Anterior cingulate cortex abnormalities associated with a first psychotic episode in bipolar disorder

Alex Fornito, Murat Yücel, Stephen J. Wood, Andreas Bechdolf, Simon Carter, Chris Adamson, Dennis Velakoulis, Michael M. Saling, Patrick D. McGorry and Christos Pantelis

Background
The anterior cingulate cortex is frequently implicated in the pathophysiology of bipolar disorder, but magnetic resonance imaging (MRI) studies have reported variable findings owing to a reliance on patient samples with chronic illness and to limited appreciation of the region’s heterogeneity.

Aims
To characterise anterior cingulate cortex abnormalities in patients with bipolar disorder experiencing their first episode of psychosis while accounting for regional anatomical variability.

Method
Grey matter volume, surface area and cortical thickness were measured in six anterior cingulate cortex subregions per hemisphere using MRI scans acquired from 26 patients with bipolar I disorder experiencing first-episode psychosis and 26 healthy controls matched for age, gender and regional morphological variability.

Results
Relative to controls, male patients displayed increased thickness in the right subcallosal limbic anterior cingulate cortex. No significant differences were identified in females for grey matter volume or surface area measures. The findings were not attributable to medication effects.

Conclusions
These data suggest that first-episode psychosis in bipolar disorder is associated with a gender-specific, right-lateralised thickness increase in anterior cingulate cortex subregions known to play a role in regulating physiological stress responses.

Declaration of interest
None.

The anterior cingulate cortex is a brain region critical for integrating cognitive and emotional functions in support of adaptive, goal-directed behaviour,1,2 and abnormalities in this region play a significant role in the pathophysiology of bipolar disorder.3 Early attention focused on a subcallosal region of the anterior cingulate cortex ventral to the genu (also termed subgenual prefrontal cortex), following initial magnetic resonance imaging (MRI) evidence of a left-lateralised volumetric reduction in this region in patients with chronic unipolar depression or bipolar disorder.4 However, other reports of right-sided subcallosal reductions5 or no group differences6,7 coupled with findings of volumetric reductions in other subregions8,9 and even grey matter increases,10,11 have led to confusion regarding the precise nature of abnormalities observed in people with bipolar disorder.

One possible reason for such inconsistencies is that much of the work to date has focused on patients with chronic illness, making it difficult to determine whether the observed changes are a result of prolonged illness duration or are apparent from earlier illness stages. Studying patient samples with first-episode psychoses can help mitigate these effects, although the findings of the only four such studies that have been published have been variable: Hirayasu et al12 replicated earlier findings4 by identifying a volumetric reduction in the left subcallosal anterior cingulate cortex of patients with a positive family history; Kubicki et al13 and Farrow et al14 found no differences in grey matter using voxel-based techniques; and Adler et al15 found evidence of increased grey matter in caudal anterior cingulate cortex regions.

A second reason for inconsistencies in the literature is that no study to date has adequately accounted for the substantial interindividual variability in sulcal and gyral anatomy of the anterior cingulate cortex, which differs between patients with bipolar disorder and healthy populations,15 and has been shown to affect volumetric and other morphometric measures in the region.16–18 Such findings indicate that spurious differences in group comparisons might emerge if patients and controls are not well matched for sulcal anatomy. To address these limitations, we applied a novel cortical surface-based protocol for parcellating the anterior cingulate cortex into functionally relevant subdivisions while accounting for the region’s anatomical variability17,18 to MRI data obtained from a sample of patients with bipolar disorder experiencing their first psychotic episode. Importantly, we individually matched patients and controls for age, gender and sulcal variability to ensure that any identified changes could not be attributed to group differences in cortical folding patterns. Our surface-based approach enabled calculation of regional grey matter volume, surface area and cortical thickness with submillimeter resolution, allowing us to detect relatively subtle changes that may be occurring in earlier stages of the disorder.

Following current theories emphasising a primary role for subcallosal abnormalities in the pathophysiology of bipolar disorder,20 we expected that patients would show particularly pronounced grey matter reductions in this region.

Method

Participants
The patient sample comprised 26 patients with bipolar I disorder experiencing a first psychotic episode who were recruited from the Early Psychosis Prevention and Intervention Centre, Melbourne, Australia. All patients were in a manic state at presentation. DSM–IV21 diagnoses were confirmed over a minimum 6-month follow-up period and assigned based on medical record review and the Structured Clinical Interview for DSM–IV (SCID).22 None of the patients had a history of childhood-onset bipolar disorder. Further details regarding recruitment procedures are...
published elsewhere.23 Twelve (eight male) patients were taking atypical antipsychotics at the time of scanning and nine (five male) were taking typical agents (mean chlorpromazine equivalents at time of scanning: 188.04 mg/day, s.d. = 119.16). Seven patients (four male) were taking lithium; two adjunctively with typical antipsychotics, four with atypicals and one as monotherapy. Two patients were medication-free. Treatment data were not available for two patients. All patients were experiencing psychotic symptoms at the time of scanning.

Prior psychiatric treatment in this sample was as follows: 16 none, 3 depression (all were on antidepressants at MRI; maximum treatment duration was 2 months), 1 post-traumatic stress disorder (not treated at study intake). One patient reported experiencing two manic episodes 5 years prior to the study but did not seek treatment. Family history of psychiatric illness was as follows: 11 none, 1 bipolar, 1 bipolar and schizophrenia, 1 schizophrenia, 4 depression, 2 depression plus anxiety. Clinical histories were unavailable for five patients (excluding these participants did not change the findings, so their data were retained for the final analysis).

Healthy controls with no personal history of mental or neurological illness and no family history of psychosis were selected from our larger database in order to individually match them to each patient for age, gender and anterior cingulate cortex sulcal morphology (see below). Exclusion criteria for all participants included a history of steroid misuse, substantial head injury and impaired thyroid function. Participants were also excluded if they had ever met diagnostic criteria for a substance use/dependence disorder, given evidence that such disorders can affect grey matter.24 Patients with comorbid psychiatric, neurological or significant medical conditions were also excluded from the study (see Velakoulis et al23 for more details). All participants gave written, informed consent in accordance with local ethics committee guidelines. Demographic details are presented in Table 1.

Magnetic resonance imaging

Image acquisition

Scans were acquired using a GE Signa 1.5 T scanner at the Royal Melbourne Hospital, Victoria, Australia. A three-dimensional volumetric SPGR sequence generated 124 contiguous coronal slices. Imaging parameters were: time to echo (TE), 3.3 ms; time to repetition (TR), 14.3 ms; flip angle, 30°; matrix size, 256 × 256; field of view, 24 × 24 cm; voxel dimensions, 0.938 × 0.938 × 1.5 mm. Data were transferred from DAT tape to a Linux Debian 3.1 workstation and coded to ensure participant confidentiality and masked rating.

Image pre-processing

Prior to classifying sulcal morphology, each participants’ image was stripped of extracerebral tissue and aligned to the N27 template via a 6° rigid-body transformation using tools contained in the FSL software package (www.fmrib.ox.ac.uk/fsl). No rescaling or warping was performed, but the images were resampled to 1 mm³ voxels in the process.

Classification of sulcal variability

There are two major variations in sulcal and gyral anatomy that can affect region-of-interest boundaries and alter regional morphometry: the incidence and extent of the paracingulate sulcus, and the confluence of the cingulate sulcus with the superior rostral sulcus.19 The paracingulate sulcus runs dorsal and parallel to the cingulate sulcus in 30–60% of cases.25 We classified the paracingulate sulcus as ‘present’ if there was a clearly identifiable sulcus running dorsal and parallel to the cingulate sulcus that was at least 20 mm in length, or ‘absent’ if no such sulcus was apparent, according to reliable and established criteria (see Fornito et al19 and Yu¨cel et al25). The superior rostral sulcus was classified as ‘continuous’ with the cingulate sulcus if the two were connected rostral to the genu of the corpus callosum; all other cases were classified as ‘separate’ (see Fornito et al19 and online Fig. DS1). All sulcal classifications were performed on the N27-aligned images using Analyze 6.0 for Linux (Mayo Software, Englewood, Colorado, USA).

Prior work has shown that the appearance of a paracingulate sulcus affects the size and location of anterior cingulate cortex subregions. When a paracingulate sulcus is present, the paralimbic anterior cingulate cortex (ACCP; primarily Brodmann area 32) extends from the depths of the cingulate sulcus across the crown of the paracingulate gyrus to the paracingulate sulcus; when the paracingulate sulcus is absent, the ACCP is buried in the depths of the cingulate sulcus19,26 (online Fig. DS1). Limbic ACC (ACCP; Brodmann area 24) is generally located between the callosal and cingulate sulci, although its size is also affected by paracingulate sulcus variability.16,17,19 This effect can be quite large, with one study suggesting that the appearance of a paracingulate sulcus leads to 39% decrease in ACCP volume and 88% increase in ACCP volume in some cases.16 Similar findings have been observed for regional surface area, although the relationship with cortical thickness is more complicated.17 Such findings, coupled with evidence that the paracingulate sulcus is less frequent in patients with bipolar disorder,17 indicate that spurious group differences may emerge if the comparison groups are not well matched for this morphological variation. To this end, we devised a

<table>
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<tr>
<th>Table 1 Sample characteristics</th>
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<tr>
<td>Patients with bipolar disorder</td>
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<td>Right/left/mixed-handed, n</td>
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<tr>
<td>Age, years, a mean (s.d.)</td>
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<tr>
<td>NART IQ, b mean (s.d.)</td>
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<td>Illness duration, years: median (minimum–maximum)</td>
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<td>PANSS score, c mean (s.d.)</td>
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<td>Positive</td>
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<tr>
<td>Negative</td>
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<td>Disorganisation</td>
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<td>Excitement</td>
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<td>Emotional distress</td>
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</table>

NART, National Adult Reading Test; PANSS, Positive and Negative Syndrome Scale.

a. Age was compared using Student’s t-tests.
b. NART IQ data were unavailable for six patients and three controls. NART IQ was compared using the Mann-Whitney U-test.
c. PANSS factor scores based on van der Gaag et al.23 Data unavailable for six patients.
four-category classification system that described the incidence of the paracingulate sulcus in both hemispheres for each individual. The four categories were: present in the left and absent in the right hemisphere (n = 9); present in both hemispheres (n = 6); absent in both hemispheres (n = 6); or absent in the left and present in the right hemisphere (n = 5). Each participant was classified according to this system and controls were then randomly selected from a larger database and individually matched to each patient on the basis of this classification, gender and age. Since paracingulate sulcus and superior rostral sulcus classifications tend to be related, this procedure also resulted in good matching for superior rostral sulcus morphology. In the right hemisphere, 8 patients and 8 controls were classified as having a continuous superior rostral sulcus, and the remaining 18 patients and 18 controls were classified as having a separate superior rostral sulcus. In the left hemisphere, 7 patients and 12 controls had a continuous classification, whereas 19 patients and 14 controls were classified as showing a separate pattern. Although there can still be considerable variation in the rostro-caudal extent of the paracingulate sulcus within participants classified as ‘present’, we have previously shown that such variations do not have a major influence on the measures examined in this study.17

Cortical surface reconstruction
The white (i.e. grey/white matter boundary) and pial (grey/ cerebrospinal fluid boundary) surfaces of the cortical ribbon were tessellated with a triangular mesh comprising ~150,000 vertices per hemisphere using methods described in detail elsewhere27–29 and as implemented in the Freesurfer software package (http://surfer.nmr.mgh.harvard.edu). The surfaces were reconstructed using the raw, unaligned images in native space to avoid unnecessary interpolation and resampling, and were visually inspected and corrected for accuracy as per guidelines on the Freesurfer website. Reconstructing these surfaces enabled calculation of surface area, grey matter volume and mean cortical thickness for each of six anterior cingulate cortex regions per hemisphere. Distinguishing between these three measures is important given that volume, the most widely used metric in anatomical MRI studies in patients with bipolar disorder, is a relatively diffuse measure that reflects the product of a cortical region’s surface area and thickness. Consequently, changes in one or the other parameter can be obscured unless both are assessed independently – an important consideration when attempting to characterise relatively subtle changes early in the illness course.

Each of the measures were calculated according to previously described methods.28 Briefly, cortical thickness was calculated at each surface point by finding the vertex on the pial surface closest to a given point on the white surface (and vice versa) and averaging these two values. As the surfaces are generated with sub-voxel resolution, the resulting thickness measures are estimated with sub-millimeter precision and have been validated against post-mortem specimens.30 The thickness values for each surface point in the regions of interest were averaged to obtain the mean thickness for that region. Regional surface area was calculated by summing the area of the triangle faces included in each region of interest for the white and pial surfaces separately, and then taking the average of the two. Grey matter volumes were calculated as the product of surface area and thickness at each surface point, averaged across all pial and white matter vertices in each region of interest.

Region-of-interest delineation
The parcellation protocol divides the ACCal and ACCpr into dorsal, rostral and subcallosal regions, yielding six regions of interest per hemisphere. Boundaries separating the dorsal, rostral and sub-callosal regions were designed to approximate previously identified functional subdivisions within the area.12,13 Boundaries distinguishing between the ACCal and ACCpr varied in accordance with paracingulate sulcus and superior rostral sulcus variability and were based on post-mortem work documenting how cytoarchitectonic areas in the region vary in accordance with sulcal morphology26 (online Fig. DS1). A more detailed justification and description of these boundaries has been provided elsewhere.19 We have recently shown that reliabilities for this method are satisfactory (all >0.8, with most >0.9).17

Intracranial volume
Intracranial volume was calculated for each individual to control for any group differences in brain size using a previously described, reliable method.23

Statistical analyses
All analyses were performed using SPSS 12.0 for Windows. Regional grey matter volumes, cortical thickness and surface area were analysed with mixed within-participant and between-participants ANOVA, with hemisphere (left or right), region (dorsal, rostral and subcallosal) and cortex (ACCal or ACCpr) as within-participant factors, and diagnosis and gender as between-participants factors. Gender was included as a factor in the analyses to determine whether diagnostic differences varied for males and females. There is growing evidence that gender interacts with diagnosis in affecting brain morphology, including the anterior cingulate cortex, in other psychotic disorders,31,32 but such effects have seldom been investigated in bipolar disorder. Volume, area and thickness were treated as independent measures analysed using separate models to simplify interpretation of the findings. This approach allows inferences regarding group differences within each measure, but does not allow any conclusions regarding relative differences across measures (see Limitations for further discussion). As sphericity assumptions were invariably violated, main effects and interactions were evaluated using Greenhouse–Geisser corrected degrees of freedom, with \( \xi = 0.05 \). Post hoc contrasts were evaluated against a Bonferroni-adjusted \( \alpha \) to correct for multiple comparisons. Effect sizes, expressed as Cohen’s \( d \), are also reported for these contrasts (negative values indicate a decrease in the patient group). Only effects involving diagnosis are reported, as these were the primary focus of the current study.

We corrected grey matter volume and surface area estimates for intracranial volume using equations described by Free et al.33 For cortical thickness, we report results of analyses of uncorrected values since the anatomical significance of the relationship between thickness and intracranial volume is unclear.34 (We note that separate analyses that did covary for intracranial volume yielded similar findings.)

Results

Anterior cingulate cortex morphometry
Group means for grey matter volume, surface area and cortical thickness are presented in Table 2. For grey matter volume, there was no main effect of diagnosis \((F(1,48) = 0.887, P = 0.351)\) or diagnosis \(\times\) gender interaction \((F(1,48) = 0.164, P = 0.687)\), nor did diagnosis interact with any of the within-participant factors. Similarly, there was no significant main effect of diagnosis \((F(1,48) = 1.248, P = 0.270)\), diagnosis \(\times\) gender interaction
Past findings

Differences in subcortical areas were expected, although the direction of the difference (i.e. grey matter increase in patients) was not. Several authors have emphasised a primary role for subcortical grey matter reductions, particularly in the left hemisphere, in the pathophysiology of bipolar disorder,\(^6\) but past MRI studies of the anterior cingulate cortex in bipolar disorder have reported variable findings with respect to the laterality, subregion and nature (grey matter increase or decrease) of the abnormality.\(^4,11\) The majority of these studies have been conducted in patients with prolonged illness, although four other studies of patients with first-episode affective psychosis have also yielded contradictory findings.\(^11,13\) Direct comparison between these reports and our findings is complicated by differences in the methods used and the fact that we had insufficient power to appropriately examine the effects of family history. This is an important consideration, given that two independent studies have previously found left subcortical reductions in familial patients.\(^4,12\) By way of speculation, the fact that the majority of our sample did not report a family history of affective illness suggests that left-sided abnormalities may be more prominent in familial cases, whereas right-sided changes may characterise sporadic patients.

Prior neglect of the potential effect of paracingulate sulcus variability on the findings is also likely to contribute to inconsistent findings in the literature. We have previously shown that paracingulate sulcus variability can have a large and complex effect on regional volume, surface area and thickness in the anterior cingulate cortex\(^7,19\) and that, as a group, patients with bipolar disorder are less likely to display this sulcus than healthy controls.\(^15\) This means that spurious group differences in estimates of regional grey matter such as volume and thickness can arise if patients and controls are not well matched for this anatomical variation. Consequently, inconsistent and contradictory findings of anterior cingulate cortex changes in patients with bipolar disorder may partly reflect differences in regional cortical folding patterns rather than true changes in the relative amount of grey matter in the region.

When such sulcal variability is accounted for, our findings suggest that first-episode psychosis in bipolar disorder is associated with a thickness increase in the right subcallosal ACC\(_L\) of male patients. Relatively few studies of bipolar disorder have examined gender effects on anterior cingulate cortex morphology in detail. Drevets et al\(^{11}\) found a left subcallosal anterior cingulate cortex abnormality in healthy women but not in healthy men. The difference between our findings and those of Drevets et al\(^{11}\) is likely due to the fact that left subcallosal reductions have been found in familial patients\(^4,12\) but not in cases with sporadic illness. In the current study, there were more male patients with bipolar disorder than female patients, which may explain the different findings.

This study implemented a novel surface-based approach to characterise anatomical abnormalities of the anterior cingulate cortex in patients with bipolar disorder experiencing their first episode of psychosis. Relative to controls matched for age, gender and paracingulate sulcus, male patients showed a significant thickness increase in the right subcallosal ACC\(_L\). No significant differences were identified for grey matter volume or surface area, or for any measure in the female group. The fact that only thickness, but not surface area or volume, was different highlights the importance of distinguishing between these measures when assessing anatomical changes in psychiatric disorders and suggests thickness may be a particularly sensitive metric for detecting such changes, especially in early illness stages. Importantly, this is the first study to match patients and controls for sulcal variability, indicating these differences are unlikely to be caused by group biases in cortical folding patterns.

### Discussion

This study implemented a novel surface-based approach to characterise anatomical abnormalities of the anterior cingulate cortex in patients with bipolar disorder experiencing their first episode of psychosis. Relative to controls matched for age, gender and paracingulate sulcus, male patients showed a significant thickness increase in the right subcallosal ACC\(_L\). No significant differences were identified for grey matter volume or surface area, or for any measure in the female group. The fact that only thickness, but not surface area or volume, was different highlights the importance of distinguishing between these measures when assessing anatomical changes in psychiatric disorders and suggests thickness may be a particularly sensitive metric for detecting such changes, especially in early illness stages. Importantly, this is the first study to match patients and controls for sulcal variability, indicating these differences are unlikely to be caused by group biases in cortical folding patterns.
cingulate cortex reduction while statistically covarying for gender in patients with chronic bipolar disorder, whereas another study of a similar region in a predominantly female sample found no group differences, suggesting the differences are more pronounced in males. Kaur et al. failed to identify a gender × diagnosis interaction in their study of the entire anterior cingulate gyrus, although they studied a paediatric sample.

To date, only three other studies have found grey matter increases in the anterior cingulate cortex of patients with bipolar disorder. Adler et al. reported an increase in a region corresponding to our rostral ACCr/ACCl in a sample of patients with long-term illness. More recently, Bearden et al. found evidence of increased grey matter in the anterior cingulate cortex of patients with established bipolar disorder, although they attributed their findings to the effects of lithium, since a subsample of patients not taking lithium at the time of scanning showed no evidence of such changes, and a significant, inverted U-shaped relationship was observed between anterior cingulate cortex grey matter and duration of exposure to lithium. However, another recent study of patients with bipolar disorder experiencing their first episode of mania also reported increased anterior cingulate cortex grey matter in a sample where only 1 patient (out of 33) was being treated with lithium. When coupled with our finding that excluding patients taking lithium did not change the results, this suggests not all grey matter increases can be attributed to the effects of this drug. It should be noted, however, that the grey matter increase reported by Adler et al. was in the caudal, rather than subcallosal anterior cingulate cortex. Reasons for this discrepancy include that Adler et al. did not consider the influence of paracingulate sulcus variability on their findings and that they did not examine gender × diagnosis interactions. Furthermore, our sample was composed entirely of patients with bipolar disorder experiencing psychotic symptoms, whereas Adler et al. did not report how many of their patients were experiencing such symptoms. This may be an important distinction, given emerging evidence for a distinct phenotype in this subgroup of patients. Further investigation of the neuroanatomical changes associated with psychotic and non-psychotic bipolar disorder will therefore be an important avenue of future research.

The gender-specific nature of our findings, coupled with the direction and laterality of the thickness difference (i.e. we found a right-sided increase, rather than decrease, in our patient group),

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**Fig. 1** Mean thickness for male and female patients and controls in each limbic (ACCl) and paralimbic (ACCr) anterior cingulate cortex subregion. Error bars represent standard deviations. Left column presents data for left hemisphere regions; right column presents data for right hemisphere regions. *P < 0.05, corrected.
Table 3 Results of post hoc contrasts comparing patients and controls in each anterior cingulate cortex subregion separately for males and females

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<th>Males</th>
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<td>0.317</td>
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<td>0.436</td>
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ACCc, limbic anterior cingulate cortex; ACCp, paralimbic anterior cingulate cortex.
*Statistically significant difference at a Bonferroni-corrected threshold of a=0.004. The correction was made for the 12 contrasts performed separately in males and females.

is interesting in light of recent evidence regarding the role of the subcallosal anterior cingulate cortex in regulating the body’s physiological stress response, particularly as mediated through the hypothalamic–pituitary–adrenal (HPA) axis. The subcallosal anterior cingulate cortex is heavily connected with the hypothalamus, amygdala and brainstem autonomic nuclei. Rodent work has shown that lesions to the right, but not left, ventral medial prefrontal cortex (which includes the subcallosal anterior cingulate cortex) significantly decrease corticosterone levels in response to external stressors, suggesting that the right subcallosal anterior cingulate cortex plays an important role in activating the HPA axis. It is, therefore, plausible that although lesions to this area reduce HPA activation, increased thickness may reflect a hyperfunctional abnormality that produces an excessive stress response. Heightened HPA activity has been demonstrated in patients with first-episode psychosis, and although the precise mechanism through which a thickness increase might lead to this excessive stress response remains unclear, a link between the two is suggested by evidence that other brain regions implicated in HPA axis activation, such as the amygdala and pituitary gland, are also enlarged in patients with first-episode affective psychosis. In this context, two notable findings are that: (a) patients with bipolar disorder show increased anatomical connectivity between the subcallosal anterior cingulate cortex and amygdala; and (b) volume of the pituitary gland, which is correlated with peripheral measures of HPA activation, is increased in ultra-high-risk individuals who eventually develop an affective psychosis, with the enlargements being most pronounced in individuals scanned in closer temporal proximity to psychosis onset. It is unclear whether an increase in anterior cingulate cortex thickness such as that observed in our data would also precede psychosis onset, although these findings do support the notion that size increases in brain regions implicated in HPA regulation are associated with an elevated stress response. Chronic hyperactivity of this circuit may account for why reports of volumetric reductions in the anterior cingulate cortex are more common in samples with chronic illness, given that prolonged elevation of corticosterone levels has been associated with decreased volume in both rodents and humans.

Taken together, these findings suggest that relative hyper trophy in brain regions critical for regulating HPA axis activation (i.e. the anterior cingulate cortex, amygdala and pituitary) are associated with an elevated stress response around the time of psychosis onset that ultimately causes volumetric contractions in later illness stages. In this context, the gender-specific nature of our findings may be related to gender differences in HPA reactivity, which is known to be elevated in males relative to females. It should be noted, however, that left-sided reductions have been observed in patients with familial bipolar disorder, with Drevets et al. positing that such changes may disinhibit right-sided activation of physiological stress responses in familial patients. Thus, although the effects of paracingulate sulcus variability on these earlier findings are unknown and the precise effects of family history remain to be characterised, it is possible that lateralised pathology of the subcallosal anterior cingulate cortex differs in sporadic and familial cases. The net effect of both would be to increase HPA reactivity, albeit through distinct mechanisms. Future work examining the role of stress, gender and family illness history in influencing the longitudinal course of neuroanatomical abnormalities in bipolar disorder will be critical for characterising these relationships further.

Limitations

In this study, we defined ‘first-episode’ as first contact with psychiatric services for a psychotic episode and we did not control for the effects of prodromal symptoms, duration of untreated psychosis or pre-psychotic affective episodes. The effects of such characteristics can only be unambiguously determined through prospective work, although one recent voxel-based study found no effect of duration of untreated psychosis (retrospectively assessed) on anterior cingulate cortex grey matter, suggesting that any such influences on our region-of-interest measures may be minimal. We also note that there was no significant correlation between thickness in this region and duration of psychosis in our patient sample (Spearman’s rho = -0.121, P = 0.574).

Excluding patients taking lithium did not significantly alter our findings, suggesting they do not reflect grey matter increases known to be related to mood stabiliser treatment. Similarly,
we found no evidence for an effect of antipsychotic class, although our power for detecting such an effect was limited. Past studies of such effects have yielded inconsistent findings, with one voxel-based investigation reporting that, relative to drug-free patients with psychosis (comprising both schizophrenia and affective psychosis), those taking typical antipsychotics had less anterior cingulate cortex grey matter, whereas those taking atypicals showed no significant changes in this region. In contrast, recent work using region-of-interest techniques has suggested that anterior cingulate cortex volume is positively correlated with exposure to typical antipsychotics and negatively correlated with exposure to atypicals. However, this study also failed to find a difference in the rate of volumetric change between patients with schizophrenia taking typicals or atypicals in the first 2–3 years following psychosis onset, suggesting that the effects of differential antipsychotic exposure on anterior cingulate cortex morphometry are minimised in the first few years of illness. Although we cannot determine whether similar changes to those reported in this paper would be observed in a medication-naive sample, the fact that the median illness duration in our sample was ~3 weeks (the longest was 10 weeks) suggests that any effects of antipsychotic medication were minimal.

We deemed our retrospective paracingulate sulcus matching procedure to be an efficient means for matching patients and controls on this important parameter since prospective matching would require very large samples (i.e. its morphology is only ascertainable after scanning). It should be noted that controls, but not patients, were selected to meet the matching criteria, meaning that no biases were introduced into the patient sample, as this group represented all patients for whom data were available. Although the matching procedure may have introduced some sampling bias in the control group, this bias would have minimised any differences between patients and controls, since the controls were being chosen explicitly because their brain had a similar morphology to that of the patient group. (Preliminary analyses indicated no significant differences between controls selected and not selected with respect to National Adult Reading Test IQ.) Matching patients and controls for both paracingulate sulcus and superior rostral sulcus morphology would require very large samples and was not possible in the current study. However, since these two morphological variations tend to be related, our paracingulate sulcus matching also resulted in good matching for superior rostral sulcus morphology. Importantly, superior rostral sulcus morphology was perfectly matched in the right hemisphere, where the primary thickness differences were, suggesting superior rostral sulcus differences cannot account for our findings.

Our attempt to account for the functional and anatomical diversity of the anterior cingulate cortex resulted in a highly multivariate data-set with many comparisons being made. Our analyses therefore attempted to strike an appropriate balance between control of type I and type II errors, while minimising complexity. To simplify analysis and interpretation of the findings, we treated grey matter volume, area and thickness as independent measures that were analysed using separate models. As we treated these measures independently, we evaluated main effects and interactions in these models using uncorrected significance thresholds, although the post hoc contrasts used to characterise the main finding of this work were tested using very stringent criteria (i.e. Bonferroni correction for 12 comparisons). This, coupled with the large effect size associated with the subcallosal difference (Cohen’s $d > 1$), indicates the effect is robust and unlikely to be a false positive. However, our failure to find differences in other regions may have reflected a lack of power. Table 3 indicates there were several regions in which moderate effect sizes were obtained (including in female patients), suggesting they warrant further investigation in larger samples. Such work should also investigate the relationship and interactions between changes in volume, area and cortical thickness, rather than treating them independently.

Future study

Our novel surface-based approach enabled us to derive a detailed characterisation of anterior cingulate cortex abnormalities in the early stages of bipolar psychosis. By explicitly accounting for individual differences in sulcal morphology, we ensured that our results are not an artifact of group differences in local cortical folding patterns. Our findings provide an impetus for future research examining the longitudinal course of neuroanatomical abnormalities in bipolar disorder, while also considering the influences of family illness history and gender differences in stress responses.

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Data supplement

**Fig. DS1** Example of region-of-interest boundaries and their relationship with local variations in cortical folding.

Left column presents a case with an ‘absent’ paracingulate sulcus and ‘continuous’ superior rostral sulcus, and right column presents a case with a ‘present’ paracingulate sulcus and ‘separate’ superior rostral sulcus. Top row presents representative sagittal slices through the T1-weighted images of two participants in the study, with major sulci marked in red. Middle row presents regions of interest overlaid on the reconstructed pial surfaces with the delineated regions of interest. The posterior yellow line represents the caudal border of the dorsal region. The anterior yellow line separates the rostral and dorsal regions dorsally, and rostral and subcallosal regions ventrally. The middle yellow line represents the posterior border of the subcallosal region. Bottom row presents the reconstructed white matter surface. Sulci on this surface correspond to indentations or ‘crevasses’, whereas gyri correspond to protrusions or ‘ridges’. As can be seen, if a paracingulate sulcus was ‘present’ the paralimbic anterior cingulate cortex (ACCP) comprised the grey matter between the fundus of the cingulate sulcus and that of the paracingulate sulcus. If a paracingulate sulcus was ‘absent’, the ACCP was located on the dorsal bank of the cingulate sulcus. Similarly, if the superior rostral sulcus and cingulate sulci were ‘separate’, the ACCP extended from the fundus of the cingulate sulcus to that of the superior rostral sulcus. If the two sulci were ‘continuous’, the ACCP was located on the rostro-ventral bank of the cingulate sulcus. The limbic ACC (ACCL) always comprised the grey matter between the callosal and cingulate sulci. Regions of interest were always delineated on the white matter surface to facilitate tracing inside sulcal walls and then projected onto the pial surface to check for accuracy and consistency prior to continuing. Note how the ACCP is not visible from the pial surface in ‘absent’ or ‘continuous’ cases.
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