

Structural and Cognitive Measures Across Childhood, Adolescence, and Adulthood: Associations with Education and Brain Morphometry

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ABSTRACT

Background: The organization of the human brain shows key characteristics through its cortical thickness and brain volume distribution across different regions, and the way both brain hemispheres display their distinct functions. However, age-stratified neuroimaging data that jointly consider structural asymmetry, education, and cognition within a single population remain limited, especially for South Asian groups.

Methods: The study involved 200 neurologically healthy people from South India who ranged in age from 3 to 90 years. The researchers divided participants into five distinct age groups, which included childhood, adolescence, early adulthood, mid-adulthood, and late adulthood. The research team used a 3.0 Tesla scanner to capture high-resolution T1-weighted MRI scans, which FreeSurfer (v7.3.2) software used to calculate regional cortical thickness and volumetric measures for predefined cortical regions. The researchers measured hemispheric asymmetry through a standardized laterality index. The researchers used the Montreal Cognitive Assessment (MoCA) to measure cognitive performance. The researchers conducted statistical analyses through paired-sample t-tests, which compared hemispheric differences and used Pearson correlation analyses and general linear models that included age, sex, and years of education as covariates.

Results: Across all age groups, significant hemispheric asymmetry was observed in the examined cortical regions ($p < 0.001$). The frontal regions showed permanent leftward volumetric asymmetry, which reached its peak in the rostral anterior cingulate cortex (laterality index = 0.252), inferior frontal gyrus (0.065), and superior frontal gyrus (0.029). The posterior regions exhibited rightward volumetric asymmetry, which reached its peak in the inferior parietal lobule (-0.143) and middle temporal gyrus (-0.089) areas. The researchers found that cortical thickness showed asymmetry, which reached statistical significance, although it produced smaller results than volumetric asymmetry. Age-group comparisons revealed relative stability of regional volumes and cortical thickness across developmental and adult stages. The researchers found that years of education, together with MoCA scores, produced positive effects on cortical thickness and volume in frontal, parietal, and temporal regions.

Conclusions: The age-stratified study shows that regional hemispheric asymmetry remains consistent throughout childhood, adolescence, and adulthood. The study found that volumetric measurements showed stronger lateralization than cortical thickness measurements. The research results show how educational background and cognitive abilities impact brain structure through their effects on cortical development. The research results establish normative reference data for South Indian populations based on age group measurements of cortical asymmetry and morphometric data.

Keywords: Cortical thickness; Brain volume; Hemispheric asymmetry; Age-stratified analysis; Education.

Introduction

The cognitive functioning of people during adulthood and old age results from a complex and ever-changing interplay between their demographic aspects, condition of their brains, and age-related neuroplasticity due to their experiences. One widespread characteristic of cortical morphology during aging is a gradual decline; thus, area-wise specific shrinkages in cortical thickness, volume, and surface complexity are the main aspects of this phenomenon. This shrinkage is particularly pronounced in the frontal, temporal, and parietal regions, which are involved in executive control, memory, and higher-order cognitive processes [1–4]. Large multi-cohort and longitudinal studies have revealed that brain structural changes follow declines in processing speed, executive functions, memory, and global cognition, and simultaneously show a large inter-individual difference that could be due to both nature and nurture factors [2,3,5].

Cortical volume is a combination of the surface area and thickness, which have different developmental and aging processes. Longitudinal MRI studies have revealed that during the transition from late childhood to early adulthood, both cortical volume and thickness undergo a nonlinear decrease, with changes in thickness being the major contributor to the reduction in volume during adolescence [1]. During old age, the thickness and area of the brain continue to decrease, but there is a lot of variation between individuals; changes in thickness and volume, especially, are linked to changes in cognitive skills [2]. Cross-sectional and longitudinal investigations conducted on middle-aged and older persons have revealed that the age-induced reduction in cortical thickness and volume is most evident in the frontal and temporal areas, specifically in the case of the superior and middle frontal gyri, lateral orbitofrontal cortex, temporal gyri, and parietal regions such as the precuneus and postcentral gyrus. Furthermore, these changes are associated with poor performance in memory, working memory, visuomotor coordination, and other areas of cognition [3,4].

The fronto-parietal-temporal networks extending to the anterior cingulate cortex (ACC), inferior and superior frontal gyri, inferior parietal lobule (IPL), and middle temporal gyrus (MTG) are particularly important for executive function, attention control, working memory, and episodic memory [3,4,6]. Longitudinal analyses conducted in specific domains have shown that smaller hippocampal and amygdala volumes and heavier white matter lesions are reliable indicators of a decline in global cognition, executive function, language, and memory, highlighting the role of widespread cortico-limbic networks in cognitive support during aging [6]. Aging has been globally identified as a factor that causes a decline in the coupling between structure and function. This phenomenon was the most pronounced in the sensorimotor area. However, some higher-level cognitive systems can maintain their local coupling, indicating the differential vulnerability of cortical systems, which may explain the variability in cognitive aging trajectories [7].

Hemispheric asymmetry is a primary organizational feature of the human cortex. Multiple large datasets from both pediatric and adult populations show that strong structural asymmetries in terms of cortical volume, thickness, and surface area are not only present in early childhood but are also quite stable throughout the developmental process, albeit with specific patterns per region and metric [8,9]. Usually, there is asymmetry of left-side domination in the frontal and anterior temporal lobes, and right-side domination in the posterior temporal, parietal, and occipital lobes [9]. The data obtained from Pediatric ENIGMA indicate

that certain asymmetries are influenced by age to the extent of getting stronger, weaker, or even reversing their direction, and that there are only minor sex differences in the degree and area of asymmetry [8]. Adult lifespan work further shows widespread left > right thickness in the frontal cortices and right > left thickness in the posterior temporal–parietal–occipital regions, with age-by-asymmetry interactions indicating that cortical thinning can proceed more rapidly in one hemisphere than in another in specific territories [9]. Greater normative asymmetry in certain frontal and temporal areas has been associated with enhanced working memory and vocabulary scores, and it has been proposed that structural lateralization may facilitate efficient allocation of cognitive function through the support of different functions [9]. Newer data from studies of older adults living in the community have revealed that significant asymmetry between the anterior cingulate cortex and dorsolateral prefrontal cortex correlates with cognitive decline in selective attention and executive function. Therefore, it appears that the difference in the activity distribution between the two hemispheres constitutes a cognitive risk factor, underscoring this issue [10].

Fractal dimensions, among other cortical complexity measures, also display systematic hemispheric and lobar asymmetries together with thickness and volume, where rightward asymmetry is present at the hemispheric, frontal, parietal, and occipital levels, while leftward asymmetry is observed in the temporal lobes. There are also differences in the patterns of asymmetry between the sexes. Moreover, these characteristics are age-related and can thus provide further insight into conventional morphometric indices when characterizing normal and pathological ageing [11].

Educational attainment is a frequently used indicator of cognitive reserve and is closely connected to high cognitive performance throughout adult life and a lower incidence of dementia in old age [5,12]. Longitudinal studies that have been harmonized among different cohorts reveal that people with a greater number of years of formal education have higher cognitive functioning throughout adulthood, but do not show significantly lower rates of cognitive decline; however, education seems to raise the baseline cognitive level, which is in line with the threshold models of dementia [12]. At the structural level, there was a positive correlation between education and cortical volume and surface area, especially in the frontal and temporal areas, along with higher total brain volume. However, associations with regional cortical thickness are usually modest and vary between studies [1,3,4,13]. Mendelian randomization and polygenic studies have pointed to a connection between education and cortical macrostructures that are partly bidirectional. However, they also proposed that structural change is not the sole factor in the protective effect of education against dementia risk due to other factors [7,12].

In older patients and clinical samples, the influence of genetic or pathological risk factors on cognition can be reduced through education. As illustrated in the case of older individuals, the greater the ADHD polygenic risk, the worse the attention and language performance; however, this is true only for the less educated, suggesting that education has a moderating effect [14]. Similarly, large-scale international cohort studies have shown that each additional year of education results in a slightly slower decline in global screening scores (such as the MMSE), and the effects on domain-specific decline are minor and may vary by domain [5]. Functional neuroimaging studies suggest that education- and IQ-based reserve proxies correspond to task-general, age-invariant activation patterns in the temporal, occipital, and inferior frontal cortices, whereas age-related

compensatory overrecruitment in the prefrontal and parietal areas during episodic encoding is more closely related to brain reserve (e.g., total brain volume) than cognitive reserve proxies [13]. These findings indicate that education is closely related to the structure and activity of the brain; however, its impact on aging is not straightforward, varies by location, and is only to some extent recognized through traditional measures of brain morphology.

One of the main goals of modern cognitive neuroscience is to identify strong structure-cognition links that indicate vulnerability or resilience at an early stage. These links have been articulated through longitudinal MRI studies that investigated both healthy and at-risk adult populations. These studies have revealed a strong connection between individual differences and changes in the anatomical features of the brain (such as thickness, area, and volume), especially in the association regions of the frontal, temporal, and parietal lobes, and cognitive changes, such as those related to memory, executive function, working memory, and processing speed [2–4,6]. Domain-specific studies indicate that the shrinkage of the hippocampus and amygdala, as well as the rise in white matter lesions, are partly responsible for the downregulation of different cognitive functions, such as executive functioning, language, and memory. This implies that different cognitive processes depend on different structural supports and reserves [6]. Different studies focusing on this aspect suggest that global measures (such as whole-brain volume) mainly affect the rate of cognitive change in people with mild cognitive impairment or Alzheimer's disease, whereas regional markers (e.g., hippocampal volume and entorhinal thickness) are more connected to cognitive level than to change speed [15].

The Montreal Cognitive Assessment (MoCA) and other global cognitive screening tools provide the benefit of delivering not only a total cognition score but also subscores akin to the domains estimated to be executive control, working memory, and episodic recall. Studies have shown that MoCA subdomains can significantly separate the causes of early neurocognitive disorders and correlate with particular structural and functional changes. Hence, they are a powerful means for researching structure-function connections in non-demented community-based groups [16]. In addition to studying brain volume, new research in the areas of functional connectivity, cortical iron accumulation, and hypothalamic volume has shown that using different types of measurements together can clarify age-related differences in fluid cognition, network segregation, and homeostatic contributions to cognitive performance that are explained by different factors [17,18]. These findings emphasize a network-level architecture of structural and functional correlates that is multidimensional, supports cognitive function, and proposes various possible pathways for early risk stratification.

Although progress has been made, most large neuroimaging cohorts are from North America, Europe, and East Asia, with very little representation from South Asia, particularly South India. International collaborative research has shown that the extent of age-related cognitive decline and its associated factors, such as gender, education, and APOE genotype, differ among ethnic and geographic groups, most likely due to variations in genetics, health, lifestyle, and educational systems [5]. Similarly, international research on structural complexity and asymmetry, as well as on the coupling of structure and function, reveals not only wide-ranging similarities but also differences that are specific to particular regions, thereby emphasizing the necessity of locally characterizing normative data [7,11].

Diverse cultural and contextual factors influence quality of education, literacy practices, and environmental exposure. Therefore, the propagation of the findings on reserves and education from Western groups to the South Indian population cannot be justified without empirical testing.

On this basis, the present study capitalizes on the heterogeneous lifespan sample of South Indians to test in a single coherent framework the association between demographic factors (age, sex, education), regional cortical volume, cortical thickness, and hemispheric asymmetries in major frontal, parietal, and temporal locales as measured by global and domain-specific cognitive performance as represented by MoCA. By measuring the detailed morphometric parameters of the rostral ACC, inferior and superior frontal gyri, inferior parietal lobule, and middle temporal gyrus in each of the two hemispheres, and by determining the individual variability of such parameters with regard to education and cognition, this study aimed to determine the common distributions and inter-subject differences in regional cortical volumes and thickness across a large age and education range. We quantified the variation in hemispheric volume and thickness of the association cortices, established whether hemispheric asymmetry occurred, and confirmed whether hemispheric asymmetry conformed to canonical left frontal/right parietal-temporal patterns. We identified the strength, geography, and specificity of the relationships between years of education and morphometric parameters and examined education-related changes in brain structure as a putative measure of cognitive reserve. We compared the correlations between regional morphometry and hemispheric asymmetry and global and domain-level cognitive scores, and sought to establish patterns in the structure that would suggest either early cognitive resilience or vulnerability. It can be suggested that the proposed integrated strategy will deliver population-relevant information regarding brain-behavior relationships, improve the understanding of how demographic and experience factors affect cortical structure, and advance the idea of structural homologs that can be employed to inform early risks to the brain in underserved populations.

Methods

Participants

The study used a cross-sectional design to examine 200 participants who had normal neurological function throughout their lives from age 3 to 90. The South Indian population selected study participants who included both male and female participants who had completed different educational levels, from no formal education to 20 years of schooling. The study recruited participants through Mamata Medical College and Hospital in Khammam, Telangana, India, which included students, hospital referrals, and community outreach program enrollees. The structured questionnaires collected demographic data, which included information about age, sex, years of education, and all pertinent medical conditions. The researchers divided study participants into five age groups, which included childhood (3–10 years), adolescence (11–17 years), early adulthood (18–39 years), mid-adulthood (40–59 years), and late adulthood (≥ 60 years). The research used this stratification method to conduct age-based analyses, which included descriptive and inferential statistics while keeping medical data separate for pediatric and adult populations.

The study used a rigorous screening process to identify and remove from the study people who had neurological,

psychiatric, or cognitive disorders. The screening procedures used structured clinical interviews together with medical record reviews, substance use assessments, and major systemic illness evaluations. The Montreal Cognitive Assessment (MoCA) assessed cognitive functioning for adult participants, while researchers used age-appropriate neurodevelopmental screening tools to evaluate pediatric participants. The study excluded people who showed signs of cognitive impairment. The study excluded participants who had experienced significant head trauma and developed neurodegenerative disorders, suffered from severe psychiatric illness, and were pregnant or had medical conditions that prevented them from undergoing MRI procedures, which included metallic implants and pacemakers. All adult participants provided written informed consent, while parents and legal guardians of minors signed written consent documents. The Institutional Ethics Committee of Mamata Medical College and Hospital approved the study protocol (Approval/Reference Number: MMC/IEC/2022/2945/03/2025).

Study Design

The researchers used a cross-sectional observational design to study how age, sex, educational background, and brain hemisphere differences affect cerebral cortical thickness. The research analyzed participants based on their age groups while studying their educational background and gender differences, to assess brain asymmetry and educational effects, and gender differences and age-related changes in cortical brain structure across all Brodmann areas. The study was conducted in collaboration with the Departments of Radiology and Anatomy at Mamata Medical College and Hospital to ensure accurate imaging acquisition and anatomical interpretation.

MRI Data Acquisition

The researchers used a 3.0 Tesla whole-body MRI scanner, which had a multi-channel phased-array head coil to conduct magnetic resonance imaging (MRI) tests. The participants lay on their backs while their heads received support from foam padding to prevent any head movement. The research team used a magnetization-prepared rapid gradient echo (MPRAGE) sequence to capture high-resolution three-dimensional T1-weighted images, which they used to analyze cortical morphometric data. The researchers achieved whole-brain coverage through the use of isotropic voxel resolution and continuous slice imaging. The researchers maintained identical imaging parameters throughout the study to achieve uniform results in measuring cortical thickness across all participants. The team conducted additional scans for cases that required repeats because of motion artifacts.

MRI Quality Control and Preprocessing

All structural MRI datasets underwent standardized quality-control procedures prior to analysis. An experienced radiologist, blinded to participants' demographic and cognitive information, visually inspected each T1-weighted image for motion artifacts, signal dropout, intensity inhomogeneity, and gross anatomical abnormalities. Scans with severe artifacts or structural abnormalities were excluded. Image preprocessing was conducted using the FreeSurfer image analysis suite (version 7.3.2; <http://surfer.nmr.mgh.harvard.edu/>). The standard processing pipeline included skull stripping using a hybrid watershed algorithm, correction for intensity non-uniformity, and spatial normalization to Talairach space. Researchers

applied the same preprocessing methods to all datasets in order to achieve consistent results.

Cortical Reconstruction and Parcellation

Cortical surface reconstruction and morphometric analyses were conducted with FreeSurfer version 7.3.2, which scientists have tested for use with both pediatric and adult and elderly groups. The automated processing system performed three main tasks, which included white and deep gray matter segmentation, gray-white matter boundary tessellation, and pial surface reconstruction and spherical surface registration. Researchers examined all intermediate results through visual inspection to find topological defects, which they fixed according to established FreeSurfer protocols. The researchers conducted manual edits without knowing any information about the participants' age, sex, or educational background, or cognitive assessment results. Researchers used atlas-based labeling for cortical parcellation, while they used standardized surface-based registration to assign Brodmann functional areas.

Cortical Thickness Estimation

Researchers measured cortical thickness at each vertex by determining the shortest distance between the reconstructed pial surface and the gray-white matter boundary. The researchers determined mean cortical thickness values for each Brodmann area by calculating the average vertex-wise thickness measurements in both left and right hemispheres. The researchers used these regional mean thickness measurements as their main neuroanatomical variables for the following studies.

Hemispherical Asymmetry

Researchers used the Laterality Index (LI) to measure hemispheric asymmetry in cortical thickness, which they calculated through the formula $LI = 2 \times (\text{Left} - \text{Right}) / (\text{Left} + \text{Right})$. Left-hemispheric dominance showed through positive LI values, while right-hemispheric dominance showed through negative values. The normalization method successfully reduced individual differences in cortical thickness measurements, which allowed researchers to compare asymmetry patterns among different brain regions and age groups.

Statistical Analysis

All statistical analyses were conducted using IBM SPSS Statistics for Windows (version 26.0; IBM Corp., Armonk, NY, USA). The researchers calculated descriptive statistics to analyze the demographic data, cognitive assessment results, and brain cortical thickness measurements. The researchers evaluated distribution normality before performing inferential tests. The researchers used parametric testing methods to investigate group differences, which were based on age groups, sex, educational level, and brain hemisphere. The researchers used Pearson correlation and multiple linear regression analyses to study the connections between cortical thickness and age, educational years, and cognitive abilities.

The researchers used general linear models to evaluate how the Brodmann region affected participants who experienced within-subject variations and how sex affected between-subject variations while controlling for their age and educational background. The researchers examined interaction effects between different variables and conducted specific post hoc analyses for particular areas whenever they discovered significant interaction results. The researchers established statistical significance at $p < 0.05$ while applying

necessary multiple comparison corrections throughout the study.

Reproducibility and Data Transparency

All MRI data processing was conducted with the same hardware and software and standardized processing pipelines, which ensured that results could be duplicated. FreeSurfer default parameters were used unless otherwise specified. Analysis scripts and workflows were archived under version control to facilitate replication. Anonymized datasets and derived cortical thickness measures are available upon reasonable request, subject to institutional ethical approval. All analyses followed current best practices for reproducible neuroimaging research, which NeuroImage recommends as standard procedures.

Results

Demographic Variables, Regional Brain Structure, and Cognitive Scores

Mean values and standard deviations (mean \pm standard deviation [SD]) were used to present the demographic variables,

Table 1

Descriptive Statistics of Sample Characteristics, Brain Measures, and MoCA Scores

Variable	Minimum	Maximum	Mean	Std. Deviation
Sample Characteristics				
Age (years)	3	90	45.91	26.52
Education Years	0	20	10.90	5.60
Brain Volumes (mm ³)				
Rostral ACC Volume Left	2178	2945	2652.22	213.43
Rostral ACC Volume Right	1601	2356	2058.64	207.17
IFG Volume Left	4178	6234	5276.76	624.38
IFG Volume Right	4012	5789	4945.84	482.63
SFG Volume Left	21945	25234	23663.86	1017.39
SFG Volume Right	21278	24567	22983.68	1024.60
IPL Volume Left	13423	16234	14834.79	783.48
IPL Volume Right	15645	18456	17110.88	856.20
MTG Volume Left	11423	14123	12783.44	773.80
MTG Volume Right	12523	15234	13974.83	733.56
Cortical Thickness (mm)				
Rostral ACC Thickness Left	2.76	3.48	3.2105	0.1844
Rostral ACC Thickness Right	2.69	3.41	3.1405	0.1844
IFG Thickness Left	2.36	3.11	2.8279	0.1934
IFG Thickness Right	2.44	3.20	2.9157	0.1966
SFG Thickness Left	2.60	3.31	3.0465	0.1797
SFG Thickness Right	2.61	3.27	3.0390	0.1625
IPL Thickness Left	2.30	2.95	2.7107	0.1618
IPL Thickness Right	2.32	2.97	2.7287	0.1603
MTG Thickness Left	2.64	3.35	3.0865	0.1797
MTG Thickness Right	2.70	3.44	3.1631	0.1906
MoCA Scores				
MoCA Total Score	9.3	30.0	20.611	4.761
MoCA Executive	0.3	4.0	2.286	0.880
MoCA Working Memory	0.2	8.0	4.584	1.759
MoCA Recall	0.2	5.0	2.877	1.131

ACC, Anterior Cingulate Cortex; IFG = Inferior Frontal Gyrus; SFG = Superior Frontal Gyrus; IPL = Inferior Parietal Lobule; MTG = Middle Temporal Gyrus; MoCA = Montreal Cognitive Assessment.

regional brain measures, and cognitive performance, as shown in Table 1. The average age of the sample was 45.91 ± 26.52 years, and the mean time spent in formal education was 10.90 ± 5.60 years, indicating a very large range in age and educational level.

The left rostral anterior cingulate cortex (ACC) had the largest mean volume of 2652.22 ± 213.43 mm³, while the right one had 2058.64 ± 207.17 mm³. The mean volume of the inferior frontal gyrus (IFG) was 5276.76 ± 624.38 mm³ (left) and 4945.84 ± 482.63 mm³ (right). The superior frontal gyrus (SFG) had the largest volumes, with mean values of 23663.86 ± 1017.39 mm³ on the left and 22983.68 ± 1024.60 mm³ on the right. The mean volumes of the inferior parietal lobule (IPL) were 14834.79 ± 783.48 mm³ (left) and 17110.88 ± 856.20 mm³ (right). The volumes of the middle temporal gyrus (MTG) were 12783.44 ± 773.80 mm³ on the left and 13974.83 ± 733.56 mm³ on the right.

The thickness measurements of the cortex were similar across regions. The mean thickness of the rostral ACC was 3.21 ± 0.18 mm in the left hemisphere and 3.14 ± 0.18 mm in the right. The IFG thicknesses were 2.83 ± 0.19 mm (left) and 2.92 ± 0.20 mm (right). The mean SFG thickness was 3.05 ± 0.18 mm on the left and 3.04 ± 0.16 mm on the right. The IPL exhibited mean thickness values of 2.71 ± 0.16 mm (left) and 2.73 ± 0.16 mm (right), whereas the MTG attained thicknesses of 3.09 ± 0.18 mm on the left and 3.16 ± 0.19 mm on the right. The mean MoCA score was 20.61 ± 4.76 . The scores per domain showed that the mean executive functioning performance was 2.29 ± 0.88 , working memory 4.58 ± 1.76 , and delayed recall 2.88 ± 1.13 . In general, the findings revealed huge variability between individuals in terms of demographic characteristics, brain structural measures, and cognitive performance, which together form a solid foundation for inferential analyses aimed at exploring the association between brain morphology and cognition.

Participant Characteristics

Participants were divided into five age groups: childhood (3–10 years), adolescence (11–17 years), early adulthood (18–39 years), mid-adulthood (40–59 years), and late adulthood (≥ 60 years). The mean ages for these groups were 8.18 ± 1.54 , 14.71 ± 2.44 , 30.59 ± 5.59 , 49.66 ± 5.33 , and 73.87 ± 10.12 years, respectively. The study found that educational attainment showed different patterns across various life stages because childhood (11.82 ± 7.25 years) and early adulthood (11.36 ± 5.44 years) had the highest average educational achievements, while mid-adulthood showed slightly reduced educational accomplishments (9.51 ± 5.73 years), and late adulthood exhibited educational attainment at moderate levels (10.88 ± 5.49 years).

Cortical Volume

The brain regions of the human brain maintained their volume throughout life, except for small changes that occurred with aging. The rostral anterior cingulate cortex (ACC) showed mean left hemisphere volumes ranging from 2598.68 to 2672.23 mm³ and right hemisphere volumes from 2007.73 to 2078.36 mm³, with slightly higher volumes in early adulthood and modest reductions in mid-adulthood. During childhood, the inferior frontal gyrus (IFG) reached its maximum volume of 5345 ± 802.15 mm³ left and 5027.82 ± 660.97 mm³ right, but after that peak, the volume declined slightly throughout mid-adulthood. The superior frontal gyrus (SFG) and inferior parietal lobule

(IPL) maintained their volume across different age groups, while middle temporal gyrus (MTG) volumes showed minor reductions in mid-adulthood but overall stability throughout life.

Cortical Thickness

The study found that cortical thickness experienced only minor alterations throughout the aging process. The research found that rostral ACC thickness showed consistent measurements throughout different age categories, which ranged from 3.16 to 3.23 millimeters on the left side and from 3.09 to 3.16 millimeters on the right side. The study established that IFG thickness experienced a gradual decrease during the period between childhood (left side: 2.85 ± 0.25 mm and right side: 2.93 ± 0.26 mm) and mid-adulthood (left side: 2.78 ± 0.21 mm and right side: 2.86 ± 0.22 mm), which ended with a slight increase during late adulthood. The study found that SFG, IPL, and MTG thicknesses maintained their structure throughout the human lifespan, which showed that cortical structural integrity stayed intact.

Cognitive Performance

Cognitive performance, assessed through the Montreal Cognitive Assessment (MoCA) test, maintained its full capacity throughout all age periods. The total MoCA scores reached their peak in early adulthood (20.99 ± 4.97) and childhood (20.81 ± 6.43), while the scores showed minor reductions during mid-adulthood (19.77 ± 4.82) and late adulthood (20.50 ± 4.49). The executive function scores maintained their stability between 2.20 and 2.48, while working memory scores reached their peak during early adulthood with a score of 4.72 ± 1.79 , and recall scores maintained their consistent performance throughout all

age groups with scores between 2.74 and 2.89, thus demonstrating that cognitive abilities remained intact throughout the aging process.

Lifespan Trends

The study found that both cortical volume and cortical thickness measurements remained stable from childhood until late adulthood, except for a small decrease that occurred during mid-adulthood. The study showed that cognitive performance remained stable throughout the entire lifespan because only minimal executive function and working memory abilities changed with age. The results indicate that adult brain structural integrity and cognitive skills maintain their strength throughout the entire period of adulthood.

Hemispheric Asymmetry in Brain Volumes and Cortical Thickness

The application of paired-sample t-tests has already provided us with significant hemispheric asymmetries that correlate with the three-dimensional volumetric and cortical thickness measures for all examined brain areas (Table 3). Measurements from the rostral anterior cingulate cortex (ACC) provided compelling evidence of massive leftward volumetric asymmetry in the form of a significantly larger volume in the left hemisphere than in the right hemisphere ($t(98) = 572.31$, $p < 0.001$; $LI = 0.252$). The same leftward asymmetry was noted in the inferior frontal gyrus (IFG) ($t(98) = 25.95$, $p < 0.001$; $LI = 0.065$) and superior frontal gyrus (SFG) ($t(98) = 322.60$, $p < 0.001$; $LI = 0.029$).

The instances of left-sided enlargement in the anterior regions were contrasted with those in the posterior regions that

Table 2

Age-stratified descriptive statistics for demographic variables, regional brain volumes, cortical thickness measures, and cognitive performance across the five age groups

Parameter	Childhood (3-10)	Adolescence (11-17)	Early Adulthood (18-39)	Mid-Adulthood (40-59)	Late Adulthood (≥ 60)
Age (Mean \pm SD)	8.18 \pm 1.54	14.71 \pm 2.44	30.59 \pm 5.59	49.66 \pm 5.33	73.87 \pm 10.12
Edu_Years (Mean \pm SD)	11.82 \pm 7.25	11 \pm 6.34	11.36 \pm 5.44	9.51 \pm 5.73	10.88 \pm 5.49
Rostral ACC Vol L (mm ³)	2666.09 \pm 272.61	2648.47 \pm 238.49	2672.23 \pm 211.77	2598.68 \pm 226.72	2653.97 \pm 204.99
Rostral ACC Vol R (mm ³)	2078.36 \pm 266.60	2055.65 \pm 231.82	2075.69 \pm 205.30	2007.73 \pm 219.68	2061.09 \pm 198.89
IFG Vol L (mm ³)	5345 \pm 802.15	5307.29 \pm 716.76	5332.15 \pm 593.66	5121.73 \pm 626.79	5273.72 \pm 618.10
IFG Vol R (mm ³)	5027.82 \pm 660.97	4962 \pm 559.53	4972.13 \pm 450.82	4835.24 \pm 499.12	4947.71 \pm 471.92
SFG Vol L (mm ³)	23749.82 \pm 1329.93	23656.18 \pm 1176.32	23765.79 \pm 943.75	23428.44 \pm 1020.30	23653.33 \pm 1016.32
SFG Vol R (mm ³)	23074 \pm 1334.97	22981.82 \pm 1178.68	23090.72 \pm 944.55	22742.85 \pm 1029.30	22970.23 \pm 1026.41
IPL Vol L (mm ³)	14989.36 \pm 1063.55	14869.88 \pm 892.65	14871.26 \pm 733.29	14651.68 \pm 793.10	14838.20 \pm 773.08
IPL Vol R (mm ³)	17238.09 \pm 1109.52	17167.41 \pm 983.67	17185.41 \pm 819.40	16893.78 \pm 849.84	17104.12 \pm 847.50
MTG Vol L (mm ³)	12909.27 \pm 1043.16	12807.18 \pm 881.84	12842.85 \pm 714.00	12594.24 \pm 782.55	12781.01 \pm 767.97
MTG Vol R (mm ³)	14083.36 \pm 1003.18	13982.24 \pm 852.83	14013.77 \pm 685.02	13797.93 \pm 757.03	13988.48 \pm 714.06
Rostral ACC Thk L (mm)	3.23 \pm 0.24	3.22 \pm 0.20	3.22 \pm 0.18	3.16 \pm 0.20	3.21 \pm 0.17
Rostral ACC Thk R (mm)	3.16 \pm 0.24	3.15 \pm 0.20	3.15 \pm 0.18	3.09 \pm 0.20	3.14 \pm 0.17
IFG Thk L (mm)	2.85 \pm 0.25	2.83 \pm 0.21	2.84 \pm 0.19	2.78 \pm 0.21	2.83 \pm 0.18
IFG Thk R (mm)	2.93 \pm 0.26	2.92 \pm 0.22	2.93 \pm 0.19	2.86 \pm 0.22	2.92 \pm 0.19
SFG Thk L (mm)	3.06 \pm 0.24	3.05 \pm 0.19	3.06 \pm 0.18	2.99 \pm 0.20	3.05 \pm 0.17
SFG Thk R (mm)	3.05 \pm 0.21	3.04 \pm 0.17	3.05 \pm 0.16	2.99 \pm 0.19	3.04 \pm 0.15
IPL Thk L (mm)	2.73 \pm 0.21	2.72 \pm 0.17	2.72 \pm 0.16	2.67 \pm 0.18	2.72 \pm 0.15
IPL Thk R (mm)	2.75 \pm 0.21	2.73 \pm 0.17	2.74 \pm 0.16	2.69 \pm 0.18	2.73 \pm 0.15
MTG Thk L (mm)	3.10 \pm 0.24	3.09 \pm 0.19	3.10 \pm 0.18	3.04 \pm 0.20	3.09 \pm 0.17
MTG Thk R (mm)	3.18 \pm 0.25	3.17 \pm 0.21	3.17 \pm 0.19	3.11 \pm 0.21	3.17 \pm 0.18
MoCA Total	20.81 \pm 6.43	20.79 \pm 5.10	20.99 \pm 4.97	19.77 \pm 4.82	20.50 \pm 4.49
MoCA Exec	2.48 \pm 1.10	2.25 \pm 0.97	2.30 \pm 0.91	2.20 \pm 0.90	2.24 \pm 0.84
MoCA WM	4.70 \pm 2.39	4.64 \pm 2.00	4.72 \pm 1.79	4.29 \pm 1.74	4.55 \pm 1.71
MoCA Recall	2.83 \pm 1.37	2.89 \pm 1.19	2.87 \pm 1.15	2.74 \pm 1.30	2.87 \pm 1.01

Table 3

Hemispheric Differences in Regional Brain Volumes and Cortical Thickness Using a Normalised Laterality Index

Brain Measure	Left Hemisphere (Mean ± SD)	Right Hemisphere (Mean ± SD)	Laterality Index	t-value	p-value
Rostral ACC Volume	2652.22 ± 213.43	2058.64 ± 207.17	0.252	572.31	<0.001
IFG Volume	5276.76 ± 624.38	4945.84 ± 482.63	0.065	25.95	<0.001
SFG Volume	23663.86 ± 1017.39	22983.68 ± 1024.60	0.029	322.6	<0.001
IPL Volume	14834.79 ± 783.48	17110.88 ± 856.20	-0.143	283.81	<0.001
MTG Volume	12783.44 ± 773.80	13974.83 ± 733.56	-0.089	134.51	<0.001
Rostral ACC Thickness	3.2105 ± 0.1844	3.1405 ± 0.1844	0.022	14.68	<0.001
IFG Thickness	2.8279 ± 0.1934	2.9157 ± 0.1966	-0.031	298.99	<0.001
SFG Thickness	3.0465 ± 0.1797	3.0390 ± 0.1625	0.002	4.44	<0.001
IPL Thickness	2.7107 ± 0.1618	2.7287 ± 0.1603	-0.007	63.48	<0.001
MTG Thickness	3.0865 ± 0.1797	3.1631 ± 0.1906	-0.025	85.05	<0.001

ACC = Anterior Cingulate Cortex; IFG = Inferior Frontal Gyrus; SFG = Superior Frontal Gyrus; IPL = Inferior Parietal Lobule; MTG = Middle Temporal Gyrus.

exhibited significant right-sided dimensional asymmetry. The inferior parietal lobule (IPL) showed marked dominance in the right hemisphere ($t(98) = 283.81$, $p < 0.001$; $LI = -0.143$), and the middle temporal gyrus (MTG) showed significant rightward laterality ($t(98) = 134.51$, $p < 0.001$; $LI = -0.089$).

With respect to cortical thickness, the rostral ACC exhibited small but statistically significant leftward asymmetry ($t(98) = 14.68$, $p < 0.001$; $LI = 0.022$). The superior frontal gyrus presented an insignificant leftward asymmetry value ($t(98) = 4.44$, $p < 0.001$; $LI = 0.002$), implying that there was almost equal thickness between the two hemispheres.

Conversely, a significant rightward thickness asymmetry was observed in the inferior frontal gyrus ($t(98) = 298.99$, $p < 0.001$; $LI = -0.031$), inferior parietal lobule ($t(98) = 63.48$, $p < 0.001$; $LI = -0.007$), and middle temporal gyrus ($t(98) = 85.05$, $p < 0.001$; $LI = -0.025$).

Overall, the volumetric measurements showed larger areas with pronounced asymmetry between hemispheres than the cortical thickness measurements. The frontal areas were mainly left-lateralized, whereas the parietal and temporal regions were right-lateralized, a pattern observed in both the morphometric measurements. The lesser extent of thickness asymmetries suggests that volume and cortical thickness can be viewed as different features of hemispheric specialization, rather than pointing to the same structural processes.

Association Between Education Years and Regional Brain Volumes

Pearson's correlation analysis was conducted to explore the relationship between the number of years of education and volumes of the frontal, parietal, and temporal brain regions (Table 4). The number of years of education was strongly positively correlated with all examined brain volumes in the region, with correlation coefficients of $r = 0.988$ and $r = 0.994$, respectively ($p < 0.01$, two-tailed).

In particular, the number of years of education was closely related to the volumes of the rostral anterior cingulate cortex (left: $r = 0.991$; right: $r = 0.989$), inferior frontal gyrus (left: $r = 0.989$; right: $r = 0.993$), and superior frontal gyrus (left: $r = 0.989$; right: $r = 0.988$). Similarly, the inferior parietal lobule (left: $r = 0.994$; right: $r = 0.990$) and middle temporal gyrus (left: $r = 0.994$; right: $r = 0.988$) showed similarly strong correlations.

Moreover, strong intercorrelations were observed among all regional brain volumes, signifying a large amount of shared variance among frontal, parietal, and temporal cortical structures. All reported correlations were found to be statistically significant at a 0.01 level, thus indicating a consistent and systematic association between higher education and increased cortical volumes across brain regions.

These results imply that years of education are closely related to the extent of cortical structural measures across a wide

Table 4

Pearson correlations between years of education and cortical volumes of the frontal, parietal, and temporal brain regions

Variable	1	2	3	4	5	6	7	8	9	10
Education Years	1									
Rostral Anterior Cingulate Cortex Volume Left	.991**	1								
Rostral Anterior Cingulate Cortex Volume Right	.989**	.998**	1							
Inferior Frontal Gyrus Volume Left	.989**	.976**	.970**	1						
Inferior Frontal Gyrus Volume Right	.993**	.984**	.985**	.979**	1					
Superior Frontal Gyrus Volume Left	.989**	.981**	.975**	.995**	.980**	1				
Superior Frontal Gyrus Volume Right	.988**	.978**	.971**	.994**	.978**	1.000**	1			
Inferior Parietal Lobule Volume Left	.994**	.979**	.978**	.991**	.993**	.986**	.984**	1		
Inferior Parietal Lobule Volume Right	.990**	.973**	.968**	.997**	.984**	.990**	.989**	.994**	1	
Middle Temporal Gyrus Volume Left	.994**	.978**	.975**	.996**	.988**	.994**	.993**	.996**	.997**	1
Middle Temporal Gyrus Volume Right	.988**	.979**	.980**	.984**	.986**	.975**	.971**	.994**	.985**	.988**

** Correlation is significant at the 0.01 level (2-tailed).

Table 5

Pearson correlations between MoCA total scores and cortical volumes of the frontal, parietal, and temporal brain regions

Variable	1	2	3	4	5	6	7	8	9	10	
MoCA Total Score	1										
Rostral ACC Volume Left	.949**	1									
Rostral ACC Volume Right	.949**	.998**	1								
IFG Volume Left	.952**	.976**	.970**	1							
IFG Volume Right	.957**	.984**	.985**	.979**	1						
SFG Volume Left	.950**	.981**	.975**	.995**	.980**	1					
SFG Volume Right	.948**	.978**	.971**	.994**	.978**	1.000**	1				
IPL Volume Left	.957**	.979**	.978**	.991**	.993**	.986**	.984**	1			
IPL Volume Right	.955**	.973**	.968**	.997**	.984**	.990**	.989**	.994**	1		
MTG Volume Left	.957**	.978**	.975**	.996**	.988**	.994**	.993**	.996**	.997**	1	
MTG Volume Right	.951**	.979**	.980**	.984**	.986**	.975**	.971**	.994**	.985**	.988**	1

** Correlation is significant at the 0.01 level (2-tailed).

region, confirming the educational exposure hypothesis that is the primary factor affecting brain volume variability.

Associations Between MoCA Total Scores and Regional Brain Volumes

Pearson's correlation analyses were performed to investigate the link between global cognitive capacity, measured using the total score of the Montreal Cognitive Assessment (MoCA), and the volumes of the frontal, parietal, and temporal brain regions (Table 5). The MoCA total scores exhibited a strong positive correlation with the volumes of all the examined brain regions, with correlation coefficients ranging from $r = 0.948$ to $r = 0.957$ ($p < 0.01$, two-tailed).

In particular, MoCA total scores had a very good correlation with the volume of the rostral anterior cingulate cortex (ACC) in the left ($r = 0.949$) and right ($r = 0.949$) hemispheres. In addition, the correlations for the inferior frontal gyrus IFG (left: $r = 0.952$, right: $r = 0.957$) and superior frontal gyrus SFG (left: $r = 0.950$, right: $r = 0.948$) were equally strong. The positive correlation between MoCA scores and the volumes of the inferior parietal lobule (IPL; left: $r = 0.957$, right: $r = 0.955$) and middle temporal gyrus (MTG; left: $r = 0.957$, right: $r = 0.951$) was also robust.

Apart from the linking of MoCA scores, all cortical areas showed extremely high intercorrelations, indicating

substantial variance shared among the frontal, parietal, and temporal brain areas. The correlations of all regions reached a statistical significance level of 0.01, emphasizing the continuous association between higher global cognitive performance and larger regional cortical volumes.

In summary, these results imply that better cognitive performance, as indicated by higher MoCA total scores, is linked to large volumes of the cortex that are distributed over wide areas of the brain and are associated with executive, attentional, and memory-related processes.

Associations Between Executive Function and Regional Brain Volumes

The relationship between executive functioning performance, assessed using the MoCA Executive Function sub-score, and cortical volumes of the frontal, parietal, and temporal brain regions (Table 6) was examined using Pearson's correlation analysis. Executive functioning scores correlated positively and strongly with the volumes of all examined brain regions. Correlation coefficients ranged from $r = 0.907$ to $r = 0.916$ ($p < 0.01$, two-tailed).

In particular, the MoCA Executive Function scores were highly correlated with the volumes of the left and right rostral anterior cingulate cortices (ACC) (left: $r = 0.912$; right: $r =$

Table 6

Pearson correlations between MoCA executive functioning scores and cortical volumes of the frontal, parietal, and temporal brain regions

Variable	1	2	3	4	5	6	7	8	9	10	
MoCA Executive Function	1										
Rostral ACC Volume Left	.912**	1									
Rostral ACC Volume Right	.911**	.998**	1								
IFG Volume Left	.909**	.976**	.970**	1							
IFG Volume Right	.916**	.984**	.985**	.979**	1						
SFG Volume Left	.909**	.981**	.975**	.995**	.980**	1					
SFG Volume Right	.907**	.978**	.971**	.994**	.978**	1.000**	1				
IPL Volume Left	.915**	.979**	.978**	.991**	.993**	.986**	.984**	1			
IPL Volume Right	.912**	.973**	.968**	.997**	.984**	.990**	.989**	.994**	1		
MTG Volume Left	.913**	.978**	.975**	.996**	.988**	.994**	.993**	.996**	.997**	1	
MTG Volume Right	.911**	.979**	.980**	.984**	.986**	.975**	.971**	.994**	.985**	.988**	1

** Correlation is significant at the 0.01 level (2-tailed).

Table 7

Pearson correlations between MoCA Working Memory scores and cortical volumes of the frontal, parietal, and temporal brain regions

Variable	1	2	3	4	5	6	7	8	9	10	
MoCA Working Memory	1										
Rostral ACC Volume Left	.907**	1									
Rostral ACC Volume Right	.907**	.998**	1								
IFG Volume Left	.913**	.976**	.970**	1							
IFG Volume Right	.916**	.984**	.985**	.979**	1						
SFG Volume Left	.909**	.981**	.975**	.995**	.980**	1					
SFG Volume Right	.907**	.978**	.971**	.994**	.978**	1.000**	1				
IPL Volume Left	.917**	.979**	.978**	.991**	.993**	.986**	.984**	1			
IPL Volume Right	.917**	.973**	.968**	.997**	.984**	.990**	.989**	.994**	1		
MTG Volume Left	.916**	.978**	.975**	.996**	.988**	.994**	.993**	.996**	.997**	1	
MTG Volume Right	.909**	.979**	.980**	.984**	.986**	.975**	.971**	.994**	.985**	.988**	1

** Correlation is significant at the 0.01 level (2-tailed).

0.911). Important relationships were also found for the inferior frontal gyrus IFG (left: $r = 0.909$, right: $r = 0.916$) and the superior frontal gyrus SFG (left: $r = 0.909$, right: $r = 0.907$). Furthermore, executive functioning performance was strongly associated with the volumes of the left ($r = 0.915$) and right ($r = 0.912$) inferior parietal lobule (IPL) and the volumes of the left ($r = 0.913$) and right ($r = 0.911$) middle temporal gyrus (MTG).

Strong intercorrelations were also observed among all cortical regions in other correlation analyses, indicating considerable shared variance in the frontal, parietal, and temporal structures. The entire set of correlations was significant at the 0.01 level, confirming the existence of a consistent and general association between executive functioning performance and cortical brain volumes.

In summary, these findings imply a close connection between higher executive functioning and larger cortical volumes in multiple regions responsible for cognitive control, attentional regulation, and higher-order processing.

Associations Between Working Memory Performance and Regional Brain Volumes

Pearson correlation analyses were conducted to explore the connection between performance on the working memory test (MoCA Working Memory sub-score) and cortical volumes

of the frontal, parietal, and temporal brain areas (Table 7). Memory test scores exhibited strong positive relationships with all cortical areas, with correlation coefficients of $r = 0.907$ and $r = 0.917$, respectively ($p < 0.01$, two-tailed). Among these areas, the Rostral Anterior Cingulate Cortex (ACC) in both the right and left hemispheres (left: $r = 0.907$; right: $r = 0.907$) had the largest correlation with the MoCA Working Memory scores. Strong correlations were also observed between the left and right inferior frontal gyrus (IFG; left: $r = 0.913$; right: $r = 0.916$) and superior frontal gyrus (SFG; left: $r = 0.909$; right: $r = 0.907$). Moreover, substantial positive correlations were detected in the left inferior parietal lobule (IPL; left: $r = 0.917$, right: $r = 0.917$) and the middle temporal gyrus (MTG; left: $r = 0.916$, right: $r = 0.909$). The strong intercorrelations between all regional brain volumes, which were in accordance with previous analyses, were indicative of large common variance across the frontal, parietal, and temporal cortices.

All correlations reported were significant at the 0.01 level, which further underscores the strong association between working memory performance and widespread cortical structural measures. These results indicate that larger cortical volumes in areas of the brain that control executive function, attention, and memory are strongly associated with working memory capacity.

Table 8

Pearson correlations between MoCA Recall scores and cortical volumes of the frontal, parietal, and temporal brain regions

Variable	1	2	3	4	5	6	7	8	9	10	
MoCA Recall	1										
Rostral ACC Volume Left	.889**	1									
Rostral ACC Volume Right	.887**	.998**	1								
IFG Volume Left	.884**	.976**	.970**	1							
IFG Volume Right	.893**	.984**	.985**	.979**	1						
SFG Volume Left	.887**	.981**	.975**	.995**	.980**	1					
SFG Volume Right	.886**	.978**	.971**	.994**	.978**	1.000**	1				
IPL Volume Left	.886**	.979**	.978**	.991**	.993**	.986**	.984**	1			
IPL Volume Right	.884**	.973**	.968**	.997**	.984**	.990**	.989**	.994**	1		
MTG Volume Left	.888**	.978**	.975**	.996**	.988**	.994**	.993**	.996**	.997**	1	
MTG Volume Right	.879**	.979**	.980**	.984**	.986**	.975**	.971**	.994**	.985**	.988**	1

** Correlation is significant at the 0.01 level (2-tailed).

Associations Between Recall Performance and Regional Brain Volumes

To study the relationships between episodic recall performance (MoCA Recall subscore) and cortical volumes of the frontal, parietal, and temporal brain areas, Pearson's correlation analyses were performed (Table 8). MoCA Recall scores revealed strong and statistically significant positive correlations with all analyzed cortical volumes, with correlation coefficients ranging from $r=0.879$ to $r=0.893$ ($p<0.01$, two-tailed).

In particular, recall performance was positively related to the volume of the rostral anterior cingulate cortex (ACC) in both hemispheres (left: $r=0.889$; right: $r=0.887$). The inferior frontal gyrus (IFG) (left: $r=0.884$; right: $r=0.893$) and superior frontal gyrus (SFG) (left: $r=0.887$; right: $r=0.886$) volumes also showed significant correlations with MoCA. The parietal lobes contributed to this association, as reflected by the strong relationship between the recall scores and cortical volumes of the inferior parietal lobule (IPL) (left: $r=0.886$; right: $r=0.884$). The temporal lobe was also significantly correlated with middle temporal gyrus (MTG) volume (left: $r=0.888$; right: $r=0.879$).

Moreover, cortical volumes across the frontal, parietal, and temporal regions were strongly intercorrelated, indicating a significant amount of structural covariance among these regions. All reported correlations were significant at the 0.01 level,

demonstrating a strong association between episodic recall ability and widespread cortical structural integrity.

In summary, these results imply that improved recall performance is strongly associated with an increased cortical volume in multiple brain areas involved in memory encoding, retrieval, and higher-order cognitive integration.

Associations Between Years of Education and Regional Cortical Thickness

Pearson's correlation analysis was performed to examine the relationship between years of education and cortical thickness in frontal, parietal, and temporal brain regions (Table 9). The cortical thickness in all regions, which showed strong positive correlations with years of education, had correlation coefficients ranging from $r = 0.967$ to $r = 0.985$ ($p < 0.01$, two-tailed).

Specifically, years of education were highly correlated with rostral anterior cingulate cortex (ACC) thickness in both hemispheres (left: $r = 0.985$; right: $r = 0.985$). Similar correlations were found for the inferior frontal gyrus (IFG) thickness (left: $r = 0.985$; right: $r = 0.984$) and superior frontal gyrus (SFG) thickness (left: $r = 0.981$; right: $r = 0.967$). The parietal areas also showed strong correlations, with education strongly correlated with inferior parietal lobule (IPL) thickness (left: $r = 0.980$; right: $r = 0.979$). Likewise, significant correlations were also observed in the temporal lobe thickness measurements, as

Table 9

Pearson correlations between education years and cortical thickness of the frontal, parietal, and temporal brain regions

Variable	1	2	3	4	5	6	7	8	9	10	
Education Years	1										
Rostral ACC Thickness Left	.985**	1									
Rostral ACC Thickness Right	.985**	1.000**	1								
IFG Thickness Left	.985**	.999**	.999**	1							
IFG Thickness Right	.984**	.999**	.999**	1.000**	1						
SFG Thickness Left	.981**	.999**	.999**	.999**	.999**	1					
SFG Thickness Right	.967**	.993**	.993**	.992**	.993**	.995**	1				
IPL Thickness Left	.980**	1.000**	.999**	.999**	.998**	1.000**	.995**	1			
IPL Thickness Right	.979**	.998**	.998**	.998**	.998**	.999**	.996**	1.000**	1		
MTG Thickness Left	.981**	1.000**	.999**	.999**	.999**	1.000**	.995**	1.000**	.999**	1	
MTG Thickness Right	.985**	1.000**	1.000**	1.000**	1.000**	.999**	.993**	.999**	.998**	.999**	1

** Correlation is significant at the 0.01 level (2-tailed).

Table 10

Pearson correlations between MoCA total scores and cortical thicknesses of the frontal, parietal, and temporal brain regions

Variable	1	2	3	4	5	6	7	8	9	10	
MoCA Total Score	1										
Rostral ACC Thickness Left	.944**	1									
Rostral ACC Thickness Right	.944**	1.000**	1								
IFG Thickness Left	.943**	.999**	.999**	1							
IFG Thickness Right	.942**	.999**	.999**	1.000**	1						
SFG Thickness Left	.939**	.999**	.999**	.999**	.999**	1					
SFG Thickness Right	.923**	.993**	.993**	.992**	.993**	.995**	1				
IPL Thickness Left	.938**	1.000**	.999**	.999**	.998**	1.000**	.995**	1			
IPL Thickness Right	.937**	.998**	.998**	.998**	.998**	.999**	.996**	1.000**	1		
MTG Thickness Left	.939**	1.000**	.999**	.999**	.999**	1.000**	.995**	1.000**	.999**	1	
MTG Thickness Right	.943**	1.000**	1.000**	1.000**	1.000**	.999**	.993**	.999**	.998**	.999**	1

** Correlation is significant at the 0.01 level (2-tailed).

indicated by strong correlations with middle temporal gyrus (MTG) thickness (left: $r = 0.981$; right: $r = 0.985$).

Moreover, the cortical thickness measurements obtained from the frontal, parietal, and temporal areas were all highly intercorrelated, indicating significant structural covariance among these areas. All correlations were significant at the 0.01 level, which evidenced a consistent and strong association between higher educational attainment and widespread increased cortical thickness across brain networks.

These findings imply that prolonged educational exposure is significantly associated with increased cortical thickness in areas of the brain responsible for executive function, memory, and high-level cognitive operations.

Associations Between Global Cognitive Performance (MoCA Total Score) and Regional Cortical Thickness

Pearson's correlation analyses indicated very strong and statistically significant positive correlations between the MoCA total scores and cortical thickness in the frontal, parietal, and temporal brain regions (Table 10). The correlation coefficients ranged from $r = 0.923$ to $r = 0.944$, revealing that all associations were significant at the 0.01 level (two-tailed).

The correlation between the MoCA total scores and rostral anterior cingulate cortex (ACC) thickness was very strong in both hemispheres (left: $r = 0.944$; right: $r = 0.944$). The inferior

frontal gyrus (IFG) (left: $r = 0.943$; right: $r = 0.942$) and superior frontal gyrus (SFG) (left: $r = 0.939$; right: $r = 0.923$) showed correlations of similar strength. The relationships in the parietal regions were also very strong, with the MoCA scores strongly correlated with inferior parietal lobule (IPL) thickness (left, $r = 0.938$; right, $r = 0.937$). In the temporal lobe, the middle temporal gyrus (MTG) showed a strong correlation between thickness and the MoCA total scores (left: $r = 0.939$; right: $r = 0.943$).

Moreover, the correlation matrix for thickness values across various regions showed very high intercorrelations, signifying the presence of substantial structural covariance in frontoparietal networks. In summary, these results indicate that the enhancement of overall cognitive performance is significantly contributed by an increase in cortical thickness that spans multiple brain areas, especially those that are interconnected with the processes of executive functioning, attention, and memory.

Associations Between Executive Function and Cortical Thickness

Pearson's correlation analysis revealed a strong and highly significant positive relationship between the MoCA executive functioning scores and cortical thickness in the frontal, parietal, and temporal brain regions (Table 11). All correlations were significant at a 0.01 level (two-tailed).

Table 11

Pearson Correlations Between MoCA Executive Score and Cortical Thickness Measures

Variable	1	2	3	4	5	6	7	8	9	10	
MoCA Executive Score	1										
Rostral ACC Thickness Left	.905**	1									
Rostral ACC Thickness Right	.905**	1.000**	1								
IFG Thickness Left	.905**	.999**	.999**	1							
IFG Thickness Right	.905**	.999**	.999**	1.000**	1						
SFG Thickness Left	.902**	.999**	.999**	.999**	.999**	1					
SFG Thickness Right	.889**	.993**	.993**	.992**	.993**	.995**	1				
IPL Thickness Left	.900**	.999**	.999**	.999**	.998**	1.000**	.995**	1			
IPL Thickness Right	.899**	.998**	.998**	.998**	.998**	.999**	.996**	1.000**	1		
MTG Thickness Left	.902**	.999**	.999**	.999**	.999**	1.000**	.995**	1.000**	.999**	1	
MTG Thickness Right	.906**	1.000**	1.000**	1.000**	1.000**	.999**	.993**	.999**	.998**	.999**	1

** Correlation is significant at the 0.01 level (2-tailed).

Table 12

Pearson Correlations Between MoCA Working Memory Score and Cortical Thickness Measures

Variable	1	2	3	4	5	6	7	8	9	10	
MoCA Working Memory Score	1										
Rostral ACC Thickness Left	.901**	1									
Rostral ACC Thickness Right	.901**	1.000**	1								
IFG Thickness Left	.901**	.999**	.999**	1							
IFG Thickness Right	.900**	.999**	.999**	1.000**	1						
SFG Thickness Left	.897**	.999**	.999**	.999**	.999**	1					
SFG Thickness Right	.880**	.993**	.993**	.992**	.993**	.995**	1				
IPL Thickness Left	.896**	.999**	.999**	.999**	.998**	1.000**	.995**	1			
IPL Thickness Right	.895**	.998**	.998**	.998**	.998**	.999**	.996**	1.000**	1		
MTG Thickness Left	.897**	.999**	.999**	.999**	.999**	1.000**	.995**	1.000**	.999**	1	
MTG Thickness Right	.901**	1.000**	1.000**	1.000**	1.000**	.999**	.993**	.999**	.998**	.999**	1

** Correlation is significant at the 0.01 level (2-tailed).

Executive functioning scores were positively correlated with the thickness of the rostral anterior cingulate cortex (ACC) in both the left and right hemispheres (left: $r=0.905$; right: $r=0.905$). In addition, the thickness of the inferior frontal gyrus (IFG) was highly correlated with executive functioning (left: $r=0.905$; right: $r=0.905$) and the thickness of the superior frontal gyrus (SFG) was positively correlated (left: $r=0.902$; right: $r=0.889$). Parietal correlations were also high with inferior parietal lobule (IPL) thickness (left: $r=0.900$; right: $r=0.899$). In the temporal lobe, the middle temporal gyrus (MTG) thickness also exhibited a strong positive correlation with executive functioning (left: $r=0.902$; right: $r=0.906$).

Moreover, cortical thickness across different regions and hemispheres is strongly correlated, suggesting a large amount of structural covariance in executive control and higher-order cognitive networks. Thus, better executive functioning indicates greater cortical thickness in the frontal-parietal-temporal areas, which is believed to be the structural basis for executive cognitive processes.

Associations Between Working Memory Performance and Cortical Thickness

The Pearson method for correlation analysis found strong and positive relationships that could be statistically significant between the MoCA Working Memory scores and the thickness of the cortex in the frontal, parietal, and temporal regions (Table 12). All associations were significant at a 0.01 level (two-tailed).

Working memory performance was strongly correlated with the thickness of the rostral anterior cingulate cortex (ACC) on both sides (left: $r = 0.901$; right: $r = 0.901$). The same was true for the inferior frontal gyrus (IFG), which showed thickness (left: $r = 0.901$; right: $r = 0.900$), and the superior frontal gyrus (SFG), which showed thickness (left: $r = 0.897$; right: $r = 0.880$). Involvement of the parietal cortex was strongly correlated with the thickness of the inferior parietal lobule (IPL) (left: $r = 0.896$; right: $r = 0.895$). In the temporal lobe, the thickness of the middle temporal gyrus (MTG) was also a strong predictor of the working memory scores (left: $r = 0.897$; right: $r = 0.901$).

Moreover, measurements of cortical thickness showed very high correlations between the regions and hemispheres, which may indicate a coordinated structural organization within the networks that support working memory. Overall, these results suggest that better working memory performance is linked

to increased cortical thickness in widely distributed frontal-parietal-temporal brain regions, consistent with neuroanatomical substrates of working memory processes.

Associations Between Recall Performance and Cortical Thickness

Pearson's correlation analysis revealed very strong and statistically significant positive relationships between the MoCA Recall scores and cortical thickness in the frontal, parietal, and temporal brain areas (Table 13). All correlations were significant at a 0.01 level (two-tailed).

Recall performance was significantly correlated with thickening of the entire rostral anterior cingulate cortex (ACC) in the left and right hemispheres (left: $r = 0.882$; right: $r = 0.882$). Moreover, these associations were strong with the left inferior frontal gyrus (IFG) thickness ($r = 0.880$), right IFG thickness ($r = 0.880$), left superior frontal gyrus (SFG) thickness ($r = 0.877$), and right SFG thickness ($r = 0.866$). The parietal cortex was involved, as indicated by strong correlations with left inferior parietal lobule (IPL) thickness ($r = 0.875$) and right IPL thickness ($r = 0.875$). In the temporal lobe, thickening of the middle temporal gyrus (MTG) was also highly positively correlated with recall ability (left: $r = 0.877$; right: $r = 0.881$).

Furthermore, intercorrelations between cortical thickness measurements across regions and hemispheres were prominent, indicating the presence of coordinated structural integrity within the neural networks related to memory. The conclusion drawn from these findings is that improved recall performance is associated with increased cortical thickness across distributed frontoparietal regions, emphasizing the structural basis of memory.

Discussion

This study presents a thorough analysis of different demographic characteristics, per-area brain morphology, differences between the two main brain hemispheres, and their relationship with education and various cognitive domains in a diverse lifespan sample. The very large age span (3–90 years) and wide range of educational levels lead to a great deal of variability among the subjects, not only in terms of their brain structure, but also in their cognitive performance. The recognition of such diversity is becoming increasingly widespread as an important factor in the comprehension of brain–behavior relationships over

Table 13

Pearson Correlations Between MoCA Recall Score and Cortical Thickness Measures

Variable	1	2	3	4	5	6	7	8	9	10	
MoCA Recall Score	1										
Rostral ACC Thickness Left	.882**	1									
Rostral ACC Thickness Right	.882**	1.000**	1								
IFG Thickness Left	.880**	.999**	.999**	1							
IFG Thickness Right	.880**	.999**	.999**	1.000**	1						
SFG Thickness Left	.877**	.999**	.999**	.999**	.999**	1					
SFG Thickness Right	.866**	.993**	.993**	.992**	.993**	.995**	1				
IPL Thickness Left	.875**	.999**	.999**	.999**	.998**	1.000**	.995**	1			
IPL Thickness Right	.875**	.998**	.998**	.998**	.998**	.999**	.996**	1.000**	1		
MTG Thickness Left	.877**	.999**	.999**	.999**	.999**	1.000**	.995**	1.000**	.999**	1	
MTG Thickness Right	.881**	1.000**	1.000**	1.000**	1.000**	.999**	.993**	.999**	.998**	.999**	1

** Correlation is significant at the 0.01 level (2-tailed).

the lifespan, especially those that develop in a non-linear manner throughout the life course and are influenced by sociocultural factors such as education [19–22].

The study's participant characteristics demonstrate a complete lifespan method which divides the study population into specific age groups ranging from childhood to late adulthood. The educational attainment levels across different age groups show different patterns because people in childhood and early adulthood achieve higher levels of education while mid-adulthood results in decreased educational attainment which matches the socioeconomic and historical factors that shape educational access throughout different stages of life. The research demonstrates that brain region volumes maintain their original size throughout human life except for slight mid-adulthood volume losses which characterise the study's findings regarding cortical volume. The rostral anterior cingulate cortex (ACC) exhibited slight volumetric decreases from early to mid-adulthood, aligning with prior work indicating that certain brain regions show minor volumetric decline with aging while their overall volume remains mostly intact [23]. The inferior frontal gyrus (IFG) reached its highest volume during childhood, but its volume decreased progressively, which aligns with the developmental pattern of cortical maturation that precedes subsequent pruning and stabilization of volume [24]. The superior frontal gyrus (SFG), inferior parietal lobule (IPL), and middle temporal gyrus (MTG) regions maintained consistent volume measurements which showed different aging patterns because of their distinct cortical aging mechanisms [25].

The research showed that cortical thickness results matched the volume measurements, which demonstrated that aging produced only minor changes in both measurements. The study found that rostral ACC thickness maintained constant values through different age groups, which demonstrated that the ACC maintains its structural integrity throughout aging process and assists in sustaining cognitive ability [26]. The IFG thickness decreases steadily from childhood until mid-adulthood before showing a minor increase during late adulthood, which indicates that each region develops through different processes that may help people age [27]. The research shows that SFG, IPL, and MTG thickness remains stable throughout a person's life because emerging evidence shows that certain important brain regions related to cognition maintain their thickness despite the typical age-related decline of cortical thickness [28].

The Montreal Cognitive Assessment (MoCA) test results demonstrated that cognitive abilities remained stable for all age groups, though younger adults and older children showed higher performance than the remaining age groups, who exhibited results between these two peaks. The executive function and recall score stability demonstrates that older adults maintain their cognitive abilities throughout their entire life span [29]. Working memory reaches its highest point during early adulthood when cognitive control abilities reach their complete development but then start to decline after that stage. The cognitive performance patterns observed in this study show that healthy aging leads to minor cognitive decline which affects specific areas while the person maintains their brain structure and neural functions [23,25].

The documented lifespan trends demonstrate that both cortical volume and thickness maintain complete stability from childhood to late adulthood. The maintained cognitive function shows preserved cortical structural integrity, which demonstrates that adult brain morphology allows healthy individuals to keep their cognitive abilities throughout their life. This challenges

the traditional view that aging invariably leads to substantial cortical atrophy and cognitive decline, suggesting instead a more nuanced pattern where specific regions and functions remain robustly preserved or compensated for [26,30].

The research results demonstrate that researchers must examine specific brain regions because they impact both brain development and cognitive abilities during the aging process. The research needs to adopt longitudinal studies with neurobiological markers to investigate how healthy cognitive aging mechanisms work and to explain the subtle structural changes discovered in this study [24,31].

The brain regional volumes and cortical thickness values of the current sample mostly followed the established normative patterns. The larger volumes of the frontal regions indicate the importance of the prefrontal cortices in the organization of the human brain, while the cortical thickness values were mostly around the same range (~2.7–3.2 mm), which is what major population imaging studies have shown that thickness is less variable between individuals than volume measures [19,32]. The wide distributions of age, education, and MoCA scores thus create a robust descriptive base for studying the relationships between the structural differences in the frontal, parietal, and temporal association cortices and cognitive variability throughout the lifespan [22,33].

During the study, large and consistent robust hemispheric asymmetries were observed in all the cortical regions. The frontal part of the brain, particularly the ACC, IFG, and SFG, showed left-sided volumetric asymmetry, whereas the parietal-temporal areas of the IPL and MTG showed right-sided asymmetry. This pattern was similar to the findings from large-scale normative and consortium-level datasets that reported a greater left-hemisphere extent in the medial and lateral prefrontal cortices and relatively larger right lateral parietal and temporal association areas [34–37].

The asymmetry patterns differed significantly between the volume and cortical thickness measurements. Although frontal volumes were mainly left-lateralized, thickness asymmetries were more region-specific, and a reversal in direction occurred in some areas, especially in the inferior frontal, parietal, and temporal cortices. This dissociation reinforces the view that volume, area, and thickness are influenced by developmental, genetic, and evolutionary factors [32,36,38]. Therefore, structural asymmetry is suggested to be a fundamental and genetically determined characteristic of cortical organization rather than simply a reflection of the total brain size [36,39]. Thus, the largely normative asymmetry profile observed in this study might provide a valuable reference framework for future studies exploring deviations related to cognitive decline or psychiatric conditions [40–42].

The current analysis found strong positive correlations between years of education and both regional cortical volume and cortical thickness across frontal, parietal, and temporal regions. However, the correlations are directionally in accordance with the cognitive reserve theories, but the strength of the associations is much more than what has been reported in a number of large cross-sectional and longitudinal studies where education has shown small and diffuse relationships characterized by brain morphometry, often more strongly with total surface area or intracranial volume than with mean cortical thickness [20,32,43–45].

Moreover, longitudinal evidence is growing, suggesting that education does not have a significant impact on the rate of cortical atrophy but rather raises the cohort's level of cognitive

and structural measures (higher intercepts) without changing the slopes of decline [46–48]. Similarly, education appears to influence the relationship between age and the brain in a complex, region-specific manner, sometimes postponing decline while being correlated with steeper late-life loss rather than having a simple monotonic effect on cortical volume or thickness [46]. Thus, the near-perfect correlations found in this study are difficult to relate to established evidence, and they strongly imply that there is a possibility of inflation because of the shared variance with age, cohort effects, intracranial volume, or global cortical measures.

The MoCA total scores were found to have strong positive correlations with both the regional cortical volume and cortical thickness in the ACC, IFG, SFG, IPL, and MTG. From an anatomical perspective, this is a plausible scenario and corresponds with extensive research that has established the notion that global cognitive screening scores reflect the integrity of brain regions, particularly the distributed networks of frontoparieto-temporal regions, rather than isolated points [33,48,49]. Atrophy of the aforementioned three regions (frontal, parietal, and temporal) has been linked to age-related declines in cognitive function due to aging (demonstrated by MoCA total and subdomain scores in executive, visuospatial, and memory performance) [33,48,50].

Moreover, in cases of neurodegenerative disorders and individuals at risk, it has been found that performance on the MoCA test is positively associated with gray matter volume or is reflected by cortical thickness in the temporal, parietal, and frontal areas, and is also considered a very sensitive indicator of the degeneration of the entire network [49,51,52]. Hence, the regional distribution of MoCA–structure correlations observed in this study is not different from the prevailing theories of global cognition. Nevertheless, the extremely large effect sizes uniformly exceed the usual findings, which are typically modest once the demographic and global brain measures are controlled [3,53,54].

The MoCA subscores for executive function and working memory exhibited robust positive associations with cortical volume and thickness in the ACC, lateral frontal gyri, IPL, and MTG. This observation aligns with the cognitive control network theory, which underscores the frontoparietal network and pivotal role of the ACC in modifying task requirements [55,56]. Structural and functional imaging studies, much clearer in their findings, have consistently pointed to the integrity of the above-mentioned regions as a reason for good performance in executive and working memory tasks at the network level rather than single-region resolution [29,48,57].

In contrast, most large-sample studies have reported small-to-moderate correlations between structures and cognitive functions, with some even indicating that executive tests show almost no association with cortical thickness after controlling for age, education, and global measures [58–60]. The very strong correlation between executive functioning and working memory across all regions examined in the current study is most likely indicative of a prevailing global cortical integrity factor rather than region-specific effects, thus reinforcing the argument that a general factor of cortical atrophy is responsible for the decline in several cognitive domains [61].

The ability to recall episodic memories was highly correlated with both the volume and thickness of the frontal, parietal, and temporal cortical association regions. This agrees with recent studies showing that the brain areas involved in the distortion of memory work and even monitoring the context need

to be connected through networks that include medial temporal regions, as well as frontal, parietal, and cingulate areas [62–64]. In all studies of healthy aging, subjective cognitive impairment, and early stage Alzheimer's disease, the cortical thickness and volume in the superior frontal, inferior parietal, posterior cingulate, and temporal regions have been repeatedly associated with recall and delayed memory performance [54,60,65,66].

However, earlier studies have shown that memory–structure relationships can be complicated and sometimes even reversed, especially in older adults, which is in line with neural efficiency or compensatory models [67,68]. Thus, the extremely large and generally positive correlations between recall and structure found in this study deviate from the intricate coexisting literature and hint at a rise again, which is a result of shared global or demographic variance being the most likely cause.

In every case, cortical volume and thickness measurements were strongly correlated with each other, and their relationships with educational level and cognitive performance were very powerful. A recent study indicated that the occurrence of such patterns demonstrates global cortical integrity or general atrophy, which tracks aging, disease burden, and global cognition more closely than any single regional measure [3,43,61]. Even though this global factor has biological significance, it still makes regional interpretation difficult and increases bivariate correlations when the covariates are not explicitly modelled.

Neuroimaging data obtained from real-world cases are subject to constraints, such as measurement error, biological variability, and developmental heterogeneity; therefore, the occurrence of correlations that come close to the theoretical maxima is, in most cases, implausible [32,69]. Therefore, the consistency of near-ceiling correlations across education, cortical measures, and multiple cognitive domains strongly suggests unmodeled confounding, shared scaling factors (e.g., head size and global thickness), or analytical dependencies.

Collectively, the current results support a network-based perception of cognition in which the functioning of the executive, working memory, recollection, and overall cognitive performance hinges upon the integrity of the distributed frontoparieto-temporal system. The interpretation of the findings would, by and large, be in line with the frameworks of cognitive and brain reserves, where higher education implies higher levels of structural and cognitive functioning at a given moment [33,70,71]. Nevertheless, the remarkable size of the marked associations denies strong causal or region-specific implications.

Thus, future analyses must make thorough adjustments for age, sex, intracranial volume, education, and global cortical measurements. Multivariate and latent factor techniques have been applied to separate the global and regional effects [48,61]. The structures of the medial temporal lobe are critical for episodic memory [54,62]. Longitudinal methods were used to determine whether the relatively preserved thickness or volume of a specific region predicted slower cognitive decline [29,65].

Conclusion

In summary, the current research reaffirms the patterns of hemispheric asymmetry that have been widely recognized and simultaneously highlights the usefulness of different ages of people throughout life for the study of brain–cognition relationships. The anatomical distribution of associations between education, the brain, and cognition is in line with current network models, but the extremely high effect sizes across the board are not in agreement with previous literature,

and probably point to global shared variance or methodological inflation. Careful multivariable modelling and longitudinal validation are necessary before making substantive conclusions about regional brain-behavior relationships.

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