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Brain imaging of the cortex in ADHD: A coordinated analysis of large-scale clinical and population-based samples

A full list of authors and affiliations appears at the end of the article.

Abstract

Objective: Neuroimaging studies show structural alterations of various brain regions in children and adults with ADHD, although non-replications are frequent. Our aim is to identify cortical characteristics related to ADHD using large-scale studies.

Methods: Cortical thickness and surface area (based on the Desikan–Killiany atlas) were compared between cases (n=2246) and controls (n=1934) for children, adolescents, and adults separately in ENIGMA-ADHD, a consortium of 36 centers. To assess familial effects on cortical measures, cases, unaffected siblings, and controls in the NeuroIMAGE study (n=506) were compared. Associations of the attention scale from the Child Behavior Checklist with cortical measures were determined in a pediatric population sample (Generation-R, n=2707).

Results: In ENIGMA-ADHD, lower surface area values were found in children with ADHD, mainly in frontal, cingulate, and temporal regions; the largest effect was for total surface area (Cohen's $d=-0.21$; $p_{FDR}<0.001$). Fusiform gyrus and temporal pole cortical thickness was also lower in children with ADHD. Neither surface area nor thickness differences were found in the adolescents/adult groups. Familial effects were seen for surface area in several regions. In an overlapping set of regions, surface area, but not thickness, was associated with attention problems in Generation-R.

Conclusion: Subtle differences in cortical surface area are widespread in children, but not in adolescents and adults with ADHD, confirming involvement of frontal cortex and highlighting regions deserving further attention. Importantly, the alterations behave like endophenotypes in families and are linked to ADHD symptoms in the population, extending evidence that ADHD behaves as a continuous trait in the population. Future longitudinal studies should clarify individual lifespan trajectories that lead to non-significant findings in adolescent/adult groups despite presence of an ADHD diagnosis.

Keywords

ADHD; cortical thickness; cortical surface area; lifespan; meta-analysis; imaging

INTRODUCTION

Attention-deficit/hyperactivity disorder (ADHD) is a common neuropsychiatric disorder characterized by age-inappropriate levels of inattention and/or hyperactivity and impulsivity. ADHD occurs in around 5-7% of children and 2.5% of adults (1, 2). ADHD can negatively

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affect multiple aspects of daily life of patients, and represents a major public health challenge (3). Neuroimaging studies in ADHD show differences between the brains of people with ADHD and those of healthy individuals in structure (4-9), function (8, 10, 11), and connectivity (12-14), albeit with small effect sizes (9). While informative, existing studies have several major limitations. First, most ADHD neuroimaging studies have been cross-sectional and performed during childhood; studies that either consider ADHD throughout the lifespan or have a longitudinal design are rare. In one such lifespan study, we recently showed that differences in intracranial volume (ICV) and subcortical volumes between patients and healthy individuals were largely restricted to childhood (9). Furthermore, an earlier longitudinal study showed slower, delayed development of cortical thickness and surface area in children with ADHD, especially in frontal-temporal regions (15). Nonetheless, large-scale studies of cerebral cortical architecture throughout the lifespan are lacking.

A second major limitation in the neuroimaging literature is that most studies on ADHD have small sample sizes and show limited reproducibility (16). Combining data from existing research by means of meta-/mega-analysis can produce more reliable results. For ADHD, meta-/mega-analyses of structural brain phenotypes are available for subcortical structures (9, 17), but the cortex has only been assessed in meta-analyses of brain-wide voxel-based morphometry (VBM) studies (5-8). The largest VBM study (931 patients and 822 controls) reported case-control differences for anterior cingulate, medial prefrontal cortex, ventromedial orbitofrontal cortex, and the insula (8). Here, we further the field by providing the first large-scale, mega-analytic examination of cortical measures across the lifespan in ADHD. We analyzed cortical surface area and thickness separately, as recent large-scale studies show that the biological mechanisms underlying such measures overlap only partially (18). Our large sample size also provides the power needed to examine clinical factors such as common comorbid disorders.

Neuroimaging analyses of ADHD have also largely not addressed a major question: are the observed brain differences a consequence of living with the disorder, or do the brain differences reflect underlying risk for the disorder? Different study designs can help us begin to address this question. Family-based studies can indicate if cortical changes are present in unaffected siblings of cases to indicate the involvement of shared genetic and/or environmental risk factors that underlie the cortical characteristics associated with the disorder. Several family studies (e.g. (19)) suggest that at least some of the brain alterations seen in patients are also present in their unaffected siblings and are associated with symptom severity in healthy individuals. Population-based studies can determine whether individuals with traits of ADHD show similar cortical changes to those associated with the full syndrome. The largest population study published to date (n=776 children) showed that higher levels of ADHD symptoms were associated with a thinner cortex in caudal middle frontal, temporal, and occipital regions (20). While this and similar studies (21) showed that brain alterations extend beyond the clinical disorder, no attempts have yet been made to directly assess the overlap between studies in clinical samples and the general population. Combined, family and population-based findings suggest that the brain differences seen in those with ADHD are not simply markers of the disorder, but larger studies, directly

comparing brain phenotypes across different informative study designs, are needed to shed more light on this.

Here, we present a mega-analysis of cortical thickness and surface area in participants with ADHD and healthy controls across the lifespan from the ENIGMA-ADHD Working Group, a world-wide collaboration aiming to characterize the characteristics of the brain of people with ADHD. All partners used standardized methods (segmentation protocols and quality control procedures), limiting methodological heterogeneity more than in previous meta-analyses. In addition to assessing case-control differences in children, adolescents, and adults, we investigated cortical brain correlates of clinical features, assessed familiarity of effects, and mapped the dimensionality of affected cortical regions in the large, independent pediatric Generation-R population study (22).

MATERIALS AND METHODS

Contributing studies

The ENIGMA-ADHD Working Group currently consists of 36 cohorts from around the world (<http://enigma.ini.usc.edu/ongoing/enigma-adhd-working-group/>). All cohorts have structural imaging data available for individuals with an ADHD diagnosis, and most sites also include data from healthy controls. An overview of the sites is given in ST1; details of image acquisition and study protocols are provided in ST2 and SA1. The dataset for the cortical analysis comprised 4,180 individuals: 2,246 people with ADHD with mean age of 19.22 years ($SD=11.31$), age range of 4-62 years, 74.1% males; 1,934 healthy controls with mean age of 18.05 years ($SD=11.26$), age range of 4-63 years, 59.8% males.

For the analysis of dimensionally-assessed ADHD traits in the general population we used data from 2,707 individuals with mean age of 10.11 ($SD=0.57$) years, age range of 8.5-11.9 years, 49.4% males (ST3) from the Generation-R cohort (22).

For all participating cohorts, approval for the analysis was available from the responsible ethics committees.

Neuroimaging

Structural T1-weighted brain MRI data were acquired and processed at the individual sites. The images were analyzed using standardized protocols to harmonize analysis and quality control processes (<http://enigma.ini.usc.edu/protocols/imaging-protocols/> and SA2) (23-25). Fully-automated and validated neuroimaging segmentation algorithms based on FreeSurfer versions 5.1 or 5.3 were used (ST2). Regions based on the Desikan-Killiany atlas were segmented, which resulted in cortical thickness and surface area values for 34 left and 34 right hemisphere regions. Two whole-hemisphere values for average thickness and average surface area were also computed. For further analysis, we used the mean of the bilateral values $((R+L)/2)$.

The Generation-R data were collected using a single, study-dedicated MRI scanner and processed using FreeSurfer version 6.0 on a high-performance computing system (Cartesius, surfsara.nl), for scanner sequence please see SA3. All imaging data were visually inspected

for inaccuracies in the surface-based reconstruction. Data not suitable for analysis were excluded (for a flowchart see SF1), providing $n=2707$. For a non response analysis, please see SA4.

Case-control differences in cortical thickness and surface area in children, adolescents, and adults

Based on the age-specificity of earlier findings (9), three age groups were assessed: children: 4-14 years, 1081 cases, 1048 controls; adolescents: 15-21 years, 432 cases, 347 controls; adults: 22-63 years, 733 cases, 539 controls. As there are marked developmental changes across the 4 to 14 year age range, we also performed supplemental analyses on age tertiles of the childhood group. For each of the age groups we determined differences between participants with ADHD and healthy controls using mixed-effect models with 'site' as a random factor in the nlme package in R. Age and sex were included as additional covariates; for the surface area analysis, intracranial volume (ICV) was also added, as surface area scales with head size (24-26). We also included analyses without ICV as a covariate given the debate over whether it should be included or not (see SA5). To calculate Cohen's d effect size estimates, adjusting for the appropriate covariates, we used the t -statistic from the Diagnosis (ADHD=1, control=0) predictor in the equation(27). To correct for multiple comparisons, we used a false discovery rate (FDR) at $q=0.05$.

Split-half validation of case-control findings

To ensure stability of effects, we performed a validation of our mega-analysis in age groups with significant results. Data were split into two halves, statistically matched for age, sex, and ICV within each site. Validation was defined as $p_{FDR} < 0.05$ in the first half and $p_{uncorrected} < 0.05$ in the second half, with matching effect directions(28).

Exploration of the influence of sex, IQ and clinical factors on cortical regions affected in ADHD

For regions and age groups showing validated case-control differences, we examined potential effects of sex, IQ, comorbid disorders, medication use and ADHD symptoms (severity) (see details in SA6). Given the exploratory nature of these analyses, we report uncorrected p -values in the Results section.

Family study

Two subsets of the ENIGMA-ADHD sample (NeuroIMAGE Amsterdam and Nijmegen (29)) had collected brain data from patients ($n=211$), their unaffected siblings ($n=175$), and unrelated controls ($n=120$). To determine familial effects on ADHD-affected cortical regions, unaffected siblings were compared with healthy controls in those cortical regions. Levels of ADHD symptoms in the unaffected siblings had been shown to not differ from those of controls (19). Multiple comparisons correction was performed based on the effective number of independent tests (M_{eff}) (30); differences between unaffected siblings and controls were considered significant at $p < 0.01$ ($M_{eff}=5$, for details please see SA7).

Association between ADHD symptoms and the cortex in the general population

ADHD symptoms were assessed in children from Generation-R using the Child Behavior Checklist (CBCL)(31). Both attention problems (Syndrome Scale) and ADHD problems (DSM-oriented scale) were examined for associations with surface/thickness in regions with validated case-control differences in ENIGMA-ADHD. R statistical software (version 3.3.3) was used to fit multiple linear regressions to model these associations. Primary analyses were adjusted for age at MRI scan, sex, ICV and ethnicity. In supplemental analyses, models were additionally adjusted for non-verbal IQ, ADHD medication status, MR-scanner software version, and motion during scanning (SA8).

RESULTS

Case-control differences in cortical surface area and thickness in children, adolescents, and adults

In children with ADHD versus control children, lower values of cortical surface area were widespread, with 24 out of 34 regions and total surface area being smaller in patients (Table 1, Figure 1, ST4). The largest effect was found for total surface area: $d = -0.21$, $p_{FDR} < 0.001$. When the child group was further subdivided in post-hoc analyses, this effect size increased to $d = -0.35$, $p_{FDR} < 0.001$ in the youngest tertile (4-9 years), which comprised 317 cases and 340 controls (ST5). More generally, the youngest group showed the largest case-control differences (ST5). No case-control differences were found in the adolescent and adult groups (ST6 and ST7; ST8 shows combined analysis of age groups). For results of the model without ICV, please see ST9.

Cortical thickness was affected in four regions (fusiform, parahippocampal, and precentral gyrus and temporal pole) in children, all being thinner in patients than controls (Table 2, Figure 1 and ST10). Further subdivision of the child group retained significant effects for fusiform gyrus ($d = -0.31$, $p_{FDR} = 0.002$) and temporal pole ($d = -0.25$, $p_{FDR} = 0.02$) in the group of children aged 10 and 11 (356 cases, 365 controls); in younger (4-9 years) and older (12-14 years) children, effects did not survive multiple comparisons correction (ST11). In adolescents and adults, no case-control differences were found (ST12 and ST13; ST14 shows combined analysis of age groups).

Validation of case-control findings

The split-half validation analysis showed seven regions for surface area and two regions for thickness to be significant in both halves (Table 1 & 2, ST15 & ST16, Figure 1). For all other regions, the direction of effects was the same in both split-halves.

Effect sizes of the validated cortical differences across the age groups are plotted in Figure 1, together with the effect sizes of subcortical brain volumes from our earlier work (9). Post-hoc analysis by adding the term Agegroup*Diagnosis to the main model indicated differences in effect sizes across the lifespan for surface area of the superior frontal gyrus and thickness of the fusiform gyrus (ST17).

Exploration of effects of sex, IQ, comorbidity, psychostimulant medication, and ADHD severity

Extending the main findings, we investigated several factors linked to ADHD, which have shown to influence brain volume in their own right. No significant interaction effects of diagnosis-by-sex were found (ST18). Correcting for IQ in surface area analyses only led to minor changes in the level of significance in the case-control comparisons. In all thickness analyses, IQ was a non-significant contributor (ST19).

For comorbidity analyses, we had information on cases of the childhood subset ($n=1081$) available (comorbidity *ever* versus *never*, lifetime) for almost 50% of participants (ST20). In total, 194 children with ADHD (39%) were ever or currently diagnosed with a comorbid psychiatric disorder. The three most frequently co-occurring disorders were oppositional defiant disorder (ODD, present in $n=79$ cases (16.0%)), anxiety disorders (observed in $n=39$ (8.6%)), and mood disorders (seen in $n=13$ (3.0%)). Presence versus absence of comorbid disorders did not affect cortical surface area; a nominal effect of ever being diagnosed with a comorbid psychiatric disorder was found for fusiform gyrus thickness, with a thinner fusiform gyrus in cases with an additional disorder in the past or present (ST21).

Current stimulant use versus no current use had a nominally significant association with surface area of two regions in frontal cortex, with those taking medication having lower surface areas (ST21).

Hyperactivity/impulsivity severity ratings on Conners' questionnaires, available for $n=240$ childhood patients, but not inattention, showed nominally significant correlation with surface area in rostral anterior cingulate cortex ($r=-0.18$, $p=0.01$), superior frontal gyrus ($r=-0.19$, $p=0.01$), and with total surface area ($r=-0.15$, $p=0.03$) (ST22).

Family study

Among the validated ADHD-associated cortical features, surface area of caudal middle frontal, lateral orbital frontal, and superior frontal gyrus and the total surface area were significantly smaller in the unaffected siblings as compared with controls (Figure 2, ST23), indicating familial effects. A similar trend was seen for the majority of the other cortical measures (SF2).

Effects of ADHD symptoms in the general population on the validated brain phenotypes

Population-based analysis showed caudal middle frontal gyrus, middle temporal gyrus, and total surface area to be associated with the attention problems scale of the CBCL (Table 3, SF3); higher levels of dimensional ADHD symptoms were associated with smaller surface areas. No associations were found with the two cortical thickness measures (Table 3). To ensure a linear fit was optimal and that the more severe end of the symptom continuum was not driving findings, models with quadratic and cubic symptom terms were also tested. AIC and BIC values were highly similar across models, suggesting little to no improvement over the simpler linear term (ST24).

Adding non-verbal IQ or ADHD medication status to the analysis model of the attention problems, did not influence results (ST25). Results also remained stable when we tested the

effect of MRI scanner software version and image quality (ST25). The quantitative amount of motion in the T1-weighted scan (32) did not seem to affect analyses (ST26).

DISCUSSION

Here, we report the largest study to date of ADHD and cortical surface area and thickness in clinical samples and a pediatric population sample. Compared with healthy controls, children with ADHD showed smaller surface area in frontal, temporal, and cingulate regions, with the effects being most prominent in the youngest children (4-9 years). Case control differences had small effect sizes, but survived validation. Differences in thickness were limited to the temporal pole and fusiform gyrus, which were thinner in children with ADHD. These differences were most prominent in the group aged 10 and 11 years. The influence of comorbidity and symptom ratings, available from subsamples, appeared limited. None of these covariates of interest showed effects surviving multiple testing correction. There were no significant associations between cortical alterations and either stimulant treatment or IQ. Family-based analyses revealed familial effects for four surface area regions, but not for any of the thickness measures. A set overlapping with family-based analyses (caudal middle frontal gyrus, total surface area) and/or severity rating analyses (total surface area) showed associations with CBCL-based ratings of attention problems, in the population-based sample; no such effects were found for thickness.

The regions affected in ADHD were widespread across the cortex. The frontal cortex differences in orbital, middle, and superior regions nicely confirmed earlier work (e.g. (8, 15)). These regions play a key role in cognitive processes related to reward and punishment, emotional processing, response inhibition, and attention - all known to be deficient in ADHD (33-35). Few studies yet have implicated structural differences in the cingulate cortex, an important structure linked to executive functioning and emotion (36), in ADHD (7, 37). Findings for the temporal cortex are particularly interesting, because both surface area and thickness were affected. The functions of this region are diverse, as it seems to be involved in semantic memory and processing of abstract concepts, attention, emotion processing and regulation (38). Integrating the current findings with our earlier subcortical results (9), the multitude of findings for brain regions involved in emotion processing is intriguing. In view of this, the network of orbito-frontal cortex, cingulate, and amygdala could be particularly interesting for future research (39, 40), as they may underlie the deficient emotional self-regulation often observed among ADHD patients (33).

Effect sizes of the observed brain differences were small, which is at a similar level as our earlier findings for subcortical volumes and ICV in ADHD (Figure 1) and comparable to effect sizes seen in other psychiatric disorders studied within the ENIGMA consortium (23, 24). Whether this reflects phenotypic heterogeneity, with only a subgroup of patients showing reduced brain structure of large(r) effect size, or homogeneously small effects existing in the majority of patients remains to be investigated. Effects were not driven by IQ. Findings in several areas seemed to scale with the severity of hyperactivity/impulsivity in patients, but the heterogeneity of assessment instruments limited the power of this analysis. As in our earlier analysis of subcortical volumes and ICV, we did not find any significant associations between psychostimulant medication and cortical dimensions, neither in case-

control nor in population-based designs. However, given our observational design and reliance on legacy data, we would not want to draw any firm conclusions from those results.

Looking across the lifespan, all case-control differences were most pronounced in children and non-significant in adolescents and adults. The same phenomenon, albeit attenuated, was seen in our recent cross-sectional study of ICV and subcortical structures (9) (Figure 1). Post-hoc analysis of potential differences in effect sizes across the three age groups in the current study confirmed age-related attenuation of effects for several structures. Those findings are in line with an earlier longitudinal study, where case-control differences in cortical thickness observed in children attenuated with increasing age, suggesting a delayed cortical maturation (41). An alternative explanation for the age-related differences might be the existence of subgroups; the childhood patient group is likely to consist of a mix of individuals who will persist and remit in adulthood, while the adult group consists largely of persisters. We cannot yet rule out low power as a reason for not detecting significant effects in the older subgroups, which were half the size of the children's group, and these initial findings concerning apparent differences across the lifespan should be confirmed in longitudinal studies.

The case-control differences observed in the childhood sample did not seem to be influenced by comorbidity. However, we noticed that the comorbidity rate in this subset was relatively low (39%). There could be several reasons for that. First, the sample we used in our analysis of comorbidity was very young (4-14 years), as we only focused on the subsample with significant case-control differences. The relatively young age could explain the lower than expected comorbidity rate, as children might simply not yet have developed some of the frequent comorbid psychiatric disorders (e.g. substance use disorders). In comparison, Taurines and coworkers (2010) (42) described in their review that 73% of 6-18 year olds with ADHD had one or more comorbid disorders. A second reason could lie in the fact that we are dealing with research diagnoses, in which comorbidity assessments were often limited to checking inclusion and exclusion criteria for a specific study aim. This is a clear limitation of dealing with legacy data from multiple different sites, where different protocols and different instruments of assessment of comorbidity and symptom severity were used. We adjusted our design accordingly and concentrated only on the three most frequent comorbidities, defining those as ever or never experienced.

Although our study was not designed to study causality, our results may shed some light on the issue of whether brain differences are a consequence of living with the disorder or a risk factor for the disorder. Our family analysis showed unaffected siblings of cases, i.e. those without a diagnosis and with levels of ADHD symptoms comparable to healthy controls, to have similar surface area differences from controls as their affected siblings. In addition, the relationship between ADHD symptoms and cortical phenotypes also held in the general population. Here, the dimensional assessment of attention problems was related to brain morphology in a linear fashion, suggesting the phenotype and underlying brain morphology to be independent of clinical diagnosis, operating along a continuum. The two different approaches show cortical alterations in ADHD-related regions to occur independent of diagnosis. The overlap between the findings from the different approaches was, however, not complete. Future studies could perform more direct comparisons between case-control and

population samples using e.g. conjunction analysis (43). The two different approaches show cortical alterations in ADHD-related regions to occur independent of diagnosis, indicating that they are neither necessary nor sufficient to cause the disorder. The overlap between the findings from the different approaches was, however, not complete. Future studies could perform more direct comparisons between case-control and population samples using e.g. conjunction analysis (41). In such a design it would be interesting to test the liability-threshold model, to better understand which factors contribute to liability for the disorder. Also, whether the observed brain differences relative to controls are indeed risk factors for ADHD, remains to be investigated in prospective longitudinal designs. Future imaging genetics studies might further clarify the neurobiological pathways and mechanisms underlying cortical differences in ADHD. While genetic information is not available in sufficient numbers from ENIGMA-ADHD, the ENIGMA Genetics Working Group recently identified genetic factors determining cortical surface area and thickness in a largely healthy population (18). Those genetic factors might in turn constitute risk factors for ADHD given recent finding of genetic overlap between the genetic contribution to ADHD and to the total surface area of the cortex. As we have recently shown for subcortical volumes and intracranial volume, further work might delineate the individual genes or gene networks underlying such genetic overlap (Klein et al., *Am. J. Psychiatry*, in press; see also (44)).

The current study has several strengths and limitations. Our major strength lies in the large sample sizes in both the clinical ($n=4180$) and population-based ($n=2707$) samples, along with the use of harmonized segmentation protocols, which provided unprecedented power to detect effects. Another strength is the split-half validation combined with stringent multiple comparison correction, showing that our findings – despite small effect sizes – are stable. Also, results from the population study suggest little effect of motion during scanning on our cortical regions of interest. The combination of case-control with family- and population-based designs to identify mechanisms is an additional strength. A limitation is that we relied on legacy data in ENIGMA-ADHD, so the participating studies differ somewhat in their aims, methods, and assessments. Given this heterogeneity, our findings might underestimate the true effects, and we may have missed effects of comorbidity, medication, and symptom severity due to insufficient power. The limited sample size of the family study together with the small effect sizes for brain differences are probably the reason why the results of the family study found the expected staircase effect, at a trend level only.

In light of the findings from the current and the earlier (9) ENIGMA studies of ADHD, what should future neuroimaging studies in ADHD look like? Effect sizes observed are small (i.e. Cohen's $d=-0.21$), with largest effects for measures of total brain volume and surface area in this and our previous study (9). Also, effects are restricted to childhood despite persistent ADHD diagnosis in adolescents and adults. Future studies should answer the question, whether (regional) effect sizes are comparable in everyone, or whether subgroups exist, in which certain regional effect sizes are more pronounced. This could be examined using clustering algorithms, such as community detection, and machine learning (45). An analysis of particular interest would be the comparison between children who remit in adulthood and those who persist. In-depth analysis of adult persisters versus adult remitters could add to our understanding of the null findings in adults, as it seems counterintuitive that the adult persisters, believed to be more severely affected, show no apparent signs of brain differences

in adulthood, but the childhood group, which is likely to be a mix of remitters and persisters when they are adults, does. Subgroups may also provide information on comorbidity and links to symptom severity in the different behavioral domains of ADHD. Most importantly, longitudinal studies are needed to study the processes that lead to the apparent reductions of case-control effects from childhood to adolescence and adulthood; only very few longitudinal samples for ADHD are currently available (15, 29). We should also not forget that the segmentation used in the current study is based on classical neuroanatomical divisions rather than a partitioning based on biological functions (44, 46). Other cortical phenotypes such as gyrification (47), or more sophisticated methods to define regional gray matter structure, and analyses of other brain measures to be captured by neuroimaging in large sample sizes (e.g., white matter integrity (48); resting state functional MRI (49)) may help us find the presumed case-control differences in adults (50, 51).

In conclusion, we identify, for the first time, cortical phenotypes affected in ADHD that are robust, and show an association with ADHD beyond narrowly-defined clinical diagnoses. Our work suggests them to behave as endophenotypes and thus extends the evidence for ADHD as a continuous trait in the population, shown for behavioral measures and genetics (52), and now for to neuroimaging phenotypes. Future studies should clarify individual lifespan trajectories and identify the underlying genetic and environmental factors shaping these trajectories.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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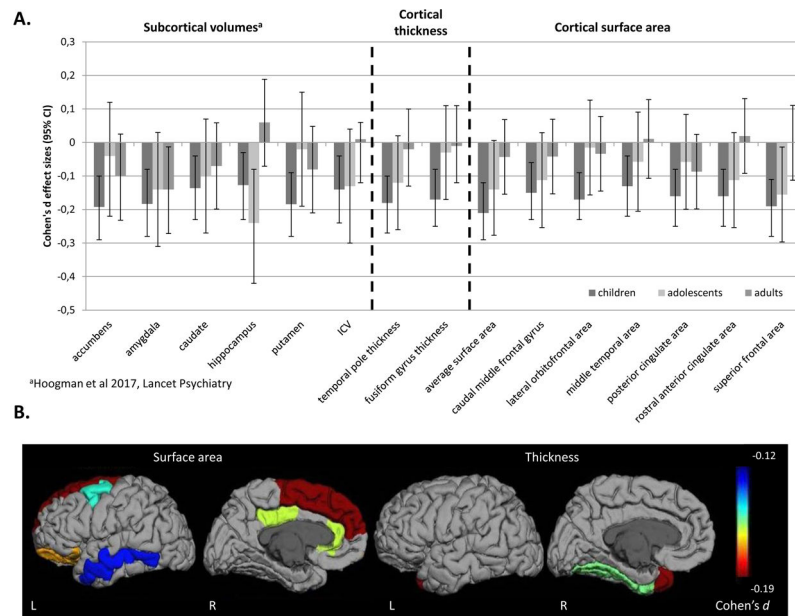


FIGURE 1. Subcortical and cortical brain differences across the lifespan.

A. Cohen's *d* effect sizes with error bars showing the 95% confidence intervals for case-control differences in ENIGMA-ADHD cortical and subcortical structural features stratified by 3 age groups: children of 14 years of age and younger, adolescents from age 15 to 21 years, and adults older than 21 years. Structural features of all regions listed on the x-axis showed significant case-control differences in children; in analyses of cortical and subcortical features, no significant effects were seen in adolescents or adults. This is reflected in the effects sizes shown, all of which reached case-control statistical significance for children but not for adolescent and adult groups, except for the hippocampus, which shows a significant case-control difference in the adolescent group as well. **B.** Displayed are the heatmaps of validated case-control differences in the childhood subset for both surface area (left) and thickness (right) in each hemisphere.

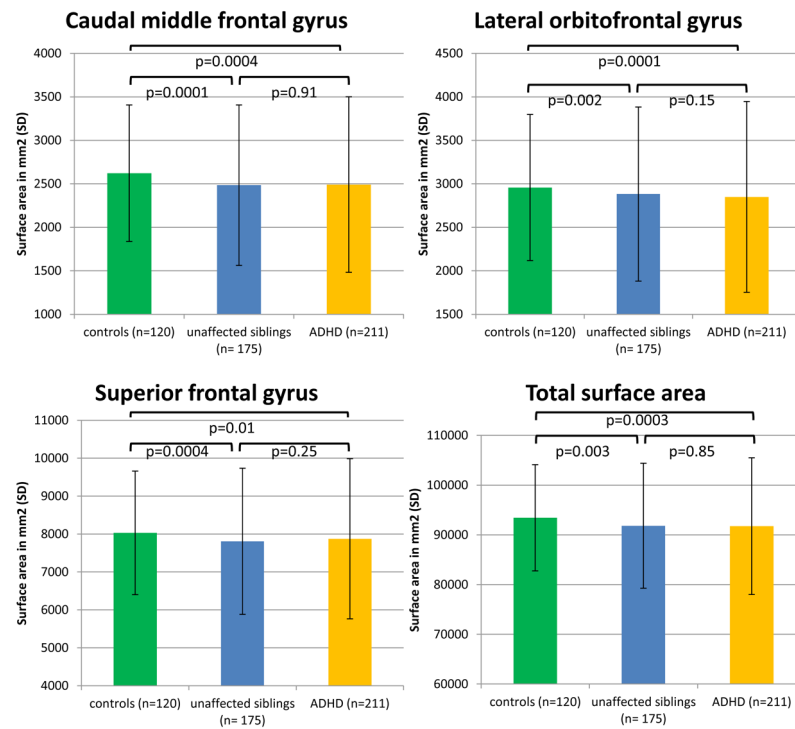


FIGURE 2.

Bar graphs showing results of familiarity analyses, comparing healthy controls, unaffected siblings and cases, in the ADHD-affected cortical regions in the NeuroIMAGE datasets (n=506). Displayed are the cortical surface areas showing effects of familiarity in the NeuroIMAGE datasets. For these regions, unaffected siblings differed from healthy controls (M_{eff} -corrected results). Cortical values are adjusted for age, gender, ICV and site.

Table 1.

Mega-analysis of case-control cortical surface area differences in children of 14 years of age and younger in ENIGMA-ADHD.

Cortical region	Controls (N)	ADHD (N)	Cohen's <i>d</i> (standard error)	95% confidence interval	p-value	FDR p-value
total surface area ^a	1048	1081	-0.21 (0.04)	-0.29 to -0.12	<0.001	<0.001
superior frontal gyrus ^a	1044	1074	-0.19 (0.04)	-0.28 to -0.11	<0.001	<0.001
lateral orbitofrontal cortex ^a	1047	1081	-0.17 (0.04)	-0.26 to -0.09	<0.001	<0.001
medial orbitofrontal cortex	1039	1070	-0.16 (0.04)	-0.24 to -0.07	<0.001	0.002
posterior cingulate cortex ^a	1042	1078	-0.16 (0.04)	-0.25 to -0.08	<0.001	0.002
rostral anterior cingulate cortex ^a	1041	1067	-0.16 (0.04)	-0.25 to -0.08	<0.001	0.002
superior temporal gyrus	987	993	-0.15 (0.05)	-0.24 to -0.07	<0.001	0.003
caudal middle frontal gyrus ^a	1046	1077	-0.15 (0.04)	-0.23 to -0.06	<0.001	0.003
fusiform gyrus	1043	1075	-0.13 (0.04)	-0.21 to -0.04	0.004	0.01
isthmus cingulate cortex	1040	1079	-0.13 (0.04)	-0.22 to -0.05	0.002	0.008
middle temporal gyrus ^a	1001	1024	-0.13 (0.04)	-0.22 to -0.04	0.004	0.01
rostral middle frontal gyrus	1044	1079	-0.13 (0.04)	-0.21 to -0.04	0.004	0.01
supramarginal gyrus	1036	1063	-0.13 (0.04)	-0.22 to -0.05	0.002	0.008
inferior parietal cortex	1041	1078	-0.12 (0.04)	-0.20 to -0.03	0.009	0.02
inferior temporal gyrus	1041	1064	-0.12 (0.04)	-0.21 to -0.04	0.005	0.01
lateral occipital cortex	1047	1078	-0.12 (0.04)	-0.21 to -0.04	0.005	0.01
precuneus	1044	1080	-0.12 (0.04)	-0.20 to -0.03	0.008	0.02
superior parietal cortex	1045	1073	-0.12 (0.04)	-0.21 to -0.04	0.004	0.01
insula	1042	1078	-0.12 (0.04)	-0.21 to -0.04	0.006	0.01
banks of superior temporal sulcus	974	999	-0.10 (0.05)	-0.19 to -0.01	0.02	0.04
pars triangularis of inferior frontal gyrus	1048	1074	-0.10 (0.04)	-0.18 to -0.01	0.02	0.04
postcentral gyrus	1032	1060	-0.10 (0.04)	-0.18 to -0.01	0.03	0.05
precentral gyrus	1041	1064	-0.10 (0.04)	-0.19 to -0.02	0.02	0.03
temporal pole	1043	1075	-0.10 (0.04)	-0.18 to -0.01	0.03	0.04

Note: Displayed are the significant regions surviving correction for multiple comparisons with FDR q-value<0.05. Regions are sorted based on the effect size of the difference between cases and controls (Cohen's *d*), with the regions with the largest effects on top. Regions are the average of left and right hemisphere surface area. Model is adjusted for age, sex, intracranial volume (ICV), and site.

^a regions surviving validation (see also ST15). For the full results please see ST4.

Table 2.

Mega-analysis of case-control cortical thickness differences in children of 14 years of age and younger in ENIGMA-ADHD.

	Controls (N)	ADHD (N)	Cohen's <i>d</i> (standard error)	95% confidence interval	p-value	FDR p- value
temporal pole ^a	1042	1075	-0.18 (0.04)	-0.27 to -0.10	<0.001	0.001
fusiform gyrus ^a	1044	1077	-0.17 (0.04)	-0.25 to -0.08	<0.001	0.003
precentral gyrus	1040	1064	-0.16 (0.04)	-0.25 to -0.07	<0.001	0.003
parahippocampal gyrus	1041	1076	-0.15 (0.04)	-0.23 to -0.06	<0.001	0.008

Note: Displayed are the significant regions surviving correction for multiple comparisons with FDR q-value<0.05. Regions are sorted based on the effect size of the difference between cases and controls (Cohen's *d*), with the regions with the largest effects on top. Regions are the average of left and right hemisphere thickness measures. Model is adjusted for age, sex and site.

^a regions surviving validation (see also ST16). For the full results please see ST10.

Table 3.

Associations between validated cortical regions and CBCL syndrome scale attention problems in Generation-R.

Cortical region	B	SE	CI lower	CI upper	β	p-value	FDR p-value
<i>Surface area</i>							
caudal middle frontal gyrus	-14.10	5.49	-24.87	-3.33	-0.04	0.01	0.03
lateral orbitofrontal cortex	-8.28	5.01	-18.10	1.54	-0.02	0.10	0.11
middle temporal gyrus	-13.63	5.86	-25.12	-2.14	-0.03	0.02	0.04
posterior cingulate cortex	-5.02	2.42	-9.77	-0.27	-0.03	0.04	0.06
rostral anterior cingulate cortex	-3.50	1.93	-7.29	0.29	-0.03	0.07	0.09
superior frontal gyrus	-7.16	11.93	-30.55	16.24	-0.01	0.55	0.55
total surface area	-323.79	77.50	-475.75	-171.82	-0.04	<0.001	<0.001
total surface area (residualized*)	-291.62	77.43	-443.44	-139.79	-0.07	<0.001	<0.001
<i>Thickness</i>							
fusiform gyrus	0.004	0.002	0.000	0.01	0.04	0.05	0.054
temporal pole	0.01	0.01	-0.001	0.03	0.04	0.07	0.07

Note: Regions are the average of left and right hemisphere surface area, and are the regions showing significant group differences in split-half analyses (ST15 and ST16). Model is adjusted for age, sex, and ethnic background. ICV is also included as a covariate in the surface area analysis. B is the unstandardized regression coefficient for the square root transformed CBCL syndrome scale attention problems score, and CI is the 95% confidence interval of that regression coefficient. β is the standardized regression coefficient.

* Given the high correlation between total surface area and ICV, we also tested a model where total surface area was first regressed on ICV, and the resulting residuals were used in the model described above, but without entering ICV. This shows that multicollinearity is not driving the effects. p-values in bold are considered significant, surviving correction for multiple comparisons with FDR q-value<0.05.