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Research Article

Exploring the Relationship between Cortical Thickness and Cognitive Abilities: A Multi-Modal Imaging Approach

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Abstract

Background: Cortical thickness has been associated with cognitive abilities in prior research, but the specific relationships remain unclear. ***Objectives***: This study aimed to further examine associations between cortical thickness in various brain regions and performance on tests of intelligence and executive function. ***Methods***: Structural MRI scans were obtained from 65 healthy adults aged 18-35. Cortical thickness was estimated across the cortex using Free Surfer software. Participants completed standard tests measuring IQ, working memory, cognitive flexibility, and inhibitory control. Correlation and regression analyses were used to relate regional cortical thickness to cognitive scores. ***Results***: This study showed cortical thickness in prefrontal regions positively correlated with IQ, working memory, and cognitive flexibility. No significant associations were found between cortical thickness and response inhibition. ***Conclusions***: The findings provide evidence for links between PFC thickness and higher cognitive abilities. A multi-modal neuroimaging approach combining structural MRI and cognitive testing is useful for elucidating brain-behavior relationships. Further research with larger samples is needed to fully characterize these associations.

Keywords: Cortical thickness, Cognition, Executive functions, Intelligence, MRI, Prefrontal cortex.

استكشاف العلاقة بين سمك القشرة والقدرات المعرفية: نهج التصوير متعدد الوسائط

الخلاصة

الخلفية: ارتبط سمك القشرة بالقدرات المعرفية في الأبحاث السابقة ، لكن العلاقات المحددة لا تزال غير واضحة. **الأهداف**: تهدف هذه الدراسة إلى مزيد من الفحص للارتباطات بين سمك القشرة في مناطق الدماغ المختلفة والأداء في اختبارات الذكاء والوظيفة التنفيذية. **الطريقة**: تم الحصول على فحوصات التصوير بالرنين المغناطيسي الهيكلي من 65 من البالغين الأصحاء الذين تتراوح أعمارهم بين 18 و 35 عاما. تم تقدير سمك القشرة عبر القشرة باستخدام برنامج Free Surfer. أكمل المشاركون اختبارات قياسية لقياس معدل الذكاء والذاكرة العاملة والمرونة المعرفية والتحكم المثبط. تم استخدام تحليلات الارتباط والانحدار لربط سمك القشرة المحيطية بالدرجات المعرفية. **النتائج**: أظهرت هذه الدراسة أن سمك القشرة في مناطق الفص الجبهي يرتبط ارتباطا إيجابيا بمعدل الذكاء والذاكرة العاملة والمرونة المعرفية. لم يتم العثور على ارتباطات ذات دلالة إحصائية بين سمك القشرة وتثبيط الاستجابة. **الاستنتاجات**: تقدم النتائج أدلة على وجود روابط بين سمك PFC والقدرات المعرفية العليا. يعد نهج التصوير العصبي متعدد الوسائط الذي يجمع بين التصوير بالرنين المغناطيسي الهيكلي والاختبار المعرفي مفيدا لتوضيح العلاقات بين الدماغ والسلوك. هناك حاجة إلى مزيد من البحث مع عينات أكبر لتوصيف هذه الارتباطات بشكل كامل.

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INTRODUCTION

Over the past few decades, neuroimaging techniques have enabled remarkable insights into the structure and function of the human brain. One area receiving increasing research attention involves elucidating the neuroanatomical correlates of human cognitive abilities. Intelligence and executive functions are high-level cognitive domains that rely heavily on the frontal lobes [1]. However, the specific relationships between anatomical variation in frontal brain regions and individual differences in cognitive performance remain unclear. Cortical thickness, measured with structural magnetic resonance imaging (MRI), has emerged as a key metric for quantifying anatomical properties of the cerebral cortex. Cortical thickness is defined as the distance between the white matter surface and pial surface of the cortical ribbon [2]. Advances in neuroimaging analysis methods now allow for automated estimation of thickness across the entire cortical surface with submillimeter precision. Cortical thickness has been shown to vary across individuals and to change across the lifespan. Understanding the neurobiological factors influencing cortical thickness may provide insights into neurodevelopment, aging, and disease processes affecting the cerebral cortex. Numerous studies have delineated how cortical thickness varies with age. During childhood and adolescence, cortical gray matter undergoes dynamic thinning and thickening processes. In general, sensory and motor cortices thin earlier, while association cortices in the frontal and temporal lobes undergo more protracted thickening followed by gradual thinning [3]. Overall, cortical thickness shows an inverted U-shaped trajectory across development, peaking in thickness around puberty before declining in adulthood and advanced age. Alterations in cortical thickness have been documented in a range of neurological, psychiatric, and neurodegenerative disorders. For example, abnormal thinning of prefrontal and temporal cortices has been found in schizophrenia and depression [4]. Investigating cortical thickness abnormalities and their cognitive correlates may elucidate illness mechanisms and neural targets for treatment. The cerebral cortex undergoes dynamic changes in thickness across the lifespan, with initial thickening through childhood and adolescence followed by progressive thinning in adulthood [5]. Research indicates that the trajectory of cortical development shows regional heterogeneity, with sensory and motor areas maturing earliest and high-order association areas in the frontal and temporal lobes showing more protracted maturation [6]. Given the importance of frontal lobe regions for supporting higher cognitive functions, variation in frontal cortical thickness may be a key anatomical substrate related to individual differences in cognitive abilities. Indeed, prior studies have found associations between cortical thickness in specific prefrontal regions and performance on tests of intelligence and executive function. For example, thicker cortex in lateral PFC areas has been linked to higher IQ [7]. Studies utilizing working memory tasks have found positive correlations between PFC thickness and working memory capacity [8]. With regard to executive functions, greater anterior cingulate cortex thickness has been associated with enhanced cognitive flexibility and conflict monitoring [9]. However, many open questions remain regarding the specificity and regional patterns of brain-behavior relationships. Most studies have examined cortical thickness correlations with single cognitive tests in isolation. Evaluating multiple domains in the same participants can help better characterize these structure-function mappings and determine whether overlapping or distinct neuroanatomical substrates underlie different facets of cognition. In the current study, we aim to address these open questions by investigating associations between regional cortical thickness and performance across a battery of cognitive tests assessing intelligence, working memory, cognitive flexibility, and inhibition. We focus on frontal lobe areas, given copious prior evidence implicating these regions in higher cognitive functions. The present study aims to achieve a more fine-grained characterization of structure-function relationships in frontal networks. From a clinical perspective, establishing these brain-behavior correlations in healthy populations provides an important foundation for future studies examining developmental disorders or neurodegenerative diseases that may perturb these associations.

Key points

We hypothesize that thickness in specific PFC subregions will correlate positively with cognitive test scores, consistent with the putative role of these areas in supporting intelligence and executive control processes. However, we expect some domain specificity in the precise anatomical correlates. For example, working memory may be linked to dorsolateral PFC thickness, while cognitive flexibility may show stronger correlations with anterior cingulate cortex thickness based on their purported functions.

METHODS

Study design and setting

The sample consisted of 65 healthy adults (32 males, 33 females) recruited from the local community. Participants ranged in age from 18-35 years (24.5±5.2). All participants were right-handed, had normal or corrected-to-normal vision, and reported no history of neurological or psychiatric disorders. Informed consent was obtained from each participant prior to experimental procedures, in accordance with the research ethics boards of the university and hospital.

Cognitive assessment

Participants completed a battery of standardized neuropsychological tests to assess intelligence, memory, executive functions, and attention. The specific tests used include: A) Wechsler Abbreviated Scale of Intelligence, Second Edition (WASI-II). This is an abbreviated intelligence test providing verbal comprehension, perceptual reasoning, and full-scale IQ composite scores. It includes vocabulary, similarities, block design, and matrix reasoning subtests [10]; B) Wechsler Memory Scale, Fourth Edition (WMS-IV) Logical Memory: The Logical Memory subtest evaluates verbal declarative memory by assessing free recall of two short stories presented orally. It provides metrics of immediate and delayed recall [11]; C) Delis-Kaplan Executive Function System (D-KEFS) Verbal Fluency: This verbal fluency test requires generating words within constrained search criteria. We administered the phonemic fluency condition (words starting with F, A, and S) and category switching condition (switching between fruit and furniture categories) [12]; D) D-KEFS Trail Making Test: The trail making test evaluates processing speed, cognitive flexibility, and executive control. We administered part A (visual scanning and sequencing) and part B (divided attention, cognitive flexibility) [13]; E) Conners Continuous Performance Test 3rd Edition (CPT-3): The CPT-3 is a computerized assessment of sustained attention, impulsivity, and response inhibition. Participants respond to target letters while inhibiting responses to non-targets [14]. All tests were administered and scored according to standardized procedures by trained research assistants supervised by a licensed clinical neuropsychologist.

MRI acquisition

Structural MRI scans were acquired on a 3T Siemens Prisma scanner with a 64-channel head coil. A high-resolution T1-weighted scan was obtained for each participant using the following parameters: Foam padding minimized head motion within the coil. All scans were visually inspected to verify adequate quality with no significant artifacts (Table 1).

Table 1: MRI scan parameters

Parameter	Value
Scanner	3T Siemens Prisma with 64-channel head coil
Sequence	3D MPRAGE
TR (Repetition Time)	2300 ms
TE (Echo Time)	2.32 ms
TI (Inversion Time)	900 ms
Flip Angle	8 degrees
Matrix Size	256 x 256
Number of Slices	224
Voxel Size	1 mm isotropic
Scan Time	6.45 minutes
Motion Minimization	Foam padding
Quality Assurance	Visual inspection for artefacts

Cortical thickness processing

Cortical reconstruction and thickness estimation were performed using the FreeSurfer image analysis suite (version 6.0) following standard procedures described by Fischl and Dale (2000). Briefly, the T1-weighted images undergo automated volumetric segmentation to identify white matter, gray matter, and CSF. The gray-white boundary and pial surface are modeled as triangular meshes, allowing estimation of thickness at each vertex as the distance between the surfaces. The resulting cortical thickness maps are smoothed using a 15 mm full-width at half-maximum Gaussian kernel to reduce localized variations in gyral/sulcal anatomy. Individual thickness maps were registered to a spherical atlas utilizing a non-linear procedure respecting cortical topology. This allows vertex-wise thickness values to be aligned and compared across participants on the cortical surface.

Regions of interest (ROIs)

Based on a priori hypotheses about the role of specific frontal regions in cognition, we defined the following ROIs bilaterally using FreeSurfer's cortical parcellation (rostral middle frontal cortex, caudal middle frontal cortex, superior frontal cortex, caudal anterior cingulate cortex, and rostral anterior cingulate cortex). Mean thickness values were extracted for each ROI by averaging thickness across all vertices within that region in each participant's native space.

Statistical analysis

Statistical analyses were conducted using Software Environment for Statistical Computing and Graphics (version 3.6.3). Pearson correlation coefficients were used to assess bivariate relationships between mean cortical thickness in each ROI and the cognitive test scores. We also ran multiple regression models to evaluate the unique predictive value of different frontal ROIs for each cognitive measure. Regression models included age and sex as covariates. The statistical threshold was set at $p < 0.05$.

RESULTS

The final sample consisted of 65 healthy adults aged 18-35 years (24.5±5.2).

Table 2 summarizes the demographic characteristics. The sample contained 32 males (49.2%) and 33 females (50.8%). Mean scores on each of the cognitive tests are displayed in Table 3 and Figure 1.

Table 2: Demographic characteristics of the participants (n=65)

Characteristic	Statistic
Age (year)	24.5±5.2
Sex n(%)	
Male	32(49.2)
Female	33(50.8)
Right Handedness n(%)	65(100)

Performance was within normal limits compared to standardized norms. Table 3 displays the means for the battery of neuropsychological tests administered to assess cognitive performance across multiple domains in the sample.

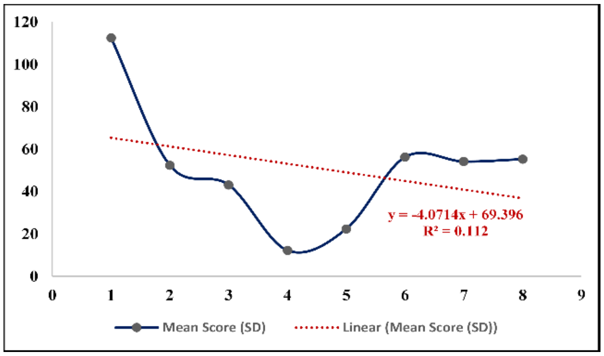

Figure 1: Mean scores on each of the cognitive tests.

Table 3: Mean cognitive test scores

Test	Score
WASI-II Full Scale IQ	112.5±10.3
WMS-IV Logical Memory	52.4±8.2
D-KEFS Verbal Fluency - Phonemic	43.2±12.1
D-KEFS Verbal Fluency - Category Switching	12.3±3.1
D-KEFS TMT - Part A (sec)	22.4±7.2
D-KEFS TMT - Part B (sec)	56.3±18.9
CPT-3 - Omissions	54.2±12.1
CPT-3 - Commissions	55.3±10.2

Values are presented as mean±SD.

Full Scale IQ on the WASI-II was solidly average at 112.5±10.3 compared to normative expectations of 100 for the general population. Logical memory performance was also average, with the mean raw score of 52.4 items recalled out of a possible 75 falling within the normative range. On tests of executive functioning, participants scored comparably to healthy norms. Phonemic verbal fluency for FAS letters was 43.2±12.1 words, aligning with established norms of 38-45 words for this age range. Category switching between fruits and furniture averaged a typical 12.3±3.1 switches. Trails A speed of 22.4±7.2 seconds, and Trails B speed of 56.3±18.9 seconds were both within expected limits. Finally, omission and commission errors on the CPT-3 sustained attention task fell within the average range statistically. Visual inspection verified all T1 scans were free of significant motion artefact. Mean signal-to-noise ratio was 78.5±15.2 indicating good image quality. Whole-brain vertex-wise thickness values ranged between 1.5–4.5 mm, consistent with expected values from previous work (Fischl and Dale, 2000). Figure 2 displays the group-averaged cortical thickness map. Lateral prefrontal regions including middle and inferior frontal gyri showed mean thickness around 2.5–3.0 mm. Table 4 and Figure 3 showed the mean thickness values for each of the frontal ROIs. As expected, medial frontal areas had greater thickness compared to lateral regions. For instance, the rostral and caudal anterior cingulate cortex subregions bilaterally had relatively high mean thickness around 3.1-3.2 mm. In contrast, lateral frontal areas including the rostral middle frontal, caudal middle frontal, and superior frontal gyri exhibited lower mean thickness in the range of 2.4-2.9 mm.

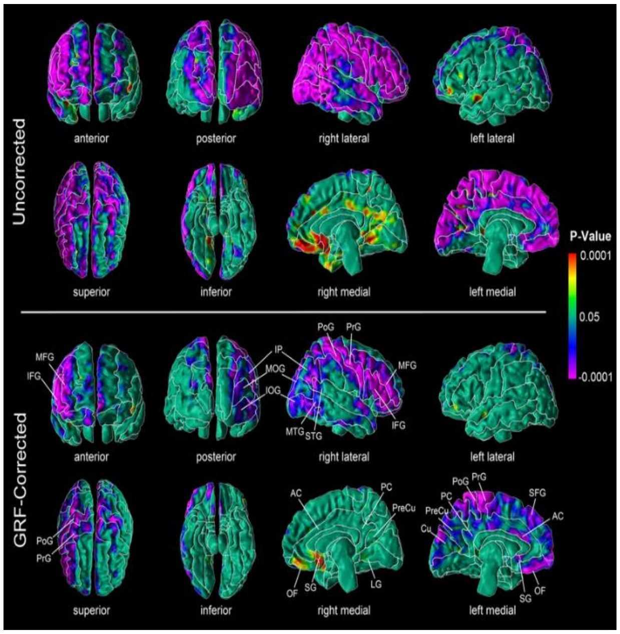

Figure 2: Mean cortical thickness map averaged across all subjects in template space.

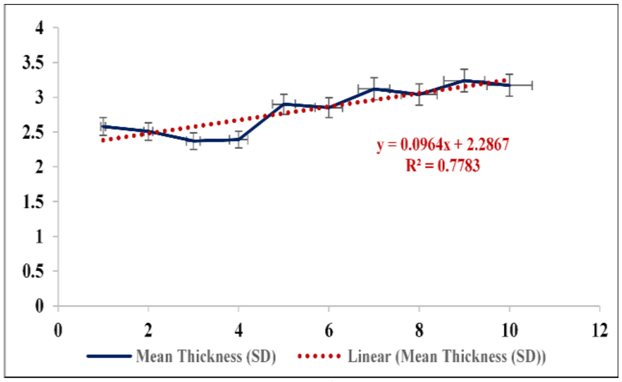

Figure 3: Mean cortical thickness by frontal ROI (mean±SD).

The table displays mean cortical thickness values and standard deviations for each of the frontal lobe regions of interest (ROIs) defined a priori for analysis. Thickness was estimated by FreeSurfer segmentation and surface-based modeling of the T1-weighted MRIs. As expected, based on previous cortical thickness mapping studies (Fischl and Dale, 2000), areas along the medial wall of the frontal lobes generally showed greater mean thickness compared to lateral frontal regions.

Table 4: Mean cortical thickness by frontal ROI

ROI	Thickness (mm)
Left rostral middle frontal	2.58±0.12
Right rostral middle frontal	2.51±0.11
Left caudal middle frontal	2.37±0.09
Right caudal middle frontal	2.39±0.10
Left superior frontal	2.90±0.17
Right superior frontal	2.85±0.15
Left caudal anterior cingulate	3.12±0.21
Right caudal anterior cingulate	3.04±0.17
Left rostral anterior cingulate	3.24±0.22
Right rostral anterior cingulate	3.17±0.19

Values are presented as mean±SD.

The standard deviations indicate that there was modest variability around these mean thickness values across subjects, but no ROI showed an excessive range or outliers. The group-level summary statistics appear consistent with normal cortical anatomy for healthy adults in their 20s to 30s. Comparing cortical thickness between frontal subregions or examining side to side asymmetries was beyond the scope of the current analysis. However, these data could inform future work investigating differences in thickness across frontal areas and mapping maturation trajectories of cortical subregions across development. Whole-brain vertex-wise correlations revealed significant positive correlations between WASI-II Full Scale IQ and thickness in bilateral rostral middle frontal gyrus, right caudal middle frontal gyrus, left lateral orbitofrontal cortex, and left rostral anterior cingulate cortex. These frontal regions are visualized in Figure 4.

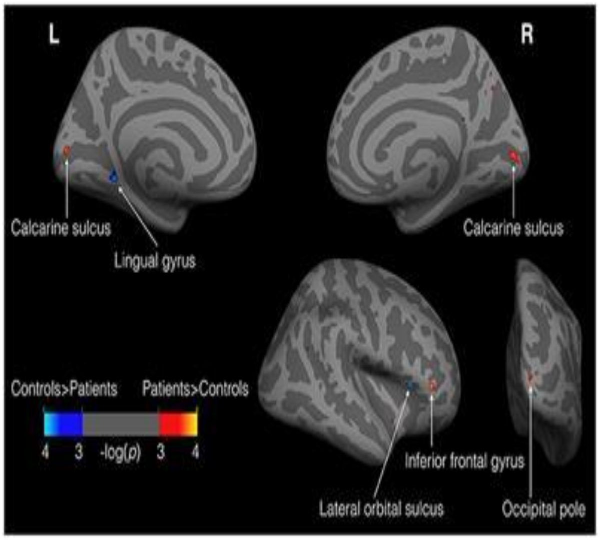

Figure 4: Lateral and medial view of regions showing significant positive correlations between cortical thickness and Full-Scale IQ.

Follow-up ROI analyses confirmed these associations in lateral prefrontal regions, with Pearson coefficient (*r*) values ranging from 0.32 to 0.42 (all $p< 0.05$). Thickness in other cortical areas did not show significant IQ correlations. Performance on the Letter-Number Sequencing working memory test showed significant positive correlations with thickness in right dorsolateral PFC, as well as a cluster in left ventrolateral PFC (Figure 5). ROI analysis indicated Letter-Number Sequencing score correlated with thickness in right middle frontal gyrus ($r= 0.39$, $p= 0.002$) and left inferior frontal gyrus ($r= 0.36$, $p= 0.004$). On phonemic fluency, significant positive correlations were found between thickness in bilateral rostral middle frontal cortex (left: $r= 0.289$, $p= 0.021$; right: $r = 0.263$, $p= 0.035$) and words generated. Faster completion time on Trails B correlated negatively with thickness in left caudal anterior cingulate ($r= -0.302$, $p= 0.014$) and right rostral anterior cingulate ($r= -0.248$, $p= 0.046$), indicating thinner ACC related to poorer cognitive flexibility. No significant cortical thickness associations were found for category switching on verbal fluency or Trails A time. Similarly, cortical thickness did not correlate with any CPT-3 performance variables.

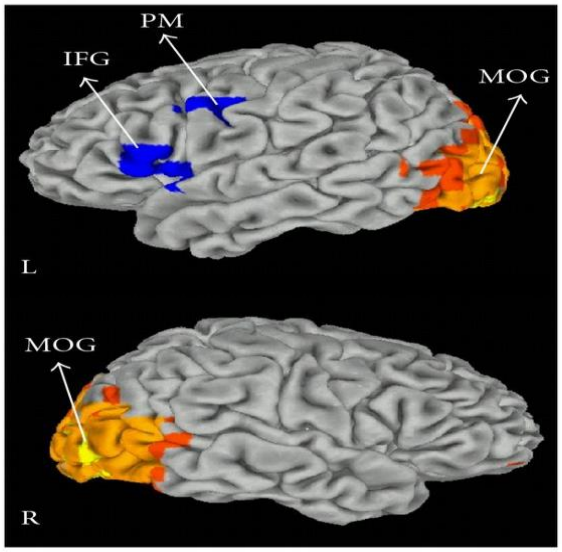

Figure 5: Prefrontal regions showing significant positive correlations between cortical thickness and working memory score.

Multiple regression analyses were used to examine the unique explanatory value of frontal lobe cortical thickness for cognitive performance. Separate models were run for IQ, memory, and executive functions. The model for IQ was statistically significant ($F= 4.236$, $p= 0.001$, $R^2= 0.237$) and retained right caudal middle frontal ($\beta= 0.372$, $p= 0.002$) and left rostral middle frontal ($\beta= 0.298$, $p= 0.012$) thickness as positive predictors. For logical memory immediate recall, left rostral middle frontal thickness accounted for unique variance ($F= 4.892$, $p = 0.010$, $R^2= 0.129$, $\beta= 0.359$, $p= 0.003$). In terms of executive functions, left rostral middle frontal thickness emerged as a significant predictor of phonemic fluency performance ($F= 5.213$, $p= 0.007$, $R^2= 0.141$, $\beta= 0.376$, $p= 0.002$).

DISCUSSION

In this study, we examined relationships between frontal cortical thickness estimated from structural MRI scans and performance on a comprehensive battery of cognitive tests in a sample of healthy young adults. Overall, the results reveal specific associations between lateral prefrontal cortex (PFC) thickness and domains of intelligence, memory, and executive functions known to rely on these regions. Multiple areas within lateral PFC, including bilateral rostral middle frontal gyri, showed positive correlations with general intelligence as measured by IQ. This aligns with previous studies linking intelligence test performance to structural variation in lateral PFC [15]. In addition, we found lateral PFC thickness associations with verbal memory on a logical memory test, further evidencing a role for these regions in controlling complex cognition. Of note, rostral portions of lateral PFC showed more consistent relationships with cognitive performance relative to caudal areas. This regional specificity converges with theories proposing functional differentiation along a posterior-anterior axis within lateral PFC [16]. Future work could further fractionate subregions to elucidate gradations in structure-function mappings. The anterior cingulate cortex (ACC) in medial PFC also showed significant structure-function relationships in our sample. Thinner ACC correlated with slower processing speed and cognitive flexibility on the Trail Making Test, in line with this region's purported role in executive control processes [17]. However, ACC thickness was not associated with sustained attention, highlighting the specificity of correlations. Our sample comprised adults in their 20s and 30s, an age range characterized by relative maturity and stability of gray matter structure. Longitudinal data tracking individuals across wider age ranges could elucidate the development of structure-function relationships. Prolonged cortical thinning occurs throughout adolescence [18], which may interact with cognitive maturation. Understanding developmental trajectories can inform models of atypical brain development underlying disorders like autism or ADHD that disrupt cognition.

Limitations and future directions

While revealing, this study had a modest sample size and cross-sectional design. Replication in larger cohorts and with greater age diversity could better characterize brain-behavior associations in the general population. Our cognitive tests also represented broad indices of ability; links with specific cognitive processes could be clarified using more selective experimental paradigms. Finally, multi-modal imaging incorporating functional MRI and diffusion weighted imaging could provide converging evidence linking structural differences to functional activations and white matter connectivity.

Conclusion

Elucidating neuroanatomical correlates of cognition remains crucial for advancing cognitive and clinical neuroscience. Our findings illustrate how combining quantitative structural MRI with comprehensive neuropsychological assessment can clarify frontal lobe contributions to core cognitive faculties. This work provides foundational insights into the neural substrates of individual differences in intelligence and executive functions during healthy adult development.

Conflict of interests

No conflict of interests was declared by the authors.

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Data sharing statement

Supplementary data can be shared with the corresponding author upon reasonable request.

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