Brain Structure in Acutely Underweight and Partially Weight-Restored Individuals With Anorexia Nervosa: A Coordinated Analysis by the ENIGMA Eating Disorders Working Group

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Abstract

Background

The pattern of structural brain abnormalities in anorexia nervosa (AN) is still not well understood. While several studies report substantial deficits in gray matter volume and cortical thickness in acutely underweight patients, others find no differences, or even increases in patients compared with healthy control subjects. Recent weight regain before

scanning may explain some of this heterogeneity. To clarify the extent, magnitude, and dependencies of gray matter changes in AN, we conducted a prospective, coordinated meta-analysis of multicenter neuroimaging data.

Methods

We analyzed T1-weighted structural magnetic resonance imaging scans assessed with standardized methods from 685 female patients with AN and 963 female healthy control subjects across 22 sites worldwide. In addition to a case-control comparison, we conducted a 3-group analysis comparing healthy control subjects with acutely underweight AN patients (n = 466) and partially weight-restored patients in treatment (n = 251).

Results

In AN, reductions in cortical thickness, subcortical volumes, and, to a lesser extent, cortical surface area were sizable (Cohen's d up to 0.95), widespread, and colocalized with hub regions. Highlighting the effects of undernutrition, these deficits were associated with lower body mass index in the AN sample and were less pronounced in partially weight-restored patients.

Conclusions

The effect sizes observed for cortical thickness deficits in acute AN are the largest of any psychiatric disorder investigated in the ENIGMA (Enhancing Neuro Imaging Genetics through Meta Analysis) Consortium to date. These results confirm the importance of considering weight loss and renutrition in biomedical research on AN and underscore the importance of treatment engagement to prevent potentially long-lasting structural brain changes in this population.

Anorexia nervosa (AN) is an eating disorder characterized by low weight, severe restrictive eating, and a high mortality owing to starvation-related complications (1). Although the pathomechanisms are unknown, biological underpinnings are widely recognized (2). In acutely underweight patients (i.e., patients at the very beginning of weight restoration treatment), sulcal widening and gray matter (GM) thinning are sometimes visible on computed tomography or magnetic resonance imaging (MRI). However, the spatial distribution and extent [and even direction, e.g., see (3,4)] of alterations vary across studies, complicating efforts to identify the mechanisms underlying MRI-observed structural brain changes in AN (5,6). Possible reasons for these heterogeneous findings include different analytic approaches (e.g., voxel- vs. vertex-based morphometry), small samples (typically 20–40 individuals per group), and clinical heterogeneity between studies (6). Recent work suggests that weight gain is closely linked to normalization of GM reductions and that adolescents show normalized brain structure after partial weight restoration (7,8). Therefore, GM changes in AN may reflect nutritional status (as opposed to trait-level alteration), and time (i.e., weight gain) between initiating weight gain–focused treatment and MRI scanning may substantially affect the extent and magnitude of structural brain changes.

To characterize GM differences, several metrics from T1-weighted MRI scans can be derived, including regional cortical thickness (CT), cortical surface area (SA), and subcortical volume. Although CT and SA were reported to have opposing underlying genetic factors and show different developmental trajectories (9,10), only 3 studies have investigated SA in AN (4,11,12). Recent large-scale coordinated research efforts have facilitated investigations of structural brain abnormalities with such metrics in multiple psychiatric disorders (13). Through these international collaborations, researchers have carried out prospective meta-analyses, i.e., analyses that were designed a priori using predefined study selection criteria, hypotheses, standardized data, and analysis protocols and did not rely on published findings, hence reducing publication bias (14). By including data collected from several research sites without the need to share individual-level data, these efforts can generate more generalizable and rigorous findings compared with a single large study and enable transdiagnostic comparisons. For example, combining data from thousands of patients with schizophrenia and unaffected control subjects, 2 recent prospective coordinated meta-analyses reported small deficits in subcortical volumes, widespread (small to moderate) cortical thinning, and equally widespread, although weaker, reductions in SA (15,16). Similar, but often smaller and more localized effects were reported for major depression, bipolar disorder, posttraumatic stress disorder, and other psychiatric disorders (13,17).

We formed the ENIGMA (Enhancing Neuro Imaging Genetics through Meta Analysis) Eating Disorders Working Group (http://enigma.ini.usc.edu/ongoing/enigma-eating-disorders/) to characterize brain alterations in eating disorders (e.g., AN and bulimia nervosa) using the same imaging analysis, quality control, and statistical analysis methods across a large number of independently collected case-control samples. Given the heterogeneity of AN studies and the possible effect of weight gain, we a priori decided to use 2 complementary approaches in the current study: 1) a case-control 2-group comparison maximizing sample size and 2) a 3-group comparison. In the latter, we subcategorized participants with AN into acutely underweight and partially weight-restored patients (i.e., patients who had already been in treatment for some time and/or gained some weight prior to MRI scanning). We then used the ENIGMA Toolbox (18) to contextualize patterns of altered CT across microscales and macroscales of brain organization. Specifically, we tested whether structural abnormalities were related to 1) histological information, e.g., cell density and/or distribution across the cortex (19); 2) regional cytoarchitectonic properties, e.g., the 5 von Economo and Koskinas structural types of isocortex (20); and 3) normative connectome properties, e.g., the spatial distribution of hubs [i.e., brain regions with many connections (21)]. Based on prior studies (8,22,23), we predicted a priori that GM volume, CT, and SA reductions would be apparent in acute AN, but would be less pronounced in partially weight-restored AN. As with previous neurodegenerative (24,25), psychiatric (26), and neurological (27) diseases, we also predicted that highly connected hub regions would be more susceptible to disease-related effects.

Methods and Materials

Study Samples

We aggregated data from 22 cohorts included in institutional review board–approved studies with a combined sample of 685 patients with AN and 963 healthy control (HC2) subjects (Table S1 in Supplement 2 and Figure S1 in Supplement 1). Patients in the 2-group case-

control comparison had to be female and meet DSM IV-TR, DSM-5, or ICD-10 criteria for AN, including a body mass index (BMI) (kg/m2) <17.5 (adults) or <10th age-adjusted BMI percentile (adolescents). HC subjects were females with a BMI >17.5 (adults) or >10th age-adjusted BMI percentile (and no current or lifetime diagnosis of any eating disorder). For exclusion criteria, previous publications on a selection of data used in the current study, and the a priori consensus process regarding the definitions of patients and groups, see sections 1.1 and 1.2 in Supplement 1.

To disentangle the impact of weight gain from diagnosis on brain structure, we also carried out analyses in up to 12 cohorts based on 3 groups: underweight patients acutely ill with AN (acAN) (n = 466), partially weight-restored patients with AN (pwrAN) (n = 251), and HC subjects (HC3) (n = 874) (Table S1 in Supplement 2 and Figure S1 in Supplement 1). The inclusion of the pwrAN group in a cross-sectional design was an attempt to assess how partial/short-term weight gain might be associated with brain structure. Of note, the HC sample in the 3-group comparison, HC3, differed from the HC sample in the 2-group comparison, HC2, as not all cohorts contributed data to the 3-group analysis (Table S1 in Supplement 2). In contrast to the AN group from the 2-group comparison, acAN cases were defined using more stringent treatment and recent weight gain criteria (1.2 in Supplement 1).

Case-Control (2-Group Comparison)

We aggregated data from 22 cohorts with a combined sample of 685 AN patients and 963 HC2 subjects (Table S1 in Supplement 2 and Figure S1 in Supplement 1). Sample size–weighted mean age across cohorts was 21 years (range, 15–27 years). Patients with AN were younger than HC2 subjects in 6 cohorts. Weighted mean BMI was 15.40 (range, 14.32–16.91) in AN patients and 21.61 (range, 20.81–23.48) in HC2 subjects. In all 22 cohorts, BMI was lower among AN patients than HC2 subjects. Age-adjusted BMI, available in 15 cohorts, was also lower in AN patients (weighted mean group difference −2.83; range, −3.83 to −1.61) compared with HC2 subjects (weighted mean group difference −0.20; range, −0.09 to 0.61). Mean age of AN onset was 16 years (range, 13–18 years). Mean illness duration was 5 years (range, 1–13 years). From zero to 58% of patients per site received antipsychotic or antidepressant medication (Table S1 in Supplement 2).

acAN Patients, pwrAN Patients, and HC3 Subjects (3-Group Comparison)

In up to 12 cohorts, data from 251 pwrAN patients were available and contrasted with 874 HC3 subjects and 466 acAN patients (Table S1 in Supplement 2 and Figure S1 in Supplement 1). pwrAN patients were on average 20 years of age (range, 14–33 years); they did not differ from acAN patients in age but were younger than HC3 subjects in 3 cohorts. The difference in weighted mean BMI was larger between pwrAN patients and HC3 subjects than between pwrAN patients and acAN patients (Table S1 in Supplement 2; 2.1 in Supplement 1; Figure S2 in Supplement 1). In pwrAN patients, mean age of onset was 15 years (range, 13–16 years). Mean illness duration was 5 years (range, 1–20 years).

Image Acquisition and Processing

All sites processed T1-weighted structural brain scans using FreeSurfer (28) and extracted, per hemisphere, subcortical volumes for 8 regions (1.3 in Supplement 1; Table S3 in

Supplement 2) and CT and SA for 34 Desikan-Killiany atlas regions (29) as well as left and right hemisphere mean thickness and total SA (Tables S4 and S5 in Supplement 2). For our main models, measures for the 8 subcortical and 34 cortical regions were averaged across hemispheres. However, all hemisphere-specific findings are listed in Tables S3–S13 in Supplement 2. Cohort-specific details on the number of scanners, vendor, strength, sequence, acquisition parameters, and FreeSurfer version run are provided in Table S2 in Supplement 2.

Statistical Meta-analyses and Follow-up Analyses

At the site level, group differences for each of the 42 regions within each sample were examined using univariate linear regression. We used R (R Foundation for Statistical Computing) linear model function lm for the 2-group comparison and glht function from the multcomp R package to assess all pairwise contrasts for the 3-group comparison using the Tukey method. Bilateral region of interest mean volume, mean CT, and total SA measures were predicted by group (AN vs. HC2), controlling for linear and quadratic age effects (and intracranial volume when the outcome was subcortical volumes) (model A in Table S15 in Supplement 2). To further assess whether group differences in CT and SA showed regional specificity, the analyses were repeated including global mean CT or total cortical SA as covariates in addition to age and age2 (model B in Table S15 in Supplement 2). To test for potential associations between partial/short-term weight gain and structural brain measures, we also included models using 3 groups (acAN, pwrAN, and HC3), covarying for age and age2 (model C in Table S15 in Supplement 2). In patients (separately in AN, acAN, and pwrAN groups), we also analyzed partial correlations between BMI and brain structure, correcting for linear and quadratic effects of age (model D in Table S15 in Supplement 2). At the site level, analysis of multiscanner cohorts (n = 5) included binary dummy covariates for n-1 scanners. Each site conducted analyses of their sample's individual subject data using R code created within the ENIGMA collaboration. Per model, only individuals with complete data were analyzed.

Site-level regression statistics were then combined in random-effects meta-analyses of Cohen's d statistics (for group differences) and partial correlation effect sizes (to assess associations with BMI) for each of the 42 brain regions. Meta-analyses were performed in R version 3.5.1 using the metafor package version 2.1-0 with site as a random effect and a restricted maximum-likelihood estimator. These same methods were applied to assess the effects of antidepressant or antipsychotic medication use, AN subtype (restrictive or binge-purge), depressive symptoms, illness duration, MRI field strength, or age as potential moderators. Moderators were included in these models through the mods flag in metafor. In all models, the intercept was included to assess differences between different levels of each moderator (e.g., clinical subtype) on the association between AN and brain structure. Throughout this article, we report false discovery rate (FDR)–corrected results separately for each modality (i.e., volume, CT, and SA) and Bonferroni-corrected results across all 42 brain regions (i.e., $p < .0012$).

Lastly, CT findings were contextualized across microscales and macroscales using the ENIGMA Toolbox (18) (1.4 in Supplement 1). Briefly, to gain insights on the microstructural properties of the significantly affected cortical regions, we first produced density plots of 2

BigBrain statistical moments (i.e., mean, indexing cellular density, and skewness, indexing cellular distribution asymmetry) and then computed the average effect sizes across each of the 5 von Economo and Koskinas cytoarchitectural types. To test whether reductions in CT preferentially localized to hub regions, we obtained normative functional and structural connectivity data and assessed spatial similarity between atrophy patterns and hub distributions. Statistical significance was assessed using spin permutation tests.

Results

Widespread Reductions in Brain Volumes and CT, but Weaker Alterations in SA of AN Patients Compared With HC Subjects (2-Group Comparison)

Subcortical Brain Volumes

We observed volume alterations in all 8 subcortical structures (model A) (Figure 1A; Table S3 in Supplement 2), with largest effects in the thalamus (Cohen's d = −0.69; 95% CI [−0.86, −0.52]). The lateral ventricles were the only structures enlarged in AN, with all other areas showing lower volume in AN. Mean (SD) absolute effect size across these regions was d = 0.42 (0.15). Effects across hemispheres correlated strongly (r = 0.99, p < .001).

Cortical Thickness

We also observed widespread reductions in CT in 29 regions passing Bonferroni correction (and 30 regions passing FDR correction; model A) (Figure 2A; Table S4 in Supplement 2). Largest effects were in the superior (d = −0.95; 95% CI [−1.20, −0.69]) and inferior (d = −0.94; 95% CI [−1.20, −0.67]) parietal gyrus. Mean (SD) effect size across these 29 regions was d = −0.65 (0.18). Effects across hemispheres correlated strongly (r = 0.94, p < .001). When additionally correcting for global mean thickness (model B), only 12 regions showed differences after Bonferroni adjustment (n = 18 regions with FDR correction) (Figure 2A; 2.2 in Supplement 1; Table S6 in Supplement 2), suggesting that differences in region-specific CT between patients and HC subjects were to some extent related to global thickness reductions.

Cortical SA

We also observed reductions in cortical SA in 16 regions passing Bonferroni correction (n = 16 with FDR correction; model A) (Figure 2B; Table S5 in Supplement 2). Largest effects were in the transverse temporal gyrus (d = −0.29; 95% CI [−0.42, −0.15]) and pars opercularis (d = −0.28; 95% CI [−0.38, −0.17]). Mean effect size across these 16 regions was d = −0.23; roughly a third of that observed for reductions in CT and half of that found for volumetric reductions. Effects across hemispheres correlated moderately (r = 0.53, p = .001). When additionally correcting for global mean SA (model B), only the paracentral and transverse temporal gyrus showed a significant difference (Figure 2B; 2.2 in Supplement 1; Table S7 in Supplement 2), suggesting that differences in region-specific cortical SA between AN patients and HC2 subjects were to a large extent driven by global reductions in SA.

Reductions in Volume, CT, and SA Are Less Severe in pwrAN Patients Than in acAN Patients (3-Group Comparison)

Subcortical Brain Volumes

Compared with the volumetric differences between acAN patients and HC3 subjects (mean [SD] dacAN-HC = 0.49 [0.18]), differences between pwrAN patients and HC3 subjects were reduced by 36% (mean dpwrAN-HC = 0.31 [0.12]), suggesting that volume reductions in pwrAN patients were smaller than in acAN patients (model C). pwrAN patients also had larger subcortical volumes than acAN patients (mean dacAN-pwrAN = 0.28 [0.09]) (Figure 1B; 2.3 in Supplement 1; Table S8 in Supplement 2). Overall, these findings suggest that reductions in subcortical volumes in pwrAN patients were smaller than those observed between acAN patients and HC3 subjects.

Cortical Thickness

Compared with the CT reductions in acAN patients (mean [SD] dacAN-HC = 0.67 [0.15]), differences between pwrAN patients and HC3 subjects were reduced by 36% (mean dpwrAN-HC = 0.43 [0.17]) (Figure 3A). CT in pwrAN patients was also larger than in acAN patients (mean dacAN-pwrAN = 0.49 [0.14]). This suggests again that CT reductions in pwrAN patients were less severe than in acAN patients compared with HC3 subjects (i.e., indicating partial normalization of CT during weight restoration). The reductions appeared to be largely driven by global CT reductions. Once controlled for global thickness, effects were reduced by 75% (acAN-HC3), 63% (pwrAN-HC3), and 86% (acAN-pwrAN) (Table S9 in Supplement 2, 2.3 in Supplement 1).

Cortical SA

Effect sizes for SA reductions were on average 52% smaller contrasting pwrAN patients to HC3 subjects (mean [SD] dpwrAN-HC = 0.10 [0.05]) compared with reductions in acAN patients (mean dAN-HC = 0.26 [0.07]) (Figure 3B). This suggests again that cortical SA reductions in pwrAN patients were less severe than in acAN patients compared with HC3 subjects (i.e., indicating partial normalization). These reductions seem to be largely driven by global SA reductions. Controlling for global SA reduced effect sizes from d = 0.26 to 0.08 for acAN-HC3 and from d = 0.10 to 0.05 for pwrAN-HC3 and increased effect sizes only slightly from d = 0.07 to 0.08 for acAN-pwrAN (Table S10 in Supplement 2; 2.3 in Supplement 1).

Multiscale Neural Contextualization

Patterns of CT reductions in AN corresponded to regions with greater, more evenly distributed (across the layers) cellular densities (Figure 4A) (19), particularly converging in parietal and frontal cytoarchitectonic classes (Figure 4B) (30). Leveraging connectivity data from the Human Connectome Project (31), AN-related atrophy implicated functional and structural corticocortical hub regions more strongly than nonhub (i.e., locally connected) regions (Figure 4C, D).

Reductions in GM Volume and CT Are Associated With BMI

In patients with AN, BMI was positively associated with volumes in the thalamus, putamen, amygdala, and hippocampus after Bonferroni correction (as well as the accumbens and pallidum after FDR correction; model D) (Table S11 in Supplement 2). The mean (SD) effect was r = 0.20 (0.03) with largest associations in the amygdala (r = 0.23; 95% CI [0.12, 0.35]).

Compared with the volumetric findings, associations between BMI and CT were larger with a mean effect of r = 0.32 (0.06), significant across 25 regions (n = 28 after FDR correction) (Table S12 in Supplement 2). For SA, associations with BMI were the weakest (mean r = 0.18 [0.04]) with only 5 significant regions (n = 7 after FDR) (Table S13 in Supplement 2). Together, these findings suggest that CT (and subcortical volumes and SA, albeit to a lesser extent) in AN might be related to BMI and therefore weight status. Effects were similar—and in the case of volume and CT slightly stronger—when using age-adjusted BMI (Tables S11–S13 in Supplement 2).

Moderator Effects

The 2-group differences in volume, thickness, and SA remained stable when covarying for the proportion of antidepressant or antipsychotic medication use, AN subtype (restrictive or binge-purge), depressive symptoms, illness duration, scanner field strength, or age (2.5 in Supplement 1). Furthermore, almost none of these clinical or technical variables showed moderating effects after FDR correction (2.5 in Supplement 1; Table S14 in Supplement 2). However, samples with a larger proportion of patients with a restrictive subtype were characterized by reduced thickness in the insula and reduced volume in the putamen and nucleus accumbens.

Discussion

In this prospective coordinated meta-analysis combining scans from 685 patients with AN (N = 1648, including HC subjects), we found widespread and sizable reductions in CT and subcortical volume in the underweight state of AN. SA was also reduced, but effect sizes were smaller. Comparison of acAN patients, pwrAN patients, and HC subjects indicated a substantial positive association between partial weight gain and all 3 structural brain metrics. This represents the largest structural neuroimaging study in AN to date. Taken together, the results suggest that AN is associated with global GM reductions (and no increases) and that these reductions might be highly state dependent, i.e., related to lower BMI.

In line with some, but not all, previous (smaller) studies (3, 4, 5,7,11,22), reductions in CT and subcortical volume in AN were on average moderate (mean Cohen's d of 0.65 and 0.42, respectively). Although cross-disorder comparisons should be considered with caution (also given the possible reversibility of these changes in AN), these reductions were 2–4 times larger than in other psychiatric disorders that are often comorbid with AN, including depression and obsessive-compulsive disorder [effect sizes 0.10–0.31 (13)] (Figure S5 in Supplement 1). In fact, until now the largest effects among all ENIGMA studies in psychiatric disorders (apart from the 22q11 deletion syndrome, which is characterized by hypertrophy) have been found in schizophrenia with Cohen's d effect sizes ranging from 0.12 to 0.46 for

subcortical structures and up to 0.53 for CT (13,15,16). Although smaller than the effects observed in neurodegenerative diseases such as Alzheimer's disease (32), the effects found here in AN are higher than those in schizophrenia and can therefore be considered the largest among psychiatric disorders.

We observed strongest effects in the superior and inferior parietal gyrus. These regions are associated with the integration of bodily stimuli (33,34) and form an attention network in synergy with temporal and prefrontal regions (35) that were also associated with AN in the current study. This might indicate that body-environment integration and attentive processes might be altered in AN, in line with previous functional neuroimaging research (36). Embedding our findings within a multiscale framework (37) revealed that patterns of CT reductions primarily affected regions with greater cellular densities as well as densely connected hub regions. Even though our connectivity networks were derived from data on young HC subjects, making inferences about altered network architecture in AN less straightforward, our findings are in line with previous psychiatric and neurological disorders (27,38), suggesting that the high metabolic demands and increased connectional flow of hub regions may account for their selective vulnerability in the manifestation of AN-related atrophy. While it is possible that these findings indicate actual cell loss (39), higher cellular density may also provide more opportunity for neuronal remodeling, which is a current hypothesis regarding the mechanisms underlying the dynamic brain changes in AN (6).

In contrast to our findings of larger alterations in volume and CT compared with other disorders, SA reductions were similar in size (mean Cohen's d = 0.23) compared with SA reductions in other psychiatric disorders, such as obsessive-compulsive disorder or schizophrenia (Cohen's d range = 0.16–0.33), and slightly smaller than those in depression (Cohen's d range = 0.26–0.57) (13). Even though effects for SA were smaller, they followed a similar pattern as for CT.

In line with this and previous studies (40), BMI showed small to moderate associations with subcortical volumes and CT (and to a smaller degree with SA). The moderating effect of AN subtype may also be related to this, as patients with a restrictive subtype are often characterized by more rapid and extensive weight loss (41, 42, 43). Interestingly, abnormally high body weight has also been associated with lower GM, and bariatric surgery seems to reverse some of these effects (44). Underlining the importance of state effects, such as weight loss and gain, our 3-group comparison showed that pwrAN patients had an attenuated reduction in all 3 GM metrics (36%–52% smaller differences compared with acAN patients). Although caution regarding causality is warranted, reversibility of pseudoatrophy in AN, i.e., increases in GM volume and CT (and even gyrification) following weight restoration, has been reported in previous cross-sectional investigations of long-term weight-restored former AN patients (11,22,45, 46, 47) and a small number of longitudinal studies (7,48, 49, 50). However, recent research suggests that normalization is easier to achieve in younger patients (23). Importantly, however, the current findings go beyond previous studies by supporting these effects across many cohorts in a coordinated meta-analytic design. Overall, these findings highlight the need to control for clinical state (acute vs. already gaining weight) in the study of AN—i.e., the drastic impact on the brain is strongly related to undernutrition and therefore rapidly changes with weight gain or treatment.

Results should be interpreted in the light of the following limitations. First, based on the neuroimaging method employed, microstructural changes cannot be detected. Therefore, we cannot exclude the persistence of irreversible scars after weight restoration at the microstructural level. This is important, as recent studies have shown elevated neuronal and glial damage markers in AN (39,51). Second, we aggregated data from different study sites, but differences in MRI scanners and acquisition protocols can introduce nonbiological variations (52). However, we covaried for potential scanner differences (within each study site) and found little evidence for moderating effects across sites. Third, we did not assess or control for comorbidities (e.g., obsessive-compulsive disorder, depression), but prior studies indicated generally smaller effects of these psychiatric disorders on brain structure (17,53). Hence, it is unlikely that our findings were better accounted for by comorbid conditions. Fourth, our study included a few HC subjects from a single site with a BMI as low as 17.5. It is possible that these individuals also showed some subthreshold eating disorder symptoms and were therefore more similar to pwrAN patients than to HC subjects. Similarly, the reported findings may also depend on the acAN group definition (and potential changes of their respective nutritional/hydration status within the first 2 weeks of therapy), and other results might be obtained with different cutoffs. However, our analysis indicated that BMI had a similar association with brain structure as a diagnostic group, suggesting that misclassification biases were unlikely. Fifth, given the cross-sectional design, our inferences regarding the effect of partial weight rehabilitation warrant replication in longitudinal studies. Last, we assume that differences on T1-weighted MRI measurements relate to true variations in brain morphology rather than errors or artifacts.

In summary, based on the largest and most representative sample to date, the current results indicate that acutely underweight individuals with AN have sizable and widespread reductions of subcortical volumes and CT and, to a lesser extent, cortical SA. Effect sizes for CT reductions are the largest detected among psychiatric disorders (13). These effects are attenuated in partially weight-restored patients, and all metrics of structural brain changes (especially cortical and subcortical GM) associate with current BMI, which mirrors the clinical state of AN. Our findings underline the importance of considering weight loss and renutrition in biomedical research on AN and the importance of effective early intervention and treatment engagement to prevent long-lasting structural brain changes.

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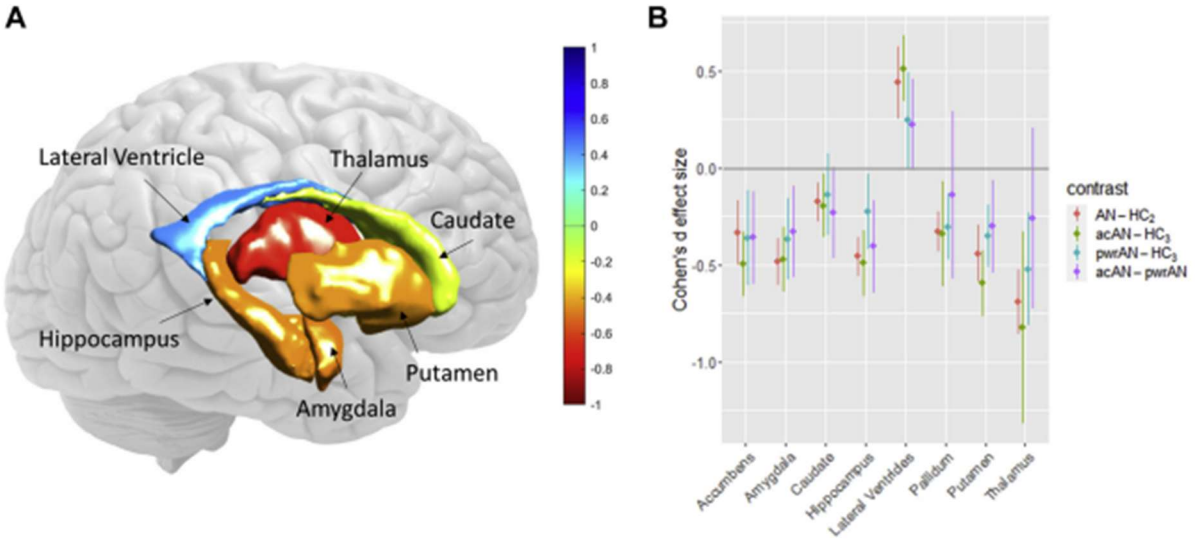

Figure 1. Subcortical volume reductions in anorexia nervosa (AN). Differences (Cohen's d) between (A) patients with AN and healthy control (HC2) subjects

(2-group comparison) and (B) all groups, also including patients acutely ill with AN (acAN), partially weight-restored patients with AN (pwrAN), and HC3 subjects

(3-group comparison). Warmer colors indicate lower volumes (Cohen's d; averaged across the left and right hemispheres, but depicted on the right side of the

brain) in patients compared with HC subjects. Error bars are 95% confidence intervals.

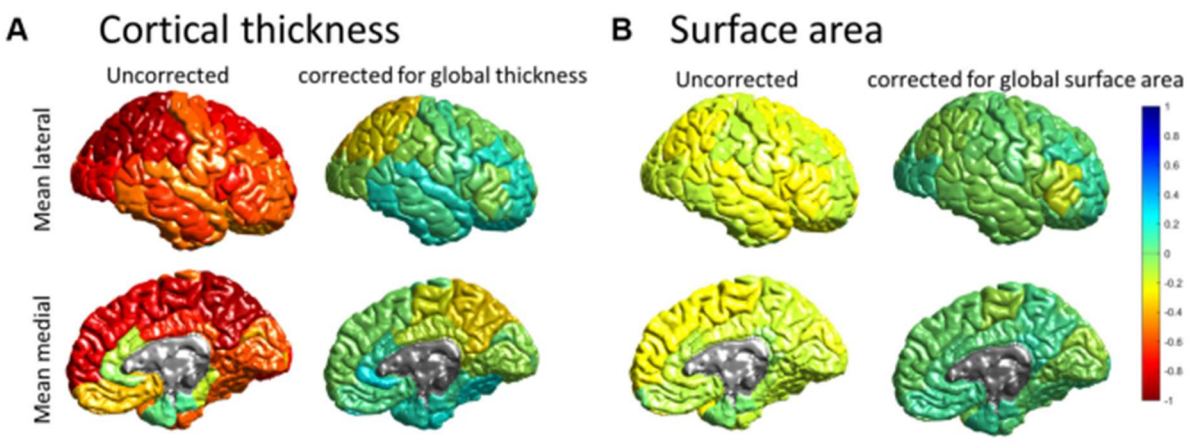

Figure 2. Reductions in (A) cortical thickness and (B) surface area between patients with anorexia nervosa and healthy control subjects (2-group comparison). Results that are uncorrected for global measures are shown on the left in each panel. Results that are corrected for global measures are shown on the

right in each panel. Warmer colors indicate reductions (Cohen's d effect size; averaged across the left and right hemispheres, but depicted on the right side of

the brain) in patients compared with healthy control subjects

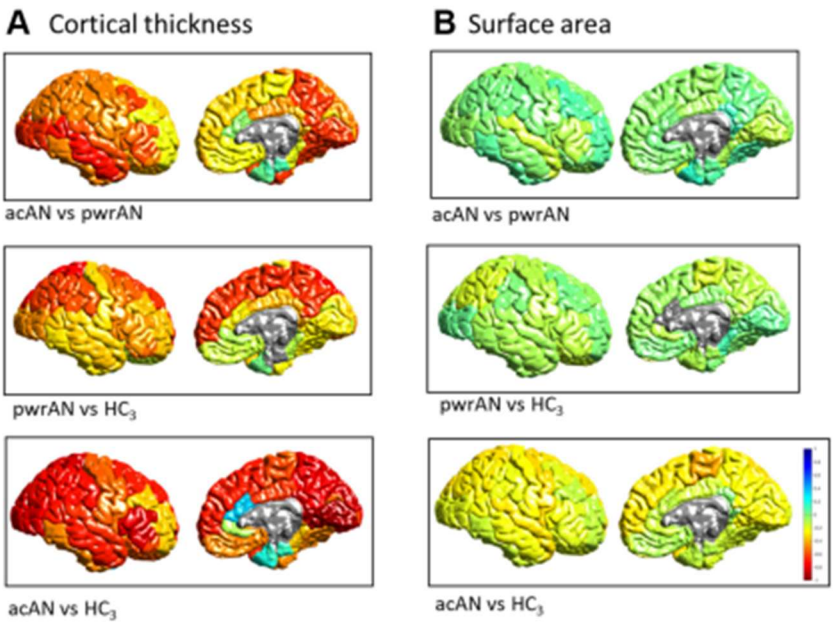

Figure 3. Pairwise reductions, shown as Cohen's

d effect sizes, in (A) cortical thickness and (B) surface area between patients acutely ill with anorexia

nervosa (acAN), partially weight-restored patients

with AN (pwrAN), and healthy control (HC3) subjects

(3-group comparison). Warmer colors indicate reductions (Cohen's d; averaged across the left and

right hemispheres, but depicted on the right side of

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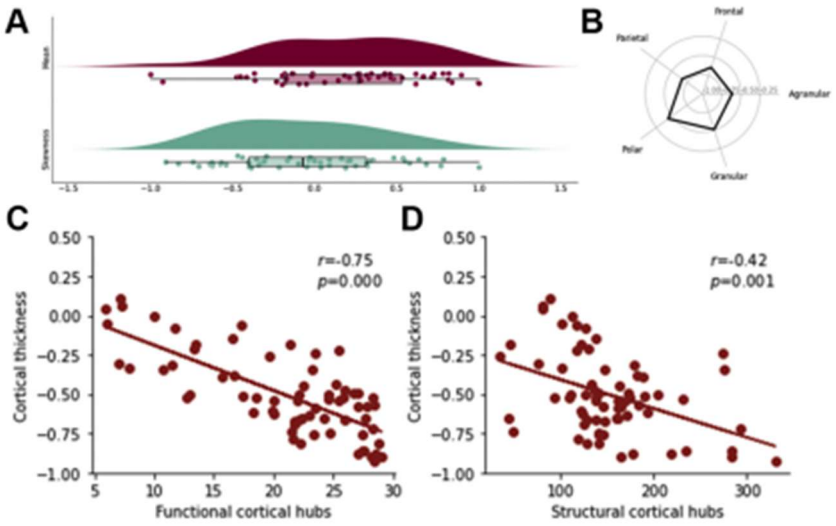

Figure 4. Neural contextualization of cortical thickness case-control differences. Cohen's d effect sizes in the context of (A) regional cytoarchitecture, specifically overall cellular density (top panel) and laminar differentiation (lower panel); (B) cytoarchitectonic classes based on postmortem work by von Economo and Koskinas (20); and degree centrality according to (C) functional and (D) structural connectivity.