Cortical Thickness, Surface Area, and Gyrification Abnormalities in Children Exposed to Maltreatment: Neural Markers of Vulnerability?

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Background: Childhood maltreatment has been shown to significantly elevate the risk of psychiatric disorder. Previous neuroimaging studies of children exposed to maltreatment have reported atypical neural structure in several regions, including the prefrontal cortex and temporal lobes. These studies have exclusively investigated volumetric differences rather than focusing on genetically and developmentally distinct indices of brain structure.

Methods: Here we used surface-based methods to examine cortical thickness, surface area, and local gyrification in a community sample of children with documented experiences of abuse ($n = 22$) and a group of carefully matched nonmaltreated peers ($n = 21$).

Results: Reduced cortical thickness in the maltreated compared with the nonmaltreated group was observed in an extended cluster that incorporated the anterior cingulate, superior frontal gyrus, and orbitofrontal cortex. In addition, reduced cortical surface area was observed within the parcellated regions of the left middle temporal area and lingual gyrus. Local gyrification deficits within the maltreated group were located within two clusters, the lingual gyrus and the insula extending into pars opercularis.

Conclusions: This is the first time structural abnormalities in the anterior cingulate and lingual gyrus have been detected in children exposed to maltreatment. Surface-based methods seem to capture subtle, previously undetected, morphological abnormalities associated with maltreatment. We suggest that these approaches detect developmental precursors of brain volume differences seen in adults with histories of abuse. Because the reported regions are implicated in several clinical disorders, they might constitute biological markers of vulnerability, linking exposure to early adversity and psychiatric risk.

Key Words: Child abuse, cortical thickness, local gyrification, maltreatment, psychopathology, surface area

Childhood maltreatment (physical, sexual, emotional abuse, or neglect) remains a major public health concern and has a profound impact on the individual, increasing risk of psychiatric problems in adolescence and adulthood, including anxiety, depression, and conduct disorder (1). There is limited understanding as to how maltreatment exposure might heighten developmental vulnerability to these outcomes. Extant neuroimaging studies, using volumetric approaches to measure gray matter volume (GMV), have reported atypical brain structure in individuals exposed to childhood adversity (2).

Adults who have experienced childhood maltreatment typically show reduced GMV in the prefrontal cortex, anterior cingulate cortex (ACC), hippocampus, and cerebellum (3–6). Children who have experienced maltreatment or institutionalization show reduced GMV in the prefrontal cortex, middle temporal gyrus, and cerebellum (7–11). Although these studies have typically imaged individuals with concurrent psychiatric disorders (limiting our ability to tease apart the influence of maltreatment from psychopathology), more recent studies have recruited nonclinically defined samples (7,11,12). Extant studies have employed volumetric methods to study structural correlates of maltreatment; however, a finer-grained characterization of atypical structural development associated with maltreatment might be helpful in a number of respects.

Volumetric approaches such as voxel- (VBM) and tensor-based morphometry are thought to reflect several structural parameters, including cortical thickness, cortical surface area, and gyrification (13,14), which capture more discrete features, including the laminar structure of the cortex (15–17), the number of cellular columns (16), and the pattern of cortical folding (18), respectively. The distinct genetic influences and differing developmental trajectories of these metrics provide a convincing rationale to investigate these properties as independent indices of brain structure (17,19). Surface-based analyses have been used to study abnormal brain development in children (20–22). Although these studies have reported regional abnormalities overlapping with those identified with traditional volumetric approaches, they have also identified structural abnormalities in novel regions.

This study investigated the impact of maltreatment on cortical thickness, surface area, and local gyrification. We recruited a group of children exposed to documented maltreatment at home and compared them with a group of nonmaltreated peers. We predicted that maltreated children would show cortical thickness, surface area, and folding differences, as compared with nonmaltreated peers, in the prefrontal cortex (e.g., orbitofrontal cortex [OFC]) and the middle temporal gyrus, consistent with volumetric studies of GMV in community samples of maltreated children without significant psychopathology (7,11). We were also keen to explore whether previously undetected anatomical differences

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between maltreated and nonmaltreated children would be detected with these more specific structural indices.

Methods and Materials

Participants

Two groups of children were recruited from the London area (Table 1). Children with documented exposure to maltreatment ($n = 22$) were recruited from a Social Services (SS) department in London. The SS teams identified potential families in their caseload. Before contacting a family (or a foster family), agreement with regard to the suitability of a case was reached with the team. The SS only put forward cases that did not have a diagnosis of learning disability and judged as competent to consent in addition to living within a stable placement (minimum of 6 months), if the child was not living with biological parents.

The allocated social worker contacted the family or foster family to introduce them to the research. Interested families were then contacted by a research assistant, and a home visit was arranged to describe the study, answer questions, and seek consent. For children living with their biological parents, assent was obtained from the child, and consent was obtained from one parent. Where there was shared parental responsibility, consent was obtained from the biological parent of the child if contactable, and SS.

Nonmaltreated comparison children ($n = 21$) matched on age, self-reported Tanner stage, sex ratio, handedness, cognitive ability, and ethnicity (Table 1) were recruited from secondary/primary schools and via advertisement in local newspapers and on the Internet. Exclusion criteria included a history of abuse, neglect, and/or exposure to domestic violence as reported by the main caregiver on the Child Bad Experience Questionnaire (23) and the Dunedin Abuse Scales (24) and previous contact with SS with regard to the quality of care or maltreatment of the child. Consent was obtained from the child and their parent(s).

All participants completed a comprehensive battery of psychological measures (see Measures section and Table 1). No participant reported a history of head trauma, neurological disease, or contraindications for magnetic resonance imaging (MRI).

Note that, of the current sample, 17 children in the Maltreated Group and 19 children in the Nonmaltreated Group were common to those recruited for our previous study on cortical volume (11). The study was approved by University College London Ethics Committee (0895/002).

Table 1. Background Characteristics and Questionnaire Data for Nonmaltreated and Maltreated Children

	Nonmaltreated ($n = 21$)		Maltreated ($n = 22$)		p
Male Sex	10 (47.62)		14 (63.64)		.36
Caucasian	10 (47.62)		7 (31.82)		.36
Tanner Stage					
Pre/early pubertal	6 (28.57)		7 (31.82)		1.00
Mid/late pubertal	15 (71.43)		15 (68.18)		1.00
Handedness	1 Left, 19 Right, 1 Ambidextrous		1 Left, 18 Right, 3 Unknown		.26
	Mean	SD	Mean	SD	
Age (Years)	12.77	1.19	12.27	1.41	.23
Socioeconomic Status					
Highest level of education[a]	2.81	1.33	2.27	1.39	.20
Wechsler Abbreviated Scale of Intelligence					
Full Scale IQ	107.48	11.52	102.55	11.57	.72
Mood and Feelings Questionnaire[b]					
Total score	11.90	8.17	10.05	8.94	.49
Trauma Symptom Checklist for Children[b]					
Anxiety	47.75	12.25	46.10	12.96	.68
Depression	45.40	9.55	44.48	11.48	.78
Anger	44.05	7.81	45.52	10.20	.61
Posttraumatic stress	44.25	6.47	47.86	11.64	.23
Dissociation	47.00	6.70	49.81	10.98	.33
State/Trait Anxiety Inventory for Children[b]					
Trait	33.33	7.45	32.38	8.44	.70
State	27.81	4.40	26.29	2.76	.19
Total	61.14	9.86	59.25	9.41	.53
Strengths and Difficulties Questionnaire[c]					
Conduct problems	1.29	1.10	3.45	2.67	.00
Peer problems	1.71	1.49	1.55	1.92	.75
Emotional problems	2.67	1.46	2.68	1.76	.98
Prosocial behavior	8.19	2.29	8.13	2.03	.92
Hyperactivity	3.15	2.48	5.13	3.11	.03

Values are *n* (%), unless otherwise indicated. All *p* values derived from *t* tests with the exception of sex, ethnicity, and Tanner stage comparisons which used Fisher's exact test.

[a]The highest level of education provided by the mother or long-term foster mother was taken as a proxy of socioeconomic status and was evaluated on a scale from 1 to 5 (1 = no formal qualifications; 5 = postgraduate level).

[b]Child rated.

[c]Parent rated.

Measures

Maltreatment History. The SS case files for the maltreated group were independently rated on Kaufman's four-point scale (25), which is rated from 0 (no abuse present) to 4 (evidence of severe abuse) by the social worker of the child in relation to neglect ($n = 19$; mean = 2.53 ± 1.12) and physical ($n = 8$; mean = 1.50 ± .54), sexual ($n = 5$; mean = 2.00 ± 1.87), and emotional abuse ($n = 18$; mean = 2.94 ± 1.06). See Supplement 1 for more detail regarding maltreatment exposure. Six case files were double-rated by a senior social work professional; there was 83% agreement in relation to presence of physical abuse, sexual abuse, and neglect and 100% agreement in relation to emotional abuse.

Cognitive Ability. Participants were administered the Vocabulary and Matrix Reasoning subtests of the Wechsler Abbreviated Scale of Intelligence (26) to estimate full scale IQ.

Socioeconomic Status. The highest level of education attained by the mother or long-term foster mother was taken as an indicator of socioeconomic status (SES) and evaluated on a 5-point scale (from 0 = formal qualification, to 5 = postgraduate or professional qualification).

Pubertal Status. The eight-item self-report Puberty development scale (27) was administered to derive a two-stage indicator of pubertal development based upon Tanner stages.

Psychiatric Symptoms. The Trauma symptom checklist for children (28) was used to assess acute and chronic posttraumatic symptomatology and other symptom clusters. The 44-item self-report measure has five clinical scales (Anger, Depression, Anxiety, Posttraumatic stress, and Dissociation). The Mood and Feelings Questionnaire (29) is a 33-item self-report measure that assesses core depressive symptoms in children. The State Trait Anxiety Inventory for children was used to assess state and trait anxiety (30). This 20-item self-report measure provides separate scores for state and trait anxiety and a composite anxiety score. The Strengths and Difficulties Questionnaire (SDQ) (31), a 25-item parent report measure, was included to assess general psychological and behavioral functioning. The SDQ includes five behavioral scales (Emotional symptoms, Conduct problems, Hyperactivity, Peer problems, and Prosocial behavior) and a total difficulties score.

MRI Acquisition

Participants were scanned with a 1.5 Tesla Siemens (Siemens Medical Systems, Munich, Germany) Avanto MRI scanner with a 32-channel head coil. A high-resolution, three-dimensional T1-weighted structural scan was acquired with a magnetization prepared rapid gradient echo sequence. Imaging parameters were: 176 slices; slice thickness = 1 mm; gap between slices = .5 mm; echo time = 2730 msec; repetition time = 3.57 msec; field of view = 256 mm × 256 mm^2; matrix size = 256 × 256; voxel size = 1 × 1 × 1 mm resolution. The scanning time was 5.5 min. Foam padding was used against the sides and the back of the head of the participant, to minimize head motion. Ear buds attenuated scanner noise.

MRI Analysis

All images were initially manually inspected for deformations or inconsistencies that might have impeded processing (e.g., movement artefacts or structural abnormalities). No participants were excluded after this inspection. All analyses were whole-brain performed in the absence of firm a priori hypotheses with these techniques for the first time in a sample of maltreated individuals. The estimated total intracranial volume was calculated within FreeSurfer for each participant. No group differences were observed between the maltreated and nonmaltreated groups ($p = .37$).

Cortical Thickness and Surface Area Measures

The FreeSurfer (v5.1.0; http://surfer.nmr.mgh.harvard.edu) surface-based pipeline (15,32–34) was used to process the T1 images into a standard space in which cortical thickness values could be derived on a participant-by-participant basis. White matter points were defined from estimates of their location on the basis of their position in Talairach space as well as the voxel intensity and local neighborhood intensities. Skull stripping and classification of white and gray matter was computed automatically on each hemisphere. A two-dimensional tessellated mesh consisting of over 300,000 vertices was constructed over the white matter surface to distinguish the gray–white matter boundary. This mesh was expanded outward to meet the gray matter and pial surface boundary. The estimated boundaries were manually edited for any errors, and inconsistencies by visual inspection and additional control points were added for gray and white matter differentiation where necessary.

Cortical thickness at each vertex was measured by calculating the shortest distance from the white matter to the pial surface. Surface area was calculated at the pial level and represents the area of vertex on the gray matter surface, calculated as the average of the area of the tessellated triangles touching that vertex. Parcellation of the cortex of each participant into gyral regions was based on the Desiken-Killiany atlas (35). Average surface area value for each parcellated region was extracted for all participants.

These measures were estimated in native space giving an unadjusted estimate of absolute cortical thickness. The cortex of each participant was normalized to the spherical standard curvature template with surface registration with cortical folding patterns to match cortical geometry across participants. The FreeSurfer surface-based analysis pipeline has been described extensively, and its validity has been supported (36,37).

Local Gyrification Index

The local gyrification index (lGI) is a supplementary measure within the FreeSurfer analysis suite. Developed by Schaer *et al.* (18), the lGI builds upon the two-dimensional linear gyrification measure developed by Zilles *et al.* (38). An advantage of this index is that it takes into account the intrinsic three-dimensional nature of the cortical surface, compared with two-dimensional methods, which are susceptible to bias from slice orientation and buried sulci. The method of Schaer has been employed in a number of studies of psychiatric conditions, including conduct disorder, psychosis, and schizophrenia (21,39,40). The lGI method uses the pial and white matter surface identification against an additional outer hull layer that tightly wraps the pial surface. The lGI value at each vertex is computed within 25-mm circular regions of interest and represents the ratio of pial to outer hull surface, an indication of sulcal cortex buried in its locality and thus the extent of cortical folding. See Schaer *et al.* (18) for further details of this approach.

Statistical Analysis

Regionally specific between-group differences in cortical thickness and lGI were investigated within the QDEC (query, design, estimate, contrast) application of FreeSurfer with two-sample *t* test models. Cortical thickness and local gyrification measurements were smoothed with a full-width-at-half-maximal kernel of 15 mm and 5 mm, respectively. Between-group differences were corrected for multiple comparisons with a Monte Carlo z-field simulation at $p < .05$ (two-tailed). Significant clusters were then used as masks to extract mean cortical thickness and local gyrification values for each participant. Cortical thickness, surface area, and local gyrification undergo dynamic changes during childhood and

adolescence and are known to be influenced by gender and age (19,41). Although there were no significant group differences in age and sex, additional group comparisons were conducted within SPSS (SPSS, Chicago, Illinois) with age and sex as covariates to ensure these variables did not account for any of the findings.

Results

Demographic Characteristics

There were no statistically significant differences between the maltreated and nonmaltreated groups in relation to age, sex ratio, ethnicity, full scale IQ, self-reported Tanner stage, SES, and handedness (Table 1). Measures of depression, anxiety, and posttraumatic symptoms were also examined and did not differ across groups. Relative to their peers, children in the maltreated group had higher parent-reported levels of conduct problems and hyperactivity scores on the SDQ.

Cortical Thickness

The cortical thickness analysis identified one cluster, in the right hemisphere, that was reduced in the maltreated group compared with the control subjects (Figure 1, cluster 1; Monte Carlo null-z simulation corrected $p < .05$). Annotation, on the basis of the Desikan-Killiany parcellation atlas (35), of the group structural data indicated that the peak coordinate fell within the ventral ACC (Table 2, cluster 1; X = 8.3, Y = 37.0, Z = −3.9) with the cluster extending across the superior frontal gyrus and into anterior aspects of the OFC. No other significant clusters survived whole brain cluster correction in either hemisphere.

Surface Area

Surface area values extracted on a gyral level were entered into SPSS. An independent group analysis was performed to identify whether any of the gyral regions differed in their average surface area values. Three regions based on the Desikan-Killiany parcellation atlas were identified to have a significantly reduced average surface area at an uncorrected level in the maltreated sample, compared with nonmaltreated peers: the right entorhinal region ($p = .034$); the left middle temporal gyrus ($p = .006$); and the left lingual gyrus ($p = .005$). A step-up false discovery rate correction was applied to control for multiple comparisons; only differences in the middle temporal gyrus ($p = .038$) (Figure 2, cluster 5) and lingual gyrus ($p = .038$) (Figure 2, cluster 6) remained significant. Table 3 summarizes the significant parcellated region statistics for the surface area analysis.

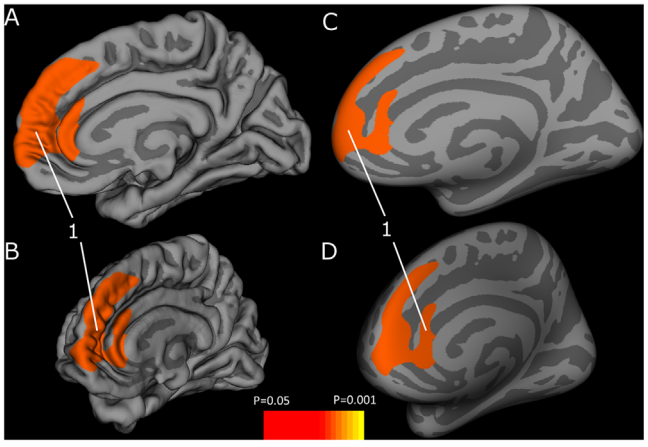

Figure 1. Significant cortical thickness clusters projected onto the pial and inflated surface of the right hemisphere in medial view **(A, C)** and a tilted frontal medial view **(B, D)**. The significant cluster shows decreased cortical thickness within the maltreated group compared with the nonmaltreated group and survived cluster correction ($p < .05$). Cluster label defined in Table 2.

lGI

The local gyrification analysis identified two significant clusters in the left hemisphere, with reduced gyrification within the maltreated group compared with the control subjects (Figure 3, clusters 2 and 3; Monte Carlo null-z simulation corrected $p < .05$). Automated annotation of the group structural data (Table 2, clusters 2 and 3) labeled the first cluster within the lingual gyrus. This cluster survived a more conservative level of Monte Carlo null-z simulation cluster correction ($p < .01$); however, the extent of the cluster was reduced. The second cluster extended across rostral aspects of the insula and into the pars opercularis with its peak coordinate sitting within the anterior insula (X = −37.6, Y = 15.5, Z = 9.8). Table 2 summarizes cluster statistics for both cortical thickness and lGI analyses.

Secondary Analyses

When significant effects were detected, the associated cortical value was extracted, and correlations were conducted with age of onset, duration, and severity of each maltreatment subtype. No significant correlations were found between any of the cortical indices and measures of maltreatment experience.

Several additional analyses were then conducted, to explore the potential impact of age and sex. Average cortical thickness in the right pre-frontal cluster was extracted for each participant (Table 2, cluster 1). The average lGI values for each of the significant clusters within the left hemisphere (Table 2, clusters 2 and 3) and the mean surface area values for significant regions (Table 3, clusters 4–6) were also extracted for each participant. Initial standardized residuals of these values were then produced in SPSS, covarying for age and sex, because these factors have been implicated in developmental changes to cortical thickness (19,42). Group comparisons were then conducted with these residuals; the previously observed pattern of group differences was unchanged for cortical thickness, surface area, and lGI.

Correlations were performed between mean cortical thickness, surface area, and local gyrification values extracted from the significant clusters/regions for each participant and the conduct problems and hyperactivity scores obtained on the SDQ. No significant associations were detected ($p < .05$ threshold), and this pattern of results remained after co-varying for age and sex. See Supplement 1 for further details.

Discussion

This study is the first to provide evidence of atypical cortical thickness, surface area, and local gyrification in maltreated children. Compared with carefully matched peers, children with documented experiences of maltreatment were found to have reduced cortical thickness in an extended right hemisphere pre-frontal cluster comprising the ventral ACC, superior frontal gyrus, and anterior OFC. Maltreated children also presented with reduced cortical surface area within two gyral regions: the left middle temporal area and the left lingual gyrus. Finally, the maltreated group was found to have reduced gyrification in two left hemisphere clusters: the first located in the lingual gyrus and the second extending across the insula into the pars opercularis. These significant group differences were observed after controlling for age and sex across all three cortical parameters. The current findings

Table 2. Significant Clusters for Cortical Thickness and lGI, Corrected for Multiple Comparisons

Cortical Index	Cluster Number	Anatomical Regions	L/R	Area (mm^2)	Talairach Coordinates (x, y, z)	$p_{cluster}$[a]
Cortical Thickness	1	Ventral anterior cingulate/superior frontal	R	2160.51	8.3, 37.0, −3.9	.003
lGI	2	Lingual gyrus	L	3954.83	−21.4, −61.3, 8.9	.0001
	3	Insula/pars opercularis	L	1825.13	−37.6, 15.5, 9.8	.027

L, left; R, right; lGI, local gyrification index.
[a]Cluster probability. All comparisons are maltreated < nonmaltreated.

suggest that the structural brain changes associated with maltreatment exposure go beyond previously documented volumetric differences in gray matter (2) and help delineate the specific structural parameters that are altered by maltreatment exposure.

Areas of the extended frontal cluster showing reduced cortical thickness in our maltreated sample have been implicated in a variety of higher order emotional and cognitive processes. The ventral ACC has been implicated in emotional regulation (43,44), the superior frontal gyrus has been implicated in working memory (45,46), and the OFC has been implicated in social and emotional regulation and flexibility (47,48). Reduced GMV in the ACC has been reported in adults exposed to childhood maltreatment (4,49). To our knowledge, structural differences in the ACC have not previously been reported in relation to maltreated children. Because GMV is influenced by surface area and cortical thickness, it is possible that prolonged exposure to maltreatment might have a cumulative impact on cortical thickness across development that is only observable as a reduction in GMV by adulthood. Alternatively, surface area differences might emerge at a later stage and independently contribute to the GMV differences observable in adulthood. Longitudinal studies are required to differentiate these possibilities.

The cluster showing reduced cortical thickness in our maltreated sample also extended into the superior frontal gyrus and OFC, consistent with volumetric studies in children. For example, reduced GMV in the superior frontal gyrus has been reported for children with histories of childhood abuse (7,50). The cortical thickness cluster extends into the most anterior aspect of the OFC. Similarly, significantly reduced GMV in the OFC has been found in children exposed to maltreatment at home (7), a pattern that might be associated with poorer social functioning in these children (7). However, there was no overlap with the OFC cluster, which showed reduced GMV in the maltreated compared with nonmaltreated children, identified in our previous VBM study, even though most participants were common across studies (11). These findings are consistent with other studies, which suggest that cortical thickness contributes only a portion of the variance to GMV measured by VBM (40).

We suggest that morphological disturbances across this extended PFC cluster in a community sample of maltreated children with no clinical diagnoses of psychiatric disorders might reflect latent neurobiological risk for future psychopathology such as posttraumatic stress disorder (51).

Our analysis also found three regions showing reduced surface area in the maltreated as compared with nonmaltreated children. First, the maltreated group also exhibited reduced surface area within the middle temporal area, consistent with reports of reduced GMV in this same region in maltreated children (7) and adults (50). In our previous VBM investigation, which had used an overlapping sample, we also found GMV abnormalities within this region (11). It is possible that these previously seen GMV differences are indicative of an underlying reduced surface area. Second, reduced surface area was also observed in the left lingual gyrus in the maltreated group, a finding we consider in more detail below.

Finally, the maltreated group, relative to their peers, also showed reduced local gyrification in two left-hemisphere clusters. The first cluster—in the lingual gyrus—overlapped with the region with reduced surface area. The lingual gyrus has been implicated in higher-order processing of visual information (52,53), specifically in early stages of face processing (54). Decreases in GMV in the right lingual gyrus have been reported for women with a history of sexual and physical abuse (3). Functional studies have also

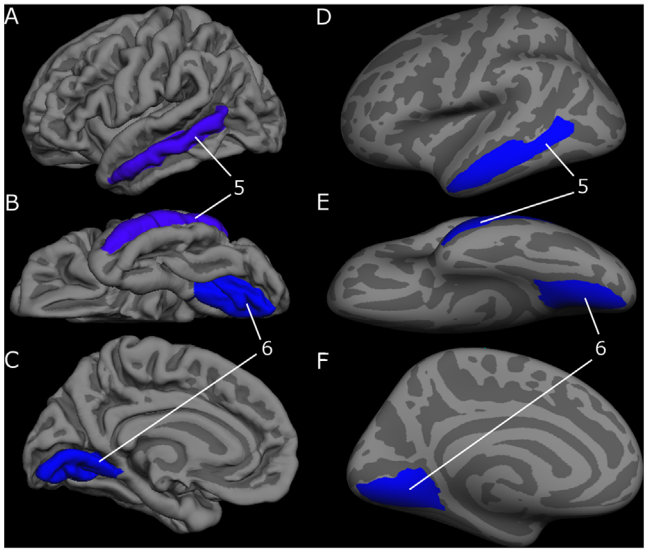

Figure 2. Significantly reduced surface area gyral regions in the left hemisphere in lateral **(A, D)**, inferior **(B, E)**, and medial **(C, F)** views. Cluster 5 is the parcellated region of the middle temporal area ($p = .006$), and cluster 6 is the lingual gyrus ($p = .005$). Cluster labels (numbers) correspond with those given in Table 3.

Table 3. Parcellated Regions Presenting with Significant Surface Area Differences Between Maltreated and Nonmaltreated Samples

Cortical Index	Region Number	Anatomical Label	L/R	Maltreated Mean	Maltreated SD	Nonmaltreated Mean	Nonmaltreated SD	*t*
Surface Area	4	Entorhinal cortex	R	528.45	93.88	633.19	194.73	2.230[a]
	5	Middle temporal gyrus	L	4451.27	596.02	4929.48	471.78	2.908[b]
	6	Lingual gyrus	L	3409.77	482.75	3851.86	505.20	2.934[b]

Values are in mm^2.
L, left; R, right.
[a]$p < .05$ uncorrected.
[b]$p < .05$ corrected (false discovery rate step-up controlling procedure).

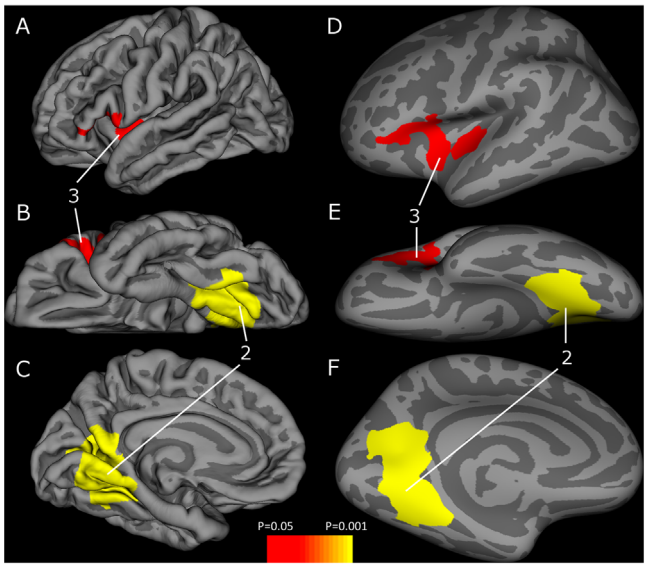

Figure 3. Significant local gyrification index clusters projected onto the pial and inflated left hemisphere in lateral **(A, D)**, inferior **(B, E)**, and tilted inferior medial **(C, F)** view. The significant clusters show decreased gyrification in maltreated children compared with control subjects. Cluster 2 survived cluster correction of $p < .01$, whereas cluster 3 survived cluster correction of $p < .05$. Cluster labels (numbers) correspond with those provided in Table 2.

identified altered lingual gyrus activation in adults reporting childhood histories of maltreatment during olfactory stimulation (55) and emotional face processing (56). One suggestion is that alterations in visual regions in maltreated individuals might reflect an adaptation to stress exposure, reflecting attenuation in sensory systems and pathways relaying recurrent aversive or traumatic experiences (57). That we observe both cortical folding and surface area differences within this same area suggests that these indices are both affected by this adaptive process. Volumetric differences within the lingual gyrus have not, to our knowledge, been identified within maltreated children before. This suggests that these cortical parameters of surface area and gyrification might represent precursors of observable GMV differences later in life. It is possible that the GMV reduction in the lingual gyrus observed in adults specifically reflects reduced gyrification and surface area in this region rather than reduced cortical thickness.

A second cluster fell within the left insula, extending into the pars opercularis. Within healthy individuals, the insula is thought to be part of a salience network that detects threat (58) integrating information into perceptual decisions about pain (59) as well as playing a key role in the empathic perception of emotion states of others (60,61). Structural studies have identified GMV decrease in the insula in children (62) and adults (63) who have experienced physical abuse and childhood maltreatment, respectively. Functionally, increased insula reactivity has been reported during processing of angry faces in maltreated children (64).

Several limitations of our study should be noted. Firstly, although self-report and parent-report measures of clinical symptoms were administered, no formal clinical psychiatric interviews were conducted. Therefore we cannot rule out the possibility that certain forms of psychiatric disorder were present in either group and went undetected. Secondly, our use of a cross-sectional design limits our ability to make causal inferences between exposure to maltreatment and the observed differences in cortical thickness, surface area, and local gyrification. Longitudinal studies of high-risk samples are required to investigate how neural differences associated with childhood adversity relate to future psychological and behavioral functioning. Finally, given the challenges inherent in accessing information about biological families in the maltreated group, we employed a univariate measure of SES (maternal education). However, a composite measure of SES would be preferable and more accurate in characterizing economic and social functioning.

In summary, this is the first study to investigate differences in cortical thickness, surface area, and local gyrification in individuals exposed to maltreatment. We provide novel evidence that maltreated children with normative levels of internalizing psychopathology present with significantly reduced cortical thickness within an extended cluster comprising the ventral anterior cingulate, superior frontal gyrus, and OFC. In addition we observed significantly reduced cortical surface area in the maltreated group in two gyral regions: the left middle temporal area and the left lingual gyrus. Finally, local gyrification was found to be significantly reduced in the left lingual gyrus and the left insula/pars opercularis.

We suggest that these findings are significant in three important respects. Firstly, they raise questions about how we understand the developmental emergence of GMV differences in maltreated individuals. For example, although GMV differences in the ACC have been observed in adult samples, they have not been seen in children (2). We suggest that reduced cortical thickness in the ACC might represent developmental precursors to the GMV differences observed in adults with histories of abuse. Secondly, our findings help shed light on the nature of previously reported GMV differences. As has been noted, volumetric techniques only capture an emergent index of several structural properties (13,14), making it difficult to infer what specific structural feature might be contributing to differences in local volume. So, for example, our finding of reduced surface area in the left middle temporal region suggests that differences in surface area and not cortical thickness might be driving the previously reported GMV differences in this region (7,11). Thus, by investigating these discrete structural parameters, we can better characterize the impact of maltreatment and the potential structural precursors to later psychopathology. Thirdly, consistent with previous structural investigations of maltreated samples, our findings point to aberration in brain regions associated with a broad range of autobiographical, emotional, and regulatory processes that might underpin increased risk for psychopathology. Structural studies of clinical groups, particularly those with posttraumatic stress disorder and depression, have also reported morphological abnormalities in these regions (10,65–68). We suggest that the observed differences in cortical thickness, surface area, and local gyrification in our community sample of maltreated children may therefore represent neural markers of increased risk for psychopathology.

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