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Brain-intelligence relationships across childhood and adolescence: A latent-variable approach

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ABSTRACT

The analysis of the relationships between cortical and intellectual development is a complex matter. Greater brain plasticity in brighter individuals has been suggested, but the associations between developmental cortical changes and variations in the general factor of intelligence (*g*) across time at the latent level have not been addressed. For filling this gap, here we relate longitudinal changes in *g* with developmental changes in cortical thickness and cortical surface area. One hundred and thirty-two children and adolescents representative of the population from the Pediatric MRI Data Repository completed the Wechsler Abbreviated Scale of Intelligence in three time points and MRI scans were also obtained (mean inter-registration interval ≈ 2 years, age range = 6.1 to 21.3 years). Longitudinal latent variable analyses revealed an increase in *g* scores amounting to a full standard deviation on average. Intelligence differences estimated at the latent level were significantly correlated related with cortical changes. Older individuals showed greater decrease in cortical values along with smaller increase in intelligence. Furthermore, thickness preservation in brighter individuals was observed at early adolescence (10–14 years).

1. Introduction

The study of the relationship between age changes in general cognitive ability (*g*) and brain maturation deserves investigation (Johnson, 2013). There are acknowledged changes in cognitive and cortical features during childhood and adolescence, and, therefore, the relationships between differences in brain structure and cognition may change across age (Van Petten, 2004).

Research has shown average cortical thinning in childhood and early adolescence (Sowell et al., 2003; Sowell, Thompson, & Toga, 2007, age range: 5 to 11 years), along with average cortical surface area expansions in adolescence (Schnack et al., 2014, age range: 9 to 60 years). Non-linear cortical thinning has been revealed after studying children (6 to 10 years), adolescents (10 to 20 years), and adults (20 to 30 years) (Zhou, Lebel, Treit, Evans, & Beaulieu, 2015): accelerated thinning was observed during adolescence and cortical surface area increased similarly with age in children and adolescents (although findings are not entirely consistent, see Alemán-Gómez et al., 2013).

Zhou et al. (2015) failed to find relationships between changes in thickness and surface area studying the same sample of individuals: age changes in both cortical indices were not coordinated. Raznahan et al. (2011, age range, 6 to 22 years) computed the annual percent of change for thickness and surface area finding similar results for both indices across ages, although boys showed higher percentages of surface area changes than girls from 6 to 14 years. Afterwards, girls and boys showed similar percentages of change.

Zhou et al. (2015) underscored the large consistency across studies regarding cortical thinning during development. However, their results were heterogeneous: some individuals did show thinning, some others did show thickening, and some hardly showed any change.

These developmental cortical differences at the individual level were also observed by Burgaleta, Johnson, Waber, Colom, and Karama (2014) who analyzed their relationship with cognitive ability changes –also at the individual level—as assessed by WASI IQ scaled scores. Their results revealed that participants showing IQ gains over time were characterized by cortical thickness preservation, whereas those showing greater cortical thinning lost IQ points over time. Therefore, IQ changes were associated with the dynamics of cortical thickness across

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development. However, Burgaleta et al. (2014) failed to find any substantial relationship between changes in cortical surface area (showing both expansion and contraction) and IQ changes.

On the other hand, Schnack et al. (2014) analyzed five age groups [below 12 years ($N = 114$), between 12 and 20 years ($N = 76$), between 20 and 30 years ($N = 152$), between 30 and 40 years ($N = 105$), and above 40 years ($N = 57$)] finding relationships between intelligence assessed at baseline and cortical changes (in thickness and surface area) and concluding that the human brain shows systematic "*intelligence-dependent development*": brightest children did show thinner cortices than less intelligent children, and faster thinning over time was observed for the former. However, this trend reversed in adulthood: thicker cortices were associated with higher intelligence scores. With respect to cortical surface area, brightest children did show larger values. Surface area expansion approached asymptotic levels during adolescence. High intelligence individuals stopped their cortical expansion at early ages, and, afterwards, decreases were shown at faster rates. In short, intelligence assessed at baseline was related with the magnitude and time of the life span at which the brain seems to show structural changes.

Schnack et al. (2014) considered intelligence at baseline only, and therefore, relationships between changes in cortical indices and intellectual changes across development were not addressed. Nevertheless, cortical-intelligence relationships might change across development. Thus, for instance, the study by Koenis et al. (2015, age range: 9 to 15 years) revealed substantial relationships between changes in the organization of structural brain networks and intellectual functioning: better local efficiency in temporal and frontal regions were related to higher intelligence scores. Individual development of intelligence seems to be coordinated with individual development of brain structural networks.

Here we study the relationships between cortical development and intellectual ability across childhood and adolescence. We pursue this main goal analyzing intellectual changes by applying longitudinal structural equation modeling (Estrada, Ferrer, Abad, Román, & Colom, 2015; Widaman, Ferrer, & Conger, 2010). Developmental changes in general cognitive ability (*g*) will be modeled at the latent level. Afterwards, changes in intelligence will be related with changes in cortical thickness and cortical surface area. Psychological and biological data were obtained from one hundred and thirty two children and adolescents at three time points separated by approx. two years each.

To our knowledge, a latent variable approach has not been applied before. A common procedure is to compute full-scale IQ scores based on the raw values obtained from the tests of a given measurement battery, and then age-norming them (e.g. computing IQ scores from the WISC). This procedure assumes that a) all the tests share the same percentage of variance with the common factor, and b) there is no measurement error. Instead of using scaled scores for intelligence at each measurement occasion, here we model the scores in a latent factor representing general intelligence (*g*). This allows computing error-free estimates of intelligence, as well as cleaner estimates of between individual differences and within individual changes over time (Barbey et al., 2012; Colom et al., 2009, 2013; Estrada et al., 2015; Gläscher et al., 2010; Haier et al., 2009; Román et al., 2014).

Because we obtained measures across childhood and adolescence, mental abilities – as well as other variables such as height or physical abilities – are expected to increase. Consider height as an example: any normative sample will increase in height between 6 and 21 years of age. Therefore, a very high correlation is expected between height and age. Computing age-normed scores of age controls for this correlation, but this approach would hide the fact that individuals are taller at *t3* than at *t1*. The same problem arises for intelligence. The latent variable approach applied here allows overcoming this situation by capturing the growth in *g* while being unaffected by the high collinearity between *g* and age.

2. Method

2.1. Participants

132 children and adolescents (74 girls, 56.1%) representative of the U.S. population (2000 Census data) from the Pediatric MRI Data Repository created for the National Institute of Mental Health MRI Study of Normal Brain Development (Evans & The Brain Development Cooperative Group, 2006) were analyzed (age range: 6.1–21.3; mean age at time 1 = 10.92, SD = 3.13). They were scanned at three time points (the mean inter-scan interval was ≈2 years). Only participants without prior history of psychiatric disorders, neurological, or other medical illnesses with central nervous system implications were selected. Also, all MRI scans analyzed here passed strict quality control (QC). Fig. 1 shows the timeline of the present study.

2.2. Cognitive measures

Intelligence was assessed with The Wechsler Abbreviated Scale of Intelligence (WASI) (Wechsler, 1999). Vocabulary, Similarities, Matrix Reasoning, and Block Design are the tests included in this battery, and they were administered at the three time points considered (Fig. 1). These tests were analyzed for modeling changes in the general factor of intelligence (*g*) across time points (*t*) – please see below for further details.

2.3. MRI acquisition

For the structural images analyzed here, a high-resolution 3D T1-weighted Spoiled Gradient Recalled (SPGR) echo sequence was applied. 1 mm isotropic data were 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.

2.4. Surface-based morphometry

MRIs were processed through the CIVET pipeline (version 1.1.9) (Ad-Dab'bagh et al., 2006; Kim et al., 2005; MacDonald, Kabani, Avis, & Evans, 2000) for obtaining measures of regional cortical thickness (CT) and cortical surface area (CSA). Specific stages for the analyses were: (1) linear registration (12-parameter) to MNI-Talairach (*ICBM152*) space, (2) images corrected for radio-frequency non-uniformities and a brain mask computed, (3) tissue classification into white matter (WM), gray matter (GM), and cerebrospinal fluid (CSF), (4) generation of high-resolution hemispheric surfaces with 40,962 vertices each, (5) registration of surfaces to a high-resolution template, (6) cortical thickness is computed by evaluating the distance, in mm, between the original WM

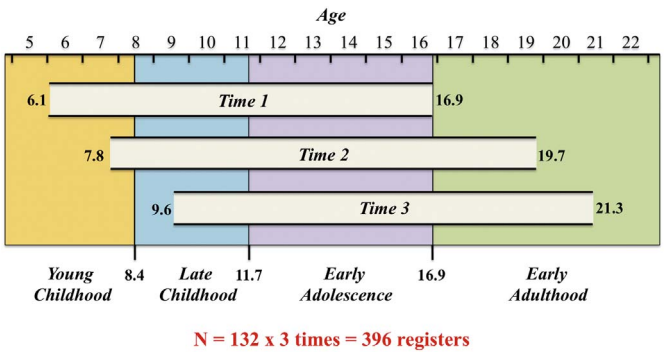

Fig. 1. Timeline of the present study.