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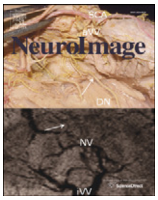

Cognitive ability changes and dynamics of cortical thickness development in healthy children and adolescents

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ABSTRACT

Intelligence quotient (IQ) scores tend to remain stable across the lifespan. Nevertheless, in some healthy individuals, significant decreases or increases in IQ have been observed over time. It is unclear whether such changes reflect true functional change or merely measurement error. Here, we applied surface-based corticometry to investigate vertex-wise cortical surface area and thickness correlates of changes in Full Scale IQ (FSIQ), Performance IQ (PIQ) and Verbal IQ (VIQ) in a representative sample of children and adolescents ($n = 188$, mean age $=$ 11.59 years) assessed two years apart as part of the NIH Study of Normal Brain Development. No significant associations between changes in IQ measures and changes in cortical surface area were observed, whereas changes in FSIQ, PIQ, and VIQ were related to rates of cortical thinning, mainly in left frontal areas. Participants who showed reliable gains in FSIQ showed no significant changes in cortical thickness on average, whereas those who exhibited no significant FSIQ change showed moderate declines in cortical thickness. Importantly, individuals who showed large decreases in FSIQ displayed the steepest and most significant reductions in cortical thickness. Results support the view that there can be meaningful cognitive ability changes that impact IQ within relatively short developmental periods and show that such changes are associated with the dynamics of cortical thickness development.

Introduction

Intelligence quotient (IQ) is one of the most relevant human psychological characteristics, as highlighted by epidemiologic studies that document long-term predictive relationships between early cognitive ability and adult physical and mental health outcomes, including longevity (Jokela et al., 2009; Whalley and Deary, 2001). Brain imaging research has shown that general cognitive ability is also associated with several features of the human brain, such as gray matter morphology (Burgaleta et al., 2013; Colom et al., 2009; Gläscher et al., 2010; Haier et al., 2009; Karama et al., 2009, 2011), trajectories of cortical development (Shaw et al., 2006), functional efficiency (Haier et al., 1988; Neubauer and Fink, 2009; van den Heuvel et al., 2009), and integrity of white matter connections (Chiang et al., 2009; Tamnes et al., 2010; Yu et al., 2008).

Contrary to other cognitive measures, IQ is an index of relative general performance, as it summarizes how well an individual performs in a cognitive battery with respect to a reference group of same-age peers. Therefore, although an individual's absolute level of performance will strongly vary across development (McArdle et al., 2002), IQ scores, which are age-adjusted, will tend to remain relatively stable (Deary et al., 2000). In keeping with this, in the current manuscript, the terms 'cognitive ability' and 'general cognitive ability' should be understood as referring to age-standardized rather than absolute measures of cognitive performance. Thus change scores, even absolute difference scores, indicate relative rather than absolute change.

Empirical data confirms that IQ is highly stable developmentally; for instance, Deary et al. (2000) reported a mean test–retest correlation between ages 11 and 77 of $r = .73$. However, although high, such a correlation nonetheless allows for occurrence of increases and decreases, sometimes significant in magnitude. Along these lines, a recent report from the NIH Study of Normal Brain Development (Waber et al., 2012) revealed that although the test–retest correlation for Full Scale

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IQ (FSIQ) was high across a 2-year interval (r = 0.81), 25% of these healthy children and adolescents showed changes of 9 points or more (nearly 2/3 standard deviation) across this interval.

Such fluctuations, which are not well understood, have often been ascribed to measurement error (Flynn, 2007), which some most certainly are. However, in keeping with recent evidence about brain plasticity and higher-order cognition (Draganski et al., 2004; Haier et al., 2009; Lövdén et al., 2010; Mackey et al., 2012; Takeuchi et al., 2010), some of these fluctuations could also represent true changes in cognitive abilities. Documentation of association between IQ changes and morphometric variations in neural structure would strongly support such a view. In this vein, Ramsden et al. (2011) studied 33 adolescents using voxel-based morphometry and found changes in two aspects of FSIQ, Verbal and Performance IQ (VIQ; PIQ), to be associated with changes in regional gray matter in sensorimotor areas. While these findings strongly suggest that IQ changes can indeed be genuine, generalization is somewhat limited by small sample size, use of different IQ tests at different ages, and sample peculiarities (e.g., about half appeared to meet criteria for dyslexia).

Here, we investigated the structural correlates of longitudinal changes in IQ in participants of the NIH MRI Study of Normal Brain Development. Individuals included in the present study (N = 188) contributed structural MRIs and concurrent IQ testing with the Wechsler Abbreviated Scale of Intelligence (WASI) at a 2-year interval. To better characterize structural changes in gray matter, corticometric methods were applied to generate two independent indices of cortical morphology: cortical thickness (CTh) and cortical surface area (CSA). Each of these metrics is known to reflect different components of cortical structure. Cortical surface area is related to the number and spacing of minicolumnar units of cells whereas cortical thickness is thought to index the number of neurons per column as well as glial support and dendritic arborization (Chklovskii et al., 2004; la Fougere et al., 2011; Rakic, 1988; Thompson et al., 2007). Changes in IQ were regressed against maps of changes in cortical thickness and surface area.

Given previous findings (Ramsden et al., 2011), we hypothesized that changes in VIQ would be positively related to gray matter structural changes in sensorimotor areas. Furthermore, because of our larger sample and hence greater statistical power, we hypothesized that we would observe additional associations with VIQ and PIQ, as well as with FSIQ. We anticipated such associations in parieto-frontal areas previously shown to be involved with individual differences in cognitive ability (Jung and Haier, 2007).

Materials and methods

Sample

Data were obtained from the Pediatric MRI Data Repository (Objective 1) created for the National Institute of Mental Health MRI Study of Normal Brain Development (Evans and Brain Development Cooperative Group, 2006), a multi-site longitudinal project aimed at providing a normative database to characterize healthy brain maturation in relation to behavior; 431 subjects underwent cognitive evaluation and MRI acquisition, distributed in six different sites (a listing of the participating sites and of the study investigators can be found at: http://www.bic.mni.mcgill.ca/nihpd/info/participating_centers.html). The sample was demographically representative of the normative US population based on age, gender, ethnicity, and socioeconomic status (Waber et al., 2007). Participants with prior history of psychiatric disorders, neurological, or other medical illnesses with central nervous system implications were excluded. Some of the participants (24%) underwent one single MRI session; 39% were scanned twice; and 37% were scanned three times. Data for visit 3 were excluded for those participants with more than two time points in order to build a simple pre-post design. Participants with only one MRI scan, missing IQ scores or failing processed MRI quality control at one or more time points were excluded. Further visual quality control (blinded to cognitive ability scores) of the native cortical surfaces detected obvious problems in a total of 36 scans (e.g., frontal lobe truncation due to failed automatic brain masking, fused gyri or clearly aberrant cortical thickness values due to ringing artifacts), that were also excluded of the analyses. The final sample analyzed retained a total of 188 subjects (mean age ± SD at the time 1: 11.59 years ± 3.46; range 6.01 to 20.01 years; 59% of participants were females; and the mean inter-scan lapse was 1.96 years. See Table 1 for further characteristics of the sample used).

Cognitive measures

The Wechsler Abbreviated Scale of Intelligence (WASI) was used for all subjects (Wechsler, 1999). The WASI includes the Vocabulary, Similarities, Matrix Reasoning, and Block Design subtests. FSIQ as well as VIQ and PIQ scores were obtained for each participant at each visit. See Table 1 for a summary of these data.

MRI acquisition protocol

A 3D T1-weighted Spoiled Gradient Recalled (SPGR) echo sequence from 1.5 Tesla scanners was acquired for each participant at each visit, with 1 mm isotropic data acquired sagittally (whole head); TR = 22–25 ms, TE = 10–11 ms. Excitation pulse = 30°, refocusing pulse = 180°. FOV = AP 256 mm, LR 160–180 mm. Matrix size = AP 256 mm, LR for 1 mm isotropic. Slice thickness of ~1.5 mm for GE scanners (with a limit of 124 slices) was allowed to guarantee whole head coverage.

MRI processing

MRI images were processed by applying a fully automated in-house pipeline, CIVET 1.1.9 (Ad-Dab'bagh et al., 2006; Kim et al., 2005; MacDonald et al., 2000) for the measurement of regional cortical thickness. CIVET was developed at the Montreal Neurological Institute and comprises several steps, extensively detailed elsewhere (Karama et al., 2009): linear registration of native T1 images to the ICBM152 template (Mazziotta et al., 1995); non-uniformity correction; tissue classification into gray matter, white matter cerebrospinal fluid and background; pial and white matter surface fitting (40962 vertices per hemisphere); non-linear surface registration to a high-resolution surface template in ICBM152 space; inverse registration of the surfaces into native space; cortical thickness calculation at each vertex with the t-link metric (Lerch and Evans, 2005); cortical thickness smoothing applying a 20 mm FWHM surface-based smoothing kernel; surface area calculation at each vertex as one third of the total area of all triangular facets

Table 1
Descriptive statistics. FSIQ = Full scale IQ. VIQ = Verbal IQ. PIQ = Performance IQ. *CTh* = cortical thickness. CSA = cortical surface area. Change = Time 2 − Time 1. All correlations are significant at $p < 0.01$.

		Age	FSIQ	VIQ	PIQ	Mean CTh	Mean CSA
Time 1	Mean (SD) min, max	11.59 (3.46) 6.09, 20.05	112.04 (12.94) 78, 160	111.12 (13.82) 74, 156	110.29 (13.04) 72, 157	3.59 (0.17) 3.18, 3.99	2.29 (0.18) 1.82,2.74
Time 2	Mean (SD) min, max	13.55 (3.49) 7.74, 21.87	113.12 (12.62) 75, 150	111.27 (13.09) 80, 147	112.12 (12.94) 74, 147	3.55 (0.17) 3.06, 3.97	2.29 (0.19) 1.78,2.73
Longitudinal correlation		–	0.83	0.74	0.80	0.86	0.98
Change	Mean (SD) min, max	1.96 (0.42) 0.85, 3.81	1.07 (7.51) −18, 24	0.15 (9.62) −29, 30	1.82 (8.46) −25, 24	−0.04 (0.09) −0.28, 0.25	0 (0.04) −0.09,0.13