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Associations between cortical thickness and general intelligence in children, adolescents and young adults

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ABSTRACT

Neuroimaging research indicates that human intellectual ability is related to brain structure including the thickness of the cerebral cortex. Most studies indicate that general intelligence is positively associated with cortical thickness in areas of association cortex distributed throughout both brain hemispheres. In this study, we performed a cortical thickness mapping analysis on data from 182 healthy typically developing males and females ages 9 to 24 years to identify correlates of general intelligence (*g*) scores. To determine if these correlates also mediate associations of specific cognitive abilities with cortical thickness, we regressed specific cognitive test scores on *g* scores and analyzed the residuals with respect to cortical thickness. The effect of age on the association between cortical thickness and intelligence was examined. We found a widely distributed pattern of positive associations between cortical thickness and *g* scores, as derived from the first unrotated principal factor of a factor analysis of Wechsler Abbreviated Scale of Intelligence (WASI) subtest scores. After WASI specific cognitive subtest scores were regressed on *g* factor scores, the residual score variances did not correlate significantly with cortical thickness in the full sample with age covaried. When participants were grouped at the age median, significant positive associations of cortical thickness were obtained in the older group for *g*-residualized scores on Block Design (a measure of visual-motor integrative processing) while significant negative associations of cortical thickness were observed in the younger group for *g*-residualized Vocabulary scores. These results regarding correlates of general intelligence are concordant with the existing literature, while the findings from younger versus older subgroups have implications for future research on brain structural correlates of specific cognitive abilities, as well as the cognitive domain specificity of behavioral performance correlates of normative gray matter thinning during adolescence.

1. Introduction

Magnetic resonance neuroimaging studies have provided evidence for associations between brain structure and human intelligence (Luders, Narr, Thompson, & Toga, 2009). These studies have examined global and regional brain volumes of several tissue classes, including gray matter (comprised of neuronal cell bodies and their dendritic arborizations) as well as white matter (comprised of axonal fibers and myelin). Total brain volume, a global index that reflects the volumes of various tissue classes across brain regions, is moderately and positively associated with the intelligence quotient (IQ) (Luders et al.,

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2009; McDaniel, 2005; Wickett, Vernon, & Lee, 2000; Witelson, Beresh, & Kigar, 2006). Positive correlations have also been reported between IQ and the total volumes of cortical regions in each lobe of the cerebral hemispheres (frontal, temporal, parietal, and occipital), as well as the hippocampus and cerebellum (Andreasen et al., 1993; MacLullich et al., 2002). Against these broad trends in empirical results, substantial variation has been reported in the strength of association between brain structure and intelligence across brain regions, as well as across brain tissue classes. For example, positive correlations have been reported between IQ and global indices of gray (Andreasen et al., 1993; Colom, Jung, & Haier, 2006; Narr et al., 2007; Reiss, Abrams, Singer, Ross, & Denckla, 1996) and white (Gignac, Vernon, & Wickett, 2003; Gur et al., 1999; Narr et al., 2007; Posthuma et al., 2002) matter volumes, but recent reviews suggest stronger associations for gray matter volumes (e.g., Luders et al., 2009).

Voxel-wise structural brain mapping methods have allowed researchers to identify specific associations between intelligence and discrete brain regions. The findings from these studies are consistent in identifying areas of the lateral and medial frontal cortex, cingulate, medial and lateral temporal cortex, superior and inferior parietal cortex, and extra-striate occipital cortex as regions where gray matter volume is specifically associated with IQ scores (see Luders et al., 2009 for review). In general, greater gray matter volumes in these regions of association cortex have been associated with higher IQ scores. Nevertheless, potentially important discrepancies have been reported as well from gray matter volumetric analyses, particularly with respect to sex and age differences. For example, Haier et al. (Haier, Jung, Yeo, Head, & Alkire, 2004) used voxel-based morphometry and reported that IQ scores were associated with gray matter volumes primarily in prefrontal cortical regions for females, while males demonstrated additional correlates in posterior (parietal–occipital) cortical regions. With respect to age differences, Haier et al. (2004) integrated their own results from young adults and older adults with findings reported by Wilke, Sohn, Byars, & Hollanda (2003) and hypothesized a developmental progression from early childhood through young adulthood to old age for neuroanatomical correlates of intelligence, involving the anterior cingulate to medial frontal areas to dorsal frontal areas, respectively.

Recently, it has been suggested that cortical thickness may be more closely related to intelligence than volumetric measures (Choi et al., 2008; Colom et al., 2009; Haier et al., 2004; Karama et al., 2009; Luders et al., 2009; Narr et al., 2007). Point estimates of the thickness of the cerebral cortex in a given location likely reflect how cortical neurons are organized (Narr et al., 2007) rather than simply indicating the density of gray matter tissue within a Cartesian search space. Thus, cortical thickness may offer more insight into the relations between brain structure and intelligence than other measures (Narr et al., 2007). To date, only a small number of studies have been published that address associations between human intelligence and cortical thickness.

Narr et al. (2007) reported positive associations between full scale IQ and cortical thickness in prefrontal and temporal areas in both hemispheres as well as a region of extra-striate cortex in the right occipital lobe. Choi et al. (2008) obtained significant positive associations between full scale IQ and cortical thickness in multiple regions along the full extent of the temporal lobe of the left hemisphere, but not in any other cortical regions; however, they did find a negative association in the left parietal lobe. Karama et al. (2009) assessed a representative sample of children and adolescents aged 6 to 18 years old using the Wechsler Abbreviated Scale of Intelligence (WASI: Wechsler, 1999) and derived general intelligence (*g*) scores based on the first principle component derived in a principle component analysis of the four WASI subtests: Vocabulary, Similarities, Block Design, and Matrix Reasoning. They reported widely distributed clusters of significant positive associations between *g* scores and cortical thickness in frontal, temporal, parietal, and occipital areas of both hemispheres, as well as the cingulate cortex bilaterally. The clusters were located in areas of association cortex and did not encompass primary sensory or motor regions.

As illustrated by the results of Karama et al. (2009), structural neuroimaging brain mapping studies of intelligence have generally supported a distributed network of multimodal association regions in association with individual differences in IQ scores. This conclusion has been formalized in the Parieto-Frontal Integration Theory of Intelligence (P-FIT; Jung & Haier, 2007), which posits that sensory information is processed by temporal and occipital regions and is subsequently integrated within parietal regions. The cingulate cortex and dorsolateral prefrontal regions mediate higher-level processes such as evaluation, problem-solving, and response selection (Jung & Haier, 2007). In their formulation of this theory, Jung and Haier (2007) integrated the results from a selection of relevant neuroimaging studies published between 1988 and 2007 and argued that while studies of associations between gray matter tissue characteristics and intelligence may seem inconsistent in terms of the precise regional specificity of reported results, they in fact form a coherent picture in their convergence on a limited number of regions of heteromodal association cortex (Jung & Haier, 2007).

Intelligence has been represented in most neuroimaging studies by estimates of general intelligence, *g*, a metric derived from the first-order factor that emerges when various subtests of more specific cognitive abilities are factor analyzed. In theory, estimates of *g* represent the core of intellectual functioning as derived from the Spearman tradition (Spearman, 1904). In popular hierarchical models of intelligence (e.g., Carroll, 1993), *g* is positioned above a set of more specialized or specific cognitive abilities, such as verbal or spatial reasoning ability. Accordingly, the question arises as to whether the unique (*g*-independent) variance in cognitive abilities shares the same structural neuroanatomical correlates as the common variance contained in *g* scores. In a recent study, Karama et al. (2011) assessed a sample of 6 to 18 year olds and derived *g* scores from the first unrotated principle factor of a factor analysis of the four WASI subtests together with three achievement tests (Calculation, Letter-Word Identification, and Comprehension; from the Woodcock–Johnson Psycho-Educational Battery—III: Woodcock, McGrew, & Mather, 2001). They described a pattern of positive associations between *g* scores and cortical thickness similar to their previous report (Karama et al., 2009). Additionally, they demonstrated that observed positive cortical thickness correlates of specific tests, e.g., WASI Vocabulary or Block Design, could be accounted for by shared variance with *g* scores. Specifically, when scores on specific WASI and Woodcock–Johnson tests were regressed on *g* scores, the residuals of the specific test scores did not produce