG represents the convolution of brain structure and is influenced by both neuronal density and intra-cranial volume (Toro and Burnod, 2005; Welker, 1990). This folding increases the potential for a greater number of neurons within the same space. When coupled with the fact that CSA may facilitate better neuronal signal processing, increased CG and CSA may provide more efficient structural organization to facilitate brain connectivity and functional development (Luders et al., 2008; Murre and Sturdy, 1995; Ruppin et al., 1993). This supports the idea that the organization and gyral structure of the cortex contributes to its function.

With respect to structural measurements and cognition, the relationship between general intelligence (IQ) and structural measures, particularly CT and CSA, is likely age-dependent. Notably, Schnack and colleagues reported that among children (∼10 years of age), higher standardized IQ scores were associated with thinner cortex within the left hemisphere (Schnack et al., 2015). This pattern differed in young adults, where thicker left hemisphere cortex was associated with higher IQ scores, suggesting that maturation-related structural changes may play an important role in the expression of IQ. Consistent with these findings, Shaw and colleagues reported a shift from a negative correlation between CT and IQ in early childhood (age range 3.8–8.4 years) to a positive correlation in late childhood (age range 8.6–11.7 years) and into early adulthood (age range 11.8–29 years) (Shaw et al., 2006). In other work with healthy children and adolescents, changes in CT, but not CSA, were associated with changes in performance IQ, verbal IQ, and full-scale IQ (Burgaleta et al., 2014). Furthermore, higher CG in middle-aged participants (44–48 years) was associated with better mental flexibility, larger brain volume, but also thinner cortex (Gautam et al., 2015). Therefore, relationships between IQ and the structural characteristics of the cortex appear to exhibit dynamic, age- and developmental stage-dependent changes.

A recent meta-analysis suggested that much of the previous literature may over-estimate/over-simplify the association between brain volume and IQ (Pietschnig et al., 2015). The association instead appears to be more complex than suggested by simple volumetric measures. Surface-based cortical measures, rather than purely volumetric measures, may therefore provide more useful information about the complex and widespread relationships between cortical structure and general IQ.

Prior work has generally focused on individual structural measures in isolation and their association with IQ. Given that neural structure–function relationships are likely more complex than can be accounted for by simple volumetric measures, it is crucial to examine the parallel associations between multiple brain structure measures (CT, CV, CSA, and CG) and multiple aspects of general IQ (perceptual reasoning (PIQ), verbal comprehension and full-scale IQ) in the same sample of healthy young adults. The primary aim of the current study is therefore to investigate the vertex-wise associations between these structural metrics and these different IQ variables. Based on prior research, we hypothesized that both CT and CV would be positively associated with all domains of IQ. However, due to inconsistent and limited evidence regarding the relationship between CSA or CG and cognitive abilities, we had no specific hypothesis regarding the relationships between these specific metrics and IQ. Thus, these latter analyses were primarily for exploratory purposes.

EXPERIMENTAL PROCEDURES

Participants

Fifty-six healthy participants between 18 and 45 years of age (mean age = 30.8 ± 8.1 years, 27 females; 29 males) participated in this study. Participants were recruited from the New England area and screened via a comprehensive telephone interview. Individuals with any history of psychiatric, neurological, or significant medical problems, current use of psychotropic medications, or current use of illicit substances were excluded. Participants were all primary native English speakers, with 14.95 years of formal education (SD = 2.18 years). 69.6% of participants were Caucasian, 14.2% were African American, 8.9% were Asian, 3.6% reported polyethnic backgrounds and 3.6% reported other ethnic backgrounds. All participants provided written informed consent prior to enrollment. The study protocol was approved by the Institutional Review Boards of McLean Hospital and Partners Healthcare, and the U.S. Army Human Research Protections Office. Other behavioral data and structural estimates from this sample have been reported elsewhere (Killgore et al., 2013), but the vertex-wise cortical measures and their associations with IQ reported in this study are novel and have not been previously reported.

Data acquisition

Neuroanatomical data. We recorded high-resolution T1-weighted magnetic resonance imaging data using a 3-Tesla Siemens TIM Trio whole-brain MR scanner located at the McLean Hospital Imaging Center. Before the scan, each participant was instructed to rest, relax and try his/her best to minimize movement during the entire scan. Head movement was further minimized with foam padding placed comfortably about the head. T1-weighted data for each participant were acquired using a 3D magnetization-prepared rapid acquisition gradient echo (MPRAGE) sequence, which consisted of 128 sagittal slices (slice thickness = 1.33 mm, voxel resolution = 1.33 × 1 × 1 mm, field of view (FOV) = 256 mm