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Neural correlates of emotional processing in psychosis risk and onset – a systematic review and meta-analysis of fMRI studies

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Abstract

Aberrant emotion processing is a well-established component of psychotic disorders and is already present at the first episode of psychosis (FEP). However, the role of emotion processing abnormalities in the emergence of psychosis and the underlying neurobiology remains unclear. Here, we systematically reviewed functional magnetic resonance studies that used emotion processing task paradigms in FEP patients, and in people at clinical high-risk for psychosis (CHRp). Image-based meta-analyses with Seed-based d Mapping on available studies (n=6) were also performed. Compared to controls, FEP patients showed decreased neural responses to emotion, particularly in the amygdala and anterior cingulate cortex. There were no significant differences between CHR subjects and controls, but a high degree of heterogeneity was identified across studies. The role of altered emotion processing in the early phase of psychosis may be clarified through more homogenous experimental designs, particularly in the CHR population.

Keywords: Emotion, Psychosis, Clinical High-Risk, Functional Magnetic Resonance Imaging, Seed-based d Mapping
1 Introduction

Emotional abnormalities, including alexithymia and blunt affect, are an established component of the presentation of psychotic disorders such as schizophrenia (1,2). There is consistent evidence for aversion to positive and neutral stimuli in schizophrenia (3) and facial emotion recognition deficits (4,5), which could be valence- or task difficulty-dependent (6). However, the neurobiology underlying the development of such abnormalities and their putative role in psychosis development remain unknown. Several meta-analyses of functional magnetic resonance (fMRI) and positron emission tomography (PET) studies showed lower activation to emotional stimuli compared to neutral stimuli in schizophrenia patients relative to healthy controls in several brain regions (5,7–9). Such finding was most consistently reported for the bilateral amygdala in relation to aversive stimuli (7) as well as to facial emotion expressions (across valences, analysing threatening expressions only, or isolating implicit and explicit processing) (8–10). Under-recruitment of other regions to emotion-related stimuli was also reported, such as in the right superior frontal gyrus (9), hippocampus, early visual processing regions, frontal cortices (8) and fusiform gyrus (10). These meta-analyses also identified aspects of study design that may underlie region-specific differences across studies; for instance, implicit or explicit task paradigms may recruit disparate brain networks (9) and comparison to a neutral condition may yield more robust results than a comparison across emotion conditions (7). With evidence showing that antipsychotic medication does not adequately treat emotion-related deficits in patients with schizophrenia (5) and that emotion processing deficits in schizophrenia are predictive of functional outcome (11), studying populations in the early stages of psychosis may inform research into more targeted therapies as well as potential new preventative treatments (12).
Despite an increase in the literature on the neural correlates of emotion processing in first episode of psychosis (FEP) and at-risk populations in the last decade, no systematic review and meta-analysis to date has attempted to synthesise this evidence. While an impairment in facial emotion recognition across positive and negative valences is reported as already present at the first episode (13,14), it is unclear whether this is also the case in people at clinical high risk for psychosis (CHRp) (15). Individuals at CHRp present with subtle, subjective disturbances in attention and cognition (16,17), attenuated psychosis symptoms and functional decline (15,18,19). Emotion processing was reported to be impaired across at-risk, FEP and chronic schizophrenia samples (20), suggesting that it may be a trait characteristic. However, other behavioural studies in CHRp showed contrasting results. Some found no deficit in emotion recognition (21,22), while others reported impaired neutral face recognition (23) and poorer sad and fearful face recognition (24). A putative explanation for such disparate results is that they might be dependent on the future transition status of CHRp participants, as it was shown that poorer neutral, and better fearful expression recognition was associated with transition status (25), and more recently, that poor functional outcome is associated with anger recognition in individuals at CHRp (26). Furthermore, behavioural manifestation of emotion processing abnormalities can be preceded by the development of underlying biological mechanisms (18). In their recent systematic review on neural correlates of social cognition (processing of socially-relevant stimuli) in psychosis proneness, Kozhuharova and colleagues found convergent activation increases in the lateral temporal cortex to emotional and neutral stimuli in CHRp individuals compared to controls, but inconsistent results for the frontal cortex and limbic regions (27). The only meta-analysis of fMRI studies on emotion processing in FEP to date, using a coordinate-
based approach (activation likelihood estimation), did not find differences in brain activation to emotional stimuli compared to healthy controls, although within-group analyses suggested that the FEP group recruited fewer regions (28). The aim of our study was to conduct an up-to-date systematic review of fMRI studies on emotion processing in the FEP and CHRp states, complemented by a robust image-based meta-analysis from available studies, which is considered a more sensitive approach than coordinate-based methods (29). We hypothesised a clear pattern of altered activation in FEP compared to healthy controls during emotional processing, that would be less pronounced in those at CHRp.

The present study aimed to systematically review and meta-analyse fMRI studies investigating emotion processing in FEP and CHRp. We focused on discrete, non-compound and culturally universal emotions (anger, fear, happiness, sadness, disgust or surprise) (30). We performed the first systematic review on this topic within the FEP population and expanded on that by Kozhuharova et al. within the CHRp population, as we discern immediate emotion recognition or discrimination from cognitively demanding tasks regardless of stimulus type. We took a critical approach and appraised the putative influence of task paradigm and participant inclusion criteria when considering the findings. Where applicable, we also appraised the brain response to the neutral condition, which is often used as a comparator in emotion processing studies. We then meta-analysed the available unthresholded statistical images of group comparisons from reviewed studies with Seed-based d Mapping (SDM), a method which has been shown to have higher sensitivity than coordinate-based meta-analyses (29). This way, we reviewed the neural correlates of emotion processing in FEP and CHRp and performed a meta-analysis of CHRp studies for the
first time. Finally, we discussed the findings in light of current hypotheses on the role of emotion processing in the development of schizophrenia.

2 Methods

2.1 Study selection for the systematic review and meta-analysis

The MEDLINE database was searched via PubMed and Ovid interfaces for published functional neuroimaging articles in either people at CHRp or with an FEP compared to a healthy control sample, during an emotion processing task, until 03 July 2019. The search terms included ‘high risk’, ‘first’, ‘episode’, ‘psychosis’, ‘function*’, ‘emotion*’ (for the full list, see Supplement). Initially, fMRI, arterial spin labelling (ASL), single photon emission computed tomography (SPECT) and positron emission tomography (PET) studies were searched for. The inclusion criteria were selected to maximise study homogeneity and consisted of: an emotion processing paradigm (i.e., the recognition or discrimination of discrete, non-compound and culturally universal emotions (30)), but not social or cognitive tasks such as theory of mind, working memory or reappraisal), task performance during a functional neuroimaging scan and a validated form of clinical assessment for inclusion of participants through a structured interview. The inclusion criteria for the FEP group comprised short duration of illness (maximum of two years) and a diagnosis of schizophrenia, schizophréniform disorder, brief psychotic disorder or affective psychosis according to the Diagnostic and Statistical Manual of Mental Disorders, version IV or 5 (DSM-IV or DSM-5) or International Classification of Disorders, version 10 (ICD-10) F20-29 or F31-33 (31,32). In case of a very short duration of illness, i.e. below the 6-month clinical period required by DSM for schizophrenia diagnosis, severe symptomatology assessed by the Positive and Negative Syndrome Scale (PANSS) (33) warranting inpatient admission was also
considered (34). For CHRp, Comprehensive Assessment of At Risk Mental States (CAARMS) or Structured Interview for Prodromal Syndromes and the Scale of Prodromal Symptoms (SIPS/SOPS) were permitted (35,36), but not self-report questionnaires (used for the assessment of schizotypy, a separate at-risk group (37)) or a purely genetic/familial risk paradigm to focus on clinical risk for psychosis. Quality of studies was assessed alongside data extraction on a pre-generated standardised data extraction form including items necessary for study replication, in line with the current recommendations for fMRI studies (38). The extracted data involved sample inclusion criteria, task paradigm and stimuli used, details of acquisition parameters including scanner type, statistical method and software used, outlier handling and consistency in result reporting. Both quality assessment and outcome measure extraction from studies was performed by two independent researchers (PBL and AK) and any disparities were clarified through discussion until a consensus was reached.

2.2 Systematic review - outcome measures

The primary outcome measure extracted from each study was the result of a comparison between brain activation in either FEP or CHRp relative to healthy controls, during the performance of an emotion processing task. Region where an effect was found and the \( p \) value reported from either a whole-brain or a region of interest (ROI) analysis were extracted. Only whole-brain images were used for the meta-analysis. Further details can be found in the Supplement regarding study heterogeneity, in terms of recorded task paradigm, stimuli type (facial/non-facial; valence), analysis contrast, between-group comparison statistical method and medication status of participants (see Supplement). For the systematic review, all reported results were recorded to avoid selection bias. Results for the emotional
condition were then grouped by brain region and are reported below when convergent in at least two articles. Subsequently, to synthesise all existing evidence on the response to the neutral condition in FEP and CHRp, all relevant results were recorded and reported regardless of convergence.

2.3 Meta-analysis

The studies identified for the systematic review were then assessed for eligibility for meta-analysis. The choice of studies included in the quantitative meta-analysis was based on the similarity of tasks used to maximise the homogeneity of methodologies, according to the current standards for neuroimaging meta-analyses (39). One study was excluded from meta-analysis on this basis, as it concerned an aversive conditioning paradigm (40). Since there is limited evidence on valence-specific regional brain activation (41,42), task paradigm involving immediate recognition of emotion was prioritised over valence homogeneity, as was done in previous neuroimaging meta-analyses of emotion in schizophrenia (8,9). Whole-brain, unthresholded group comparison images (t-maps) were used for the meta-analysis, to maximise sensitivity (43). Accordingly, ROI group comparison t-maps were excluded. To include images only normalised to the same standardised space, the more common MNI template was prioritised. Study authors were contacted directly to access raw images of the individual studies. The images requested were group comparison unthresholded t-statistic maps (t-maps) between a clinical population (FEP / CHRp) and a healthy control sample. SDM 6.21 meta-analyses raw study t-map images by transforming them into Hedge’s d effect-size maps, inferring individual subject images through multiple imputation, and meta-analysing the images through fitting a random-effects model (29). The default recommended parameters during pre-processing (a grey
matter mask and a 20 mm anisotropic FWHM kernel), and 1,000 imputations for the FWE correction were used. An uncorrected threshold of \( p = 0.005 \) was used for the initial search, to then determine significant effects at a threshold-free cluster enhancement threshold (TFCE) of \( p_{\text{TFCE}} < 0.05 \). TFCE was used, as it was validated as neither too conservative nor too liberal in neuroimaging meta-analysis performed with SDM (43). In brief, TFCE enhances sensitivity of the analysis by incorporating both peak height as well as cluster extent in result calculation, thus avoiding pre-defined arbitrary cluster extent threshold (44). Where in a single study the same participants performed more than one relevant task, the images were combined using the Combine images tool in SDM to include only original samples in the final meta-analysis. The same process was performed for studies which shared their samples (45,46). Heterogeneity statistics were extracted for peaks returned by meta-analysis directly from \( I^2 \), \( Q^2 \) and \( H^2 \) maps generated by SDM and displayed in MRIcron v1.0.20190902. These are reported in the Supplement in Table S2 as well as Figure S1 (including a whole-brain image of the \( I^2 \) statistic distribution, recommended by the SDM developers to indicate the degree of variation in result estimate attributable to study heterogeneity (47)).

3 Results

3.1 Studies included in systematic review and meta-analysis

The PRISMA diagram of the systematic review search process (48) is depicted in Figure 1 (see Supplement for the full PRISMA checklist). A total of 4,189 non-duplicate records were retrieved during the search. After initial screening, 19 potentially relevant fMRI studies and 1 PET study were identified. Further, full-text assessment of candidate eligibility was performed, followed by reference screening of the identified articles.
Three fMRI studies were excluded due to 1) inappropriate statistical analysis (i.e., no group comparison), 2) at-risk state being identified via self-report and not via a structured clinical interview, and 3) inconsistency between statistical analysis and reported results (i.e., unmet quality assessment criteria). The PET study was excluded as the emotion processing task was applied before the scan and associations between the two was not analysed. No SPECT or ASL studies directly investigating associations with emotion processing were found.

Fig 1. PRISMA diagram of the systematic review search process.

Sixteen fMRI papers were included in the systematic review, of which five assessed individuals at CHRp, nine included FEP patients, and two comprised both CHRp and FEP
samples. Of these sixteen papers, twelve were found eligible for meta-analysis. Of the twelve eligible studies, six were made available by the authors, including the two which assessed both an FEP and a CHRp sample compared to the same group of healthy controls. Table 1 provides details of the studies included in the systematic review and reasons for exclusion from meta-analysis. Table S1 provides methodological details of studies included in the meta-analysis.

Table 1. Main methodological details of studies included in the systematic review and meta-analysis (green).

| First author | Clinical group | Year | Paradigm | Processing type | Inclusion/exclusion in meta-analysis |
|--------------|----------------|------|----------|-----------------|-------------------------------------|
| Tseng et al. | FEP and CHRp   | 2016 | Facial and voice emotion recognition | Explicit | Included |
| Modinos et al. | FEP and CHRp | 2015 | IAPS valence recognition | Explicit | Included |
| Knolle et al. | FEP          | 2018 | Oddball recognition task | Implicit | Included |
| Yang et al.  | FEP          | 2018 | Facial emotion recognition | Explicit | Excluded - data unavailable |
| Berge et al. | FEP          | 2014 | Facial emotion discrimination | Explicit | Included |
| Ebisch et al. | FEP      | 2013 | Emotional human interaction video viewing | Implicit | Excluded - no comparable contrast |
| Villalta-Gil et al. | FEP | 2013 | Facial emotion discrimination | Explicit and Implicit | Excluded - data unavailable |
| Catalucci et al. | FEP    | 2011 | Emotional image viewing | Explicit | Excluded - incompatible normalisation template |
| Reske et al. | FEP         | 2009 | Facial emotion recognition | Explicit | Excluded - data unavailable |
| Das et al.   | FEP         | 2007 | Facial emotion viewing | Explicit | Excluded - data unavailable |
| Hempel et al. | FEP       | 2003 | Facial emotion discrimination | Explicit | Excluded - incompatible normalisation template |
| Quarmley et al. | CHRp | 2019 | Aversive conditioning with facial conditioned stimulus | Implicit | Excluded - no comparable task |
| van der Velde et al. | CHRp | 2015 | IAPS viewing and attendance | Explicit | Included |
| Derntl et al. | CHRp        | 2015 | Facial emotion recognition | Explicit | Excluded - data unavailable |
| Gee et al.   | CHRp         | 2012 | Facial emotion recognition and discrimination | Explicit | Excluded - data unavailable |
| Seiferth et al. | CHRp     | 2008 | Facial emotion recognition | Explicit | Included |
3.2 Systematic review – results in FEP patients

The most commonly reported finding in FEP patients was decreased activation of the amygdala in response to emotional stimuli, in six of eleven studies (45,46,49–52). Attenuated responses were also common in the anterior cingulate (ACC) (51–54), medial frontal / prefrontal (50,51,53,55–57), and lingual cortex (46,49,50,52), with four studies reporting findings in each of these regions. Attenuated responses were also reported in the thalamus (49–51), hippocampus (50,52,53), inferior frontal gyrus (55,56), left postcentral gyrus (50,55), frontal operculum (50,52), angular gyrus (55,57) and cerebellum (50,52).

These studies used a diversity of task paradigms, stimuli types, analysis contrast and stimuli (uniformity of task paradigms and sample characteristics can be found in the Supplement). No lateralisation of results was evident. Overall, attenuated responses to emotional stimuli in FEP subjects relative to controls were more common than increases in activation. The most consistent findings of activation increases were in the posterior cingulate cortex (PCC) (53,55) and precuneus (55,56). Two studies reported no significant group differences with facial emotion tasks (34,46).

Only two studies reported results for a neutral condition. Modinos et al. compared a neutral condition to a baseline condition (fixation cross) and found greater activation in the left inferior frontal gyrus/anterior insula, as well as in bilateral amygdala (45) in FEP relative to controls. Reske et al. reported attenuated activation of the left orbitofrontal region to the neutral condition in FEP subjects, but greater activation to neutral than to sad or happy faces in the hippocampus (55).
3.3 Meta-analysis – results in FEP patients

Five t-maps from four studies were available for meta-analysis (Table S1) (45,46,50,52). Tseng et al. and Modinos et al. largely shared their participants, hence the t-maps from their studies were combined using the ‘Combine images’ tool in SDM, and the degrees of freedom were calculated for the average sample size (as in (58)). Therefore, the final meta-analysis pooled data from a total of 48 patients and 73 healthy controls.

The meta-analysis of t-maps of brain activation to emotional versus neutral stimuli in FEP patients compared to healthy controls indicated that patients showed significantly decreased activation in a large widespread cluster ($Z = -(5.284-1.631)$, $k = 63,496$, $p_{TFCE} < 0.05$). The cluster comprises peaks in several brain regions classically involved in emotion processing, such as the left insula ($x = -38$, $y = 2$, $z = -10$, $Z = -4.655$, $p_{TFCE} = 0.000999987$), left amygdala ($x = -26$, $y = -2$, $z = -14$, $Z = -4.027$, $p_{TFCE} = 0.000999987$), right hippocampus ($x = 28$, $y = -38$, $z = 4$, $Z = -3.950$, $p_{TFCE} = 0.000999987$), left hippocampus ($x = -18$, $y = -10$, $z = -12$, $Z = -4.093$, $p_{TFCE} = 0.000999987$), anterior cingulate ($x = 0$, $y = 40$, $z = 4$, $Z = -3.611$, $p_{TFCE} = 0.000999987$), and occipital cortex ($x = -42$, $y = -72$, $z = 14$, $Z = -3.565$, $p_{TFCE} = 0.000999987$) (Fig. 2). See Supplement for full cluster information (Table S2) as well as heterogeneity analyses (Table S3, Figure S1).
3.4 Systematic review – results in people at CHRp

Two articles of the seven suitable for the review reported greater activation of the PCC in CHRp than in healthy controls (59,60). Four studies reported differential responses in the inferior frontal gyrus/ventrolateral prefrontal cortex: two found less activation in the CHRp group (45,61), another found less activation, but only after combining the CHRp and schizophrenia groups (40), and one found a greater response (59). No other results were convergent between studies. Two studies found no significant group differences (40,46).

Three studies assessed the fMRI response to neutral stimuli. Seiferth et al. (61) compared the activation parameters from regions that showed an interaction between the facial emotion recognition task and group (CHRp and HC), i.e., from inferior frontal gyri for happy and neutral; left superior frontal gyrus for angry, neutral and fearful; and left thalamus for sad and neutral stimuli. They found greater activations to neutral stimuli than the respective emotional conditions in the CHRp group compared to
healthy volunteers in all these regions. Comparing the neutral condition to a fixation cross baseline, Modinos et al. found greater activations in left inferior frontal gyrus/anterior insula in the CHRp group compared to controls. Finally, van der Velde et al. compared the neutral condition to a blank screen baseline and found less activation in left temporal pole and bilateral PCC in CHRp.

3.5 Meta-analysis – results in people at CHRp

For the CHRp meta-analysis, six t-maps from four studies were collected (Table S1) (45,46,60,61). The maps from the studies by Tseng et al. and Modinos et al. were combined as for the FEP meta-analysis. The same process was performed for the two maps provided from van der Velde et al. (60) from group comparisons of activation to different attentional dimensions (‘View’ and ‘Attend’) of the same emotion > neutral comparison on the same sample, relevant to the scope of this meta-analysis (Table S1). Therefore, the final meta-analysis pooled data from a total of 45 CHR individuals and 48 healthy controls.

The meta-analysis of t-maps of brain activation to emotional versus neutral stimuli in individuals at CHRp compared to healthy controls returned one small cluster of decreased activation to emotional stimuli in the left inferior temporal gyrus at an uncorrected level (x = -48, y = -50, z = -14, Z = -2.719, k = 3, puncorr=0.003) (Fig. 3). This result did not survive p<sub>TFCE</sub> < 0.05 correction. Since this meta-analysis returned no corrected effects, a heterogeneity analysis was not performed.
Fig 3. Results of the meta-analysis of group-comparison t-maps in the CHRp population compared to healthy controls. Results shown on a standard template at $p_{\text{uncorr}} < 0.005$ for display purposes.

4 Discussion

The main finding of our systematic review with meta-analysis is that patients with an FEP display attenuated neural responses to emotional stimuli relative to neutral stimuli, compared to that of healthy controls, in brain regions implicated in emotion processing (referred to as hypoactivation below), such as the amygdala and ACC. In individuals at CHRp, relative convergence between studies involved greater neural responses in the PCC relative to healthy controls. However, this was only reported in two of seven studies, and was not evident in meta-analysis.

The finding of hypoactivation of the amygdala in FEP patients is consistent with previous work in chronic schizophrenia (7–10) and supports previous suggestions that altered amygdala response to emotion is stable across disease stage (62). However, a previous coordinate-based meta-analysis found no difference between FEP patients and healthy controls in amygdala recruitment during emotion processing, although within-group analyses suggested a more extensively recruited network in healthy
controls than in FEP patients (28). This inconsistency may stem from a more sensitive methodology being used in the present study through an image-based meta-analysis, which is found to be more sensitive to coordinate-based methods (29). In the healthy brain, amygdala recruitment is a robust finding in neuroimaging studies of emotion (41,42,63–65). It has been proposed that the role of the amygdala relates to determining the emotional salience of a stimulus, independently from its affective appraisal (42,62,66,67). Hence, amygdala hypoactivation in psychosis has been hypothesised to result from either poor recruitment in the processing of emotional stimuli (9); increased tonic responsivity to non-salient, neutral stimuli (7,8,10,68); or both (62). On an individual level, the result of an fMRI contrast depends on both the response to the experimental condition and that to the control condition (69). Accordingly, a greater relative response to the control condition or a greater relative decrease in activation to the experimental condition could result in a hypoactivation in this region at the individual level. Adding a group variable results in further comparison between individual-level contrasts, complicating the understanding of what the group-level result may reflect (69). This issue can be addressed by directly assessing activation to the neutral condition (e.g., neutral > fixation cross baseline contrast). In chronic schizophrenia patients, a recent meta-analysis of brain activation to neutral stimuli compared to a baseline condition found increased amygdala responsivity compared to healthy controls (68). In our systematic review, only two of eleven eligible studies assessed a neutral > baseline contrast in FEP patients and found inconsistent results which did not involve the amygdala. As such, this limited number of studies precludes addressing the hypothesis of whether amygdala hypoactivation, measurable at a first psychosis episode, is driven by an underlying hyperresponse to the neutral comparator condition. This is of special interest, as evidence from post-mortem and preclinical research suggest increased amygdala reactivity in
schizophrenia may be due to either increased activity of a local feedforward excitation circuit (70) or decreased regulation from the prefrontal cortex (62), which could be concomitant to decreased GABA-synthesising enzyme GAD67 function in the hippocampus (70). Indeed, amygdala hyperresponsivity has been shown in a neurodevelopmental model of psychosis, in which a functional loss of parvalbumin interneurons in the hippocampus is associated with increased dopaminergic activity in the striatum (71–73). On the other hand, behavioural meta-analyses showed a more consistent impairment in emotional but not neutral facial expression recognition in FEP and schizophrenia (13,14). Together with the current understanding of the role of the amygdala in salience identification, these findings would suggest lower amygdala recruitment during the viewing of emotional stimuli in psychosis. Moreover, decreased amygdala activation to emotional stimuli and increased activation to neutral stimuli are not mutually exclusive (62). If both were present, an emotion > neutral contrast would show relatively lower activation to emotional stimuli, just as it would if only response to emotional stimuli was lower but response to neutral was unchanged, or if response to neutral stimuli was heightened but that to emotional stimuli was unchanged (69). Furthermore, either of the three response patterns could be present in different individuals and collectively showing as amygdala hypoactivation, as it was shown that paranoid but not nonparanoid schizophrenia patients show increased baseline amygdala perfusion (74). Future studies directly assessing activation to the neutral condition in FEP patients and healthy controls are needed to better characterise the role of the amygdala in psychosis expression.

Hypoactivation of the ACC to emotional stimuli in FEP patients was also a consistent finding in both our systematic review and the meta-analysis, converging with previous
meta-analytic findings in schizophrenia (8,10). Similarly as for the amygdala, the inconsistency with a previous meta-analysis may derive from the different methodological approaches applied (28,29). The ACC has been implicated in facial emotion stimuli processing (41,42,63,64), the most predominantly used stimulus type across studies. The ACC receives strong projections from the amygdala (70), supporting the involvement of these two regions in emotion processing. An automated meta-analysis of fMRI studies in healthy controls found that, in contrast to the amygdala, the ACC was activated across paradigms involving emotion, memory and pain stimuli and its recruitment was not selective for emotion in a reverse inference analysis (75). Moreover, ACC lesions are associated with various affective disorders including anxiety and apathy (67), and ACC activation has been associated with internal state monitoring (76). Decreased (77) or absent (78) ACC response during pain processing in patients with schizophrenia compared to healthy controls has also been reported, supporting the view that its role spans beyond emotion processing. Since ACC subdivisions were associated with various functions (e.g., rostral ACC in emotional paradigms more than its dorsal subdivision), ACC subdivision volume reductions in schizophrenia may reflect functional segregation (79). However, a meta-analysis of structural neuroimaging studies in FEP reported no significant differences in ACC volume relative to healthy controls (80), suggesting the potential involvement of more subtle, functional changes such as functional connectivity abnormalities of this region (81,82). Taken together, the evidence above suggests that while abnormal amygdala recruitment in psychosis may be specifically linked to emotion processing abnormalities, ACC hypoactivation may be reflective of a more generalised affective abnormality, potentially involving interoceptive processes.
Several other findings from the studies on FEP patients in regions associated with emotion processing are of note. Decreased response to emotion in the lingual gyrus (46,49,50,52) and the medial frontal gyrus/medial prefrontal cortex (50,51,53,55–57) in FEP patients was reported by several articles (except (55)). These results were confirmed by meta-analysis. As both prefrontal and occipital regions have been implicated in emotion processing in healthy volunteers (63,64,83), our findings suggest altered involvement of such regions in emotion processing in FEP groups. Finally, the insula is also commonly associated with emotion processing (41,63,64,83). In FEP, decreases in this region/frontal operculum were reported in three articles (50,52,56), and increases by another two (55,57). The meta-analysis could only include one of those studies and returned significant bilateral hypoactivation in this region. Overall, the results suggest prefrontal, occipital and insula involvement in the pathophysiology of emotion alterations in FEP patients.

In people at CHRp, the only convergent finding was of increased PCC response to emotion, reported by two reviewed studies including facial stimuli (59,60). This was also identified by a recent review on social cognition deficits in CHRp (27), suggesting this area may be overly responsive to socially-relevant emotional cues. Interestingly, two studies found increased activation in the inferior frontal gyrus to the neutral condition in the CHRp group (45,61). Hyperresponsivity to the neutral condition was also reported by another publication, but in the left temporal pole and bilateral PCC (60). Since all three studies used different methods for analysing the neutral condition (comparison of activation parameters to the neutral condition (61), neutral>fixation cross comparison (45) and neutral>blank screen comparison (60)), more evidence is needed to characterise neural response to neutral stimuli in CHRp. Furthermore, none
of these findings were supported by meta-analysis, and we identified no other convergent results between CHRp studies.

The absence of effects surviving p_{TFCE} < 0.05 correction from our meta-analysis on CHRp studies could be due to more task paradigm-specific responses in this group, or heterogeneity of the samples included. About 26% of people at CHRp transition to frank psychosis within two years of initial assessment (84), therefore samples comprise individuals with a variety of outcomes. In addition, CHRp status is not a formal diagnosis but a collection of three potentially concurrent at-risk criteria spanning a wide symptomatic continuum and/or genetic factors (35). Of the studies reviewed, only one (85) reported the CHRp sub-type composition of their sample. Future studies reporting this will expand our understanding of emotional responsivity according to CHRp subtype and clarify whether this is a potential source of heterogeneity in imaging findings. Finally, people at CHRp often have a formal diagnosis of another Axis I disorder, such as anxiety or depression (86,87), and the potential concomitant use of antidepressant or anxiolytic medication may have an effect on the imaging data in response to emotion stimuli (88,89). More consistent task paradigm, stimuli and CHRp assessment criteria across studies would aid understanding of the nature of emotion-related neuroimaging abnormalities in the CHRp state.

Overall, the effects of antipsychotic medication on the results remain unclear. Antipsychotics have been shown to have no effects on emotion perception in chronic patients (90). In the present review, one paper (50) re-examined the antipsychotic-naïve FEP group upon clinical improvement with antipsychotic treatment after 3-6 weeks and found no differences in brain activation to emotion of FEP patients to HCs.
However, a separate study found predominantly stable fMRI activation abnormalities during sad and happy mood induction in medicated FEP patients (54). Moreover, four of the studies reviewed (46,51,57,91) regressed medication status onto fMRI signal and found no effect. Hence, although current evidence of antipsychotic medication effects on the neural basis of emotion processing in FEP remains to be determined, the evidence suggests that it is likely to have negligible effects on the fMRI results reviewed. This may indicate a need for more targeted treatments for emotion processing deficits in these groups to improve functional and clinical outcomes.

There are some limitations to the current work. Firstly, the number of t-maps made available for the meta-analyses was small. However, the SDM validation process indicated that three raw images were the minimum to reach 100% sensitivity on the analysis, exceeding that of coordinate-based methods (43). Furthermore, we assessed the heterogeneity of the results obtained for the FEP meta-analysis and found no variation attributable to study heterogeneity in the peaks reported in Results. Hence, despite generalisability may be limited, the present results can be considered reliable. Moreover, as the first such meta-analysis of its kind, future greater availability of data is warranted. The meta-analytic results were also supported by a systematic review, where results from all studies identified were synthesised, thus avoiding selection bias e.g., due to inclusion of results within pre-specified brain regions only. Secondly, some task and sample variability in the studies included was present. More specifically, auditory stimuli were used by two studies (40,46), and the age range of CHRp participants was wider than that of FEP participants, with two studies including adolescents (40,85). However, this approach may be more ecologically valid, and overall through our stringent clinical inclusion criteria we ensured that the analysed
samples were as homogenous as possible to increase the clinical validity of the review. Due to two out of three datasets analysed including antipsychotic-naïve patients with an FEP, we could not perform a meta-regression assessing antipsychotic medication status on the results of the meta-analysis. However, the systematic review indicated that most studies found no effects of antipsychotic medication on the results, and the samples analysed were mostly antipsychotic-naïve or free. Regrettably, we could not assess the putative influence of task design on meta-analysis results (9) due to the limited number of studies employing an implicit task paradigm (Table 1). Finally, because two of the studies that included both FEP and CHRp participants had used the same control group, we could not reliably perform a combined meta-analysis of FEP + CHRp t-maps. In the context of a combined meta-analysis, this shared control group would be treated as two independent groups, which could lead to spurious results as in fact these were the same individuals. Nevertheless, for illustrative purposes we include such analysis in the Supplement (Supplementary Methods, Supplementary Results and Figure S2).

In conclusion, while widespread hypoactivations to emotional compared to neutral stimuli were reported and corroborated by meta-analysis for FEP studies, the inconsistency of neuroimaging results in CHRp studies was matched by no significant effects in the corresponding meta-analysis. Three questions arise from this work to be addressed in future studies. Firstly, the nature of hypoactivations in FEP remains to be clarified, especially in the context of the neutral comparison condition. Secondly, more consistency in CHRp participant inclusion and imaging paradigms would help elucidate whether abnormal fMRI response to emotion is present and detectable in this group. Finally, greater raw data availability will help expand the present findings and this can
be facilitated through data upload on open source depositories. These efforts will help elucidate the role of emotion abnormalities in the pathophysiology of psychosis risk and onset and inform the development of much-needed treatments for psychosis symptomatology beyond positive symptoms.

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7 Declaration of interest

The authors declare no conflict of interest.
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SUPPLEMENTARY MATERIAL

Neural correlates of emotional processing in psychosis risk and onset – a systematic review and meta-analysis of fMRI studies

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| First author | Year | Clinical group | Sample size | % Males | Mean age | % AP | Scanner brand | Magnet strength | Task(s) | Contrast |
|--------------|------|----------------|-------------|---------|----------|------|---------------|----------------|---------|----------|
| Knolle et al. | 2018 | FEP            | 13          | 34      | 54%      | 53%  | Siemens       | 3T             | Oddball recognition task | Negative emotional oddball > neutral oddball |
| Tseng et al.  | 2016 | FEP            | 17          | 20      | 72%      | 40%  | GE            | 1.5T           | Facial and voice emotion recognition | Emotion > neutral (facial) and High > low prosody (voice) |
| Modinos et al.| 2015 | FEP            | 15          | 20      | 73%      | 45%  | GE            | 1.5T           | IAPS valence rating | Emotion > neutral |
| Berge et al.  | 2014 | FEP            | 18          | 19      | 56%      | 47%  | Philips       | 1.5T           | Facial emotion discrimination | Emotion > neutral |
| Tseng et al.  | 2016 | CHRp           | 17          | 20      | 56%      | 40%  | GE            | 1.5T           | Facial and voice emotion recognition | Emotion > neutral (facial) and High > low prosody (voice) |
| Modinos et al.| 2015 | CHRp           | 18          | 20      | 56%      | 45%  | GE            | 1.5T           | IAPS valence rating | Emotion > neutral |
| van der Velde et al. | 2015 | CHRp           | 15          | 16      | 53%      | 55%  | Philips       | 3T             | IAPS viewing and attendance | View negative > view neutral and Attend negative > Attend neutral |
| Seifert et al. | 2008 | CHRp           | 12          | 12      | 83%      | 83%  | Siemens       | 1.5T           | Facial emotion recognition | Emotion > neutral |

%AP, percentage of participants on antipsychotic medication. FEP, first episode of psychosis. CHRp, clinical high-risk for psychosis.

Demographic details of the FEP and CHRp samples are reported separately for studies including both groups.
Uniformity of studies included – FEP

Nine studies used facial emotion expressions as stimuli (1–9). One study additionally used pictures and words from the International Affective Picture System (IAPS) set (1), one used outdoor scenes (9) and another one applied a second task with emotional prosody recognition (2). Three studies contained an emotion recognition (labelling) task, and all others used a different and unique paradigm such as emotion matching or discrimination (Table 1). Of the remaining two studies, one employed observation of scenes of touch by an inanimate object or another person, the latter with different valence, without the viewing of involved persons’ face (10). The remaining study utilised highly disgusting images, as well as highly pleasant stimuli such as small animals, food and wounds (11).

Overall, 10 studies included a non-emotional, neutral condition in their experiment (1–10) and 6 used it as comparison for the emotional condition (1–3,5,7,9). More specifically, between-group contrasts involved (1) several combined emotional valences > neutral (1,2,8), (2) a conjunction analysis of several emotional valences > neutral (10), (3) a single emotional valence > neutral (5,8,9,11), (4) a group*task ANOVA (3,4), (5) a single emotional valence recognition (implicit/explicit) > gender discrimination (7), or (6) all emotional valences across the task performed (6).

Four studies included antipsychotic-naïve patients only (4,8,9,11). One of these re-scanned patients at post-treatment follow-up (8). Three studies included only antipsychotic-medicated patients into their study (3,6,7). The remaining 4 studies
included both medication-naïve patients and those taking antipsychotic medication (1,2,5,10).

**Uniformity of studies included – CHRp**

The most common paradigm was facial emotion recognition (2,12–14), whereby the participant is asked to label the emotional expression being presented. Three of them also used a neutral condition for comparison (2,12,14). Tseng et al. additionally used a task with prosodic emotional stimuli of high or low intensity (2). One other study used neutral facial stimuli, however the paradigm involved fear conditioning with a scream (15). Two studies used the International Affective Picture System (IAPS, (16)); one asked participants to rate their subjective emotional arousal to negative or positive stimuli of high or low arousal (1), while the other included conditions of viewing neutral images and/or reappraisal of negative ones (17).

Between-group contrasts involved (1) several combined emotional valences > neutral (1,2), (2) a conjunction analysis of several emotional > neutral (12), (3) a single emotional valence > neutral (15,17), (4) a group*task ANOVA (14), or (5) emotional valence labelling > gender labelling/emotion matching (13).

Participants included in the above studies were predominantly free of any psychoactive medication, although only one study included antipsychotic-free individuals (1). Two studies included participants on antipsychotic medication (2,15), three studies additionally allowed antidepressant medication (12–14) and the remaining study included participants also on psychostimulant medication (17).
Search terms for the Ovid MEDLINE database. The same search terms were used for the Pubmed interface but restricted to title and abstract. No other restrictions were placed.

("clinical high" OR "ultra high" OR "at risk" OR "risk" OR transition* OR "high risk" OR prodrom* OR "attenuated" OR "ultra-high-risk" OR "clinical-high-risk" OR "CHR" OR "UHR" OR "first" OR "episode" OR "spectrum" OR "early" OR "onset" OR "first-onset") AND ("psychosis" OR psychot* OR schizophren* OR "mental state") AND ("limbic" OR emotion* OR "mPFC" OR "medial prefrontal cortex" OR "medial PFC" OR amygdal* OR "BLA" OR hippocamp* OR "ACC" OR "ACG" OR "anterior cingulate" OR "orbitofrontal" OR "insula") AND ("limbic" OR emotion* OR "mPFC" OR "medial prefrontal cortex" OR "medial PFC" OR amygdal* OR "BLA" OR hippocamp* OR "ACC" OR "ACG" OR "anterior cingulate" OR "orbitofrontal" OR "insula") AND ("PET" OR "positron emission tomography" OR "SPECT" OR "single photon emission computed tomography" OR "MRI" OR "fMRI" OR "functional magnetic resonance imaging" OR "PET/MR" OR "PET/MRI" OR "voxel" OR "BOLD" OR "blood-oxygen-level-dependent imaging" OR "perfusion" OR "arterial spin" OR "ASL" OR "magnetic resonance spectroscopy" OR "MRS" OR function*)
## The PRISMA checklist for reporting the systematic review and meta-analysis

| Section/topic       | #   | Checklist Item                                                                 | Reported on page # |
|--------------------|-----|-------------------------------------------------------------------------------|--------------------|
| **TITLE**          |     |                                                                               |                    |
| Title              | 1   | Identify the report as a systematic review, meta-analysis, or both.            | 1                  |
| **ABSTRACT**       |     |                                                                               |                    |
| Structured summary | 2   | Provide a structured summary including, as applicable: background; objectives; data sources; study eligibility criteria, participants, and interventions; study appraisal and synthesis methods; results; limitations; conclusions and implications of key findings; systematic review registration number. | 2                  |
| **INTRODUCTION**   |     |                                                                               |                    |
| Rationale          | 3   | Describe the rationale for the review in the context of what is already known. | 3-5                |
| Objectives         | 4   | Provide an explicit statement of questions being addressed with reference to participants, interventions, comparisons, outcomes, and study design (PICOS). | 5-6                |
| **METHODS**        |     |                                                                               |                    |
| Protocol and registration | 5 | Indicate if a review protocol exists, if and where it can be accessed (e.g., Web address), and, if available, provide registration information including registration number. | NA*                |
| Eligibility criteria | 6 | Specify study characteristics (e.g., PICOS, length of follow-up) and report characteristics (e.g., years considered, language, publication status) used as criteria for eligibility, giving rationale. | 5-6                |
| Information sources | 7 | Describe all information sources (e.g., databases with dates of coverage, contact with study authors to identify additional studies) in the search and date last searched. | 5                  |
| Search             | 8   | Present full electronic search strategy for at least one database, including any limits used, such that it could be repeated. | Supplement         |
| Study selection    | 9   | State the process for selecting studies (i.e., screening, eligibility, included in systematic review, and, if applicable, included in the meta-analysis). | 6-7                |
| Data collection process | 10 | Describe method of data extraction from reports (e.g., piloted forms, independently, in duplicate) and any processes for obtaining and confirming data from investigators. | 6                  |
| Data items         | 11  | List and define all variables for which data were sought (e.g., PICOS, funding sources) and any assumptions and simplifications made. | 6                  |
| Risk of bias in individual studies | 12 | Describe methods used for assessing risk of bias of individual studies (including specification of whether this was done at the study or outcome level), and how this information is to be used in any data synthesis. | 6                  |
| Summary measures   | 13  | State the principal summary measures (e.g., risk ratio, difference in means). | NA**               |
| Synthesis of results | 14 | Describe the methods of handling data and combining results of studies, if done, including measures of consistency (e.g., I²) for each meta-analysis. | 7-8                |
| Risk of bias across studies | 15 | Specify any assessment of risk of bias that may affect the cumulative evidence (e.g., publication bias, selective reporting within studies). | NA***              |
### Additional analyses

16 Describe methods of additional analyses (e.g., sensitivity or subgroup analyses, meta-regression), if done, indicating which were pre-specified.

**RESULTS**

| Study selection | Give numbers of studies screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally with a flow diagram. | 8-9 and Figure 1 |
| Study characteristics | For each study, present characteristics for which data were extracted (e.g., study size, PICOS, follow-up period) and provide the citations. | 6-8 |
| Risk of bias within studies | Present data on risk of bias of each study and, if available, any outcome level assessment (see item 12). | 8 |
| Results of individual studies | For all outcomes considered (benefits or harms), present, for each study: (a) simple summary data for each intervention group (b) effect estimates and confidence intervals, ideally with a forest plot. | NA** |
| Synthesis of results | Present results of each meta-analysis done, including confidence intervals and measures of consistency. | 10-11 and 12 |
| Risk of bias across studies | Present results of any assessment of risk of bias across studies (see Item 15). | NA*** |
| Additional analysis | Give results of additional analyses, if done (e.g., sensitivity or subgroup analyses, meta-regression [see Item 16]). | NA**** |

**DISCUSSION**

| Summary of evidence | Summarize the main findings including the strength of evidence for each main outcome; consider their relevance to key groups (e.g., healthcare providers, users, and policy makers). | 13-17 |
| Limitations | Discuss limitations at study and outcome level (e.g., risk of bias), and at review-level (e.g., incomplete retrieval of identified research, reporting bias). | 17-18 |
| Conclusions | Provide a general interpretation of the results in the context of other evidence, and implications for future research. | 18-19 |

**FUNDING**

| Funding | Describe sources of funding for the systematic review and other support (e.g., supply of data); role of funders for the systematic review. | 19 |

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* The protocol for this systematic review was not pre-registered.
** Original group comparison t-maps were used instead of reported results.
*** Due to the low numbers of studies included in each meta-analysis, risk of bias across studies was not performed.
**** No additional analyses were performed.

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*From: Moher D, Liberati A, Tetzlaff J, Altman DG, The PRISMA Group (2009). Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. PLoS Med 6(7): e1000097. doi:10.1371/journal.pmed1000097.*

*For more information, visit: [www.prisma-statement.org](http://www.prisma-statement.org).*
Table S2. Local peak details of the meta-analysis of brain activation to emotion in FEP patients versus healthy controls. Results are shown for the peak with the largest Z value for defined brain regions, pTFCE < 0.05.

| Local peaks: | MNI coordinate | SDM-Z | P     | Description                                      |
|--------------|----------------|-------|-------|-------------------------------------------------|
| -6,-76,6     | -5.284          | 0.000999987 | Left inferior network, inferior longitudinal fasciculus |
| 6,-72,2      | -5.243          | 0.000999987 | Right lingual gyrus, BA 17                         |
| -4,-84,8     | -5.073          | 0.000999987 | Left calcarine fissure / surrounding cortex, BA 18 |
| 2,-72,20     | -4.924          | 0.000999987 | Left cuneus cortex, BA 18                         |
| 10,-76,2     | -4.857          | 0.000999987 | Right inferior network, inferior longitudinal fasciculus |
| 10,-70,16    | -4.711          | 0.000999987 | (undefined)                                      |
| 28,2,-12     | -4.669          | 0.000999987 | (undefined), BA 34                               |
| -38,2,-10    | -4.655          | 0.000999987 | Left insula, BA 48                               |
| -8,-52,-6    | -4.62           | 0.000999987 | Left cerebellum, hemispheric lobule IV / V, BA 18 |
| 22,-58,2     | -4.604          | 0.000999987 | Corpus callosum                                  |
| 26,-62,6     | -4.521          | 0.000999987 | Right calcarine fissure / surrounding cortex, BA 19 |
| 66,-24,-6    | -4.434          | 0.000999987 | Right middle temporal gyrus, BA 21                |
| 4,-82,16     | -4.364          | 0.000999987 | Right cuneus cortex, BA 18                       |
| 6,-44,-6     | -4.364          | 0.000999987 | Cerebellum, vermic lobule IV / V                  |
| 54,6,-2      | -4.286          | 0.000999987 | Right temporal pole, superior temporal gyrus, BA 38 |
| 2,2,40       | -4.205          | 0.000999987 | Right median cingulate / paracingulate gyri, BA 24 |
| -12,-66,-6   | -4.201          | 0.000999987 | Left lingual gyrus, BA 18                        |
| 62,-38,2     | -4.18           | 0.000999987 | Right middle temporal gyrus, BA 22                |
| 54,0,-12     | -4.151          | 0.000999987 | Right superior temporal gyrus, BA 21              |
| -18,-28,-6   | -4.13           | 0.000999987 | Left optic radiations                            |
| -48,-30,8    | -4.129          | 0.000999987 | Left superior temporal gyrus, BA 48               |
| 16,-44,-12   | -4.112          | 0.000999987 | Right cerebellum, hemispheric lobule IV / V, BA 30 |
| -18,-10,-12  | -4.093          | 0.000999987 | Left hippocampus                                  |
| -30,6,-16    | -4.056          | 0.000999987 | (undefined), BA 38                               |
| 2,52,-10     | -4.028          | 0.000999987 | Right superior frontal gyrus, medial orbital, BA 11 |
| -26,-2,-14   | -4.027          | 0.000999987 | Left amygdala, BA 34                             |
| 14,-12,-12   | -4.017          | 0.000999987 | Right cortico-spinal projections                  |
| 54,-12,8     | -4.007          | 0.000999987 | Right heschi gyrus, BA 48                        |
| 56,-14,-8    | -3.99           | 0.000999987 | Right superior temporal gyrus, BA 22              |
| 10,-10,-12   | -3.985          | 0.000999987 | Right pons                                       |
| 28,-38,4     | -3.95           | 0.000999987 | Right hippocampus, BA 37                         |
| 12,-60,30    | -3.933          | 0.000999987 | Right median network, cingulum                    |
| 24,-34,4     | -3.93           | 0.000999987 | Right hippocampus, BA 27                         |
| 30,24,-6     | -3.907          | 0.000999987 | Right inferior frontal gyrus, orbital part, BA 47 |
| Z-Coordinate | T-Value | p-Value   | Region                                           |
|-------------|--------|----------|-------------------------------------------------|
| -14,-48,-4  | 3.901 | 0.000999987 | Left lingual gyrus, BA 30                        |
| 54,-52,-6    | 3.887 | 0.000999987 | Right inferior temporal gyrus, BA 21            |
| 2,-72,28     | 3.869 | 0.000999987 | Left cuneus cortex                              |
| 38,-18,12    | 3.861 | 0.000999987 | Right insula, BA 48                             |
| 24,-16,-14   | 3.83  | 0.000999987 | Right hippocampus                               |
| -12,-16,36   | 3.822 | 0.000999987 | Left median network, cingulum                   |
| 52,-4,0      | 3.812 | 0.000999987 | Right superior temporal gyrus, BA 48            |
| -22,8,-8     | 3.802 | 0.000999987 | Left lenticular nucleus, putamen, BA 48         |
| -34,18,-12   | 3.801 | 0.000999987 | Left insula, BA 47                              |
| -14,-64,14   | 3.801 | 0.000999987 | Left calcarine fissure / surrounding cortex, BA 17 |
| -50,-50,10   | 3.788 | 0.000999987 | Left middle temporal gyrus, BA 21               |
| 12,-34,0     | 3.774 | 0.000999987 | (undefined), BA 27                             |
| -24,-36,-2   | 3.76  | 0.000999987 | Left hippocampus, BA 37                        |
| -22,12,-12   | 3.756 | 0.000999987 | Left inferior network, uncinate fasciculus     |
| 34,18,-14    | 3.74  | 0.000999987 | Right insula, BA 47                             |
| 8,-18,2      | 3.737 | 0.000999987 | Right anterior thalamic projections             |
| -10,-12,42   | 3.723 | 0.000999987 | Left median cingulate / paracingulate gyri     |
| 12,-30,-6    | 3.707 | 0.000999987 | Right lingual gyrus, BA 27                     |
| 6,-66,30     | 3.695 | 0.000999987 | Right precuneus                                 |
| 0,-10,42     | 3.674 | 0.000999987 | Left median cingulate / paracingulate gyri, BA 23 |
| -42,-20,6    | 3.635 | 0.000999987 | Left heschl gyrus, BA 48                       |
| 48,20,-6     | 3.633 | 0.000999987 | Right inferior frontal gyrus, orbital part      |
| -18,-36,0    | 3.624 | 0.000999987 | Left hippocampus, BA 27                        |
| 6,-50,22     | 3.614 | 0.000999987 | Right precuneus, BA 23                         |
| 8,-48,34     | 3.614 | 0.000999987 | Right median cingulate / paracingulate gyri, BA 23 |
| 0,40,4       | 3.611 | 0.000999987 | Left anterior cingulate / paracingulate gyri    |
| -50,0,2      | 3.608 | 0.000999987 | Left rolandic operculum, BA 48                  |
| 44,8,40      | 3.604 | 0.000999987 | Right middle frontal gyrus, BA 6                |
| 46,50,22     | 3.594 | 0.000999987 | Right angular gyrus, BA 41                      |
| -42,-72,14   | 3.565 | 0.000999987 | Left middle occipital gyrus, BA 37             |
| 46,4,-10     | 3.533 | 0.000999987 | Right insula                                    |
| -12,-18,0    | 3.495 | 0.000999987 | Left anterior thalamic projections              |
| 6,-26,6      | 3.463 | 0.000999987 | Right thalamus                                  |
| 44,-40,4     | 3.446 | 0.000999987 | Right arcuate network, posterior segment        |
| 32,-18,-16   | 3.444 | 0.000999987 | Right hippocampus, BA 20                        |
| 24,12,-6     | 3.438 | 0.000999987 | Right lenticular nucleus, putamen, BA 48        |
| 20,-56,14    | 3.432 | 0.000999987 | Right precuneus, BA 17                         |
| 54,-60,-8    | 3.404 | 0.000999987 | Right inferior temporal gyrus, BA 37            |
| 30,-14,-4    | 3.366 | 0.000999987 | Right striatum                                  |
| -8,54,-8     | 3.356 | 0.000999987 | Left superior frontal gyrus, medial orbital, BA 11 |
| 46,-8,46     | 3.354 | 0.000999987 | Right precentral gyrus, BA 6                    |
| 34,10,4      | 3.35  | 0.000999987 | (undefined), BA 48                             |
| 40,16,-14    | 3.348 | 0.000999987 | Right insula, BA 38                             |
| -58,42,14    | 3.347 | 0.000999987 | Left superior temporal gyrus, BA 42             |
| X-Mean | Y-Mean | Z-Mean | p    | Anatomical Location                                      |
|--------|--------|--------|------|--------------------------------------------------------|
| 34.88  | -2     | -3.338 | 0.000999987 | Right inferior occipital gyrus, BA 19               |
| 34.10  | 26     | -3.322 | 0.000999987 | Right superior longitudinal fasciculus III         |
| -58.24 | 6      | -3.286 | 0.000999987 | Left superior temporal gyrus, BA 22                |
| -36.26 | -6     | -3.279 | 0.000999987 | Left inferior frontal gyrus, orbital part, BA 47   |
| -22.62 | 16     | -3.264 | 0.000999987 | (undefined), BA 17                               |
| -52.4  | -6     | -3.261 | 0.000999987 | Left superior temporal gyrus, BA 38                |
| 62.10  | 20     | -3.239 | 0.000999987 | Right postcentral gyrus, BA 43                     |
| 42.38  | 24     | -3.225 | 0.000999987 | Right middle frontal gyrus, BA 45                  |
| 56.2   | -10    | -3.224 | 0.000999987 | Right rolandic operculum, BA 48                    |
| 46.40  | 10     | -3.22  | 0.000999987 | Right superior temporal gyrus, BA 41               |
| -8.68  | 22     | -3.217 | 0.000999987 | Left calcarine fissure / surrounding cortex, BA 23 |
| 10.50  | 8      | -3.207 | 0.000999987 | Right precuneus, BA 29                            |
| -12.50 | 6      | -3.203 | 0.000999987 | Left calcarine fissure / surrounding cortex, BA 30 |
| 10.46  | 2      | -3.184 | 0.000999987 | Right anterior cingulate / paracingulate gyri, BA 10|
| -30.90 | 0      | -3.124 | 0.000999987 | Left middle occipital gyrus, BA 18                 |
| 14.46  | 36     | -3.108 | 0.000999987 | Right median cingulate / paracingulate gyri         |
| 16.10  | 24     | -3.098 | 0.000999987 | Right caudate nucleus                               |
| -44.64 | 12     | -3.094 | 0.000999987 | Left middle temporal gyrus, BA 37                  |
| -2.18  | 2      | -3.086 | 0.000999987 | Left thalamus                                       |
| 36.20  | 44     | -3.076 | 0.000999987 | Right superior longitudinal fasciculus II          |
| -42.52 | 16     | -3.063 | 0.000999987 | Left arcuate network, posterior segment            |
| 8.90   | 2      | -3.059 | 0.000999987 | Right calcarine fissure / surrounding cortex, BA 17|
| 38.12  | 24     | -3.059 | 0.000999987 | Right frontal inferior longitudinal fasciculus     |
| 10.52  | -4     | -3.055 | 0.000999987 | Right superior frontal gyrus, medial orbital, BA 10|
| 38.85  | 50     | -3.049 | 0.000999987 | Right middle frontal gyrus, BA 9                   |
| -38.32 | 4      | -3.018 | 0.000999987 | Left inferior network, inferior fronto-occipital fasciculus |
| -16.22 | 2      | -2.983 | 0.000999987 | Left striatum                                       |
| -30.72 | 22     | -2.967 | 0.000999987 | Left middle occipital gyrus, BA 19                 |
| 24.18  | 48     | -2.961 | 0.000999987 | Right superior frontal gyrus, dorsolateral, BA 8   |
| -44.16 | -6     | -2.949 | 0.000999987 | Left inferior frontal gyrus, orbital part           |
| -46.28 | 0      | -2.945 | 0.000999987 | Left inferior frontal gyrus, triangular part, BA 47|
| 50.12  | 32     | -2.921 | 0.000999987 | Right inferior frontal gyrus, opercular part, BA 44 |
| 50.70  | 0      | -2.918 | 0.000999987 | Right middle temporal gyrus, BA 37                 |
| 8.40   | 34     | -2.907 | 0.000999987 | Right superior frontal gyrus, medial, BA 32        |
| 30.10  | 8      | -2.999 | 0.000999987 | Right fronto-insular tract 5                       |
| 4.56   | 28     | -2.887 | 0.000999987 | Right superior frontal gyrus, medial, BA 10        |
| 50.56  | 32     | -2.886 | 0.000999987 | Right angular gyrus, BA 39                         |
| X, Y, Z   | T      | p       | Description                                             |
|----------|--------|---------|---------------------------------------------------------|
| 44, 38, 20 | 2.859  | 0.000999987 | Left superior temporal gyrus, BA 41                     |
| 24, -2.48 | 2.836  | 0.000999987 | Right frontal superior longitudinal                     |
| 28, -36, -12 | 2.811  | 0.000999987 | Right parahippocampal gyrus, BA 37                      |
| 54, 30, 2  | 2.793  | 0.000999987 | Right inferior frontal gyrus, triangular part, BA 45    |
| 0, 54, 12  | 2.785  | 0.000999987 | Left superior frontal gyrus, medial                     |
| -24, 56, -2 | 2.783  | 0.013000011 | Left superior frontal gyrus, orbital part, BA 11        |
| -36, 10, 38 | 2.772  | 0.004000008 | Left superior longitudinal fasciculus II                |
| -46, -8, 44 | 2.77   | 0.003000021 | Left precentral gyrus, BA 6                             |
| -44, -40, 24 | 2.748  | 0.000999987 | Left supramarginal gyrus, BA 41                         |
| 0, 18, -6  | 2.731  | 0.000999987 | Left olfactory cortex                                   |
| -21, 12, -8 | 2.715  | 0.000999987 | Left olfactory cortex, BA 25                           |
| -36, 12, 34 | 2.71   | 0.004000008 | Left middle frontal gyrus, BA 44                        |
| 24, 10, 48 | 2.707  | 0.000999987 | Right middle frontal gyrus, BA 8                        |
| 2, 30, 26  | 2.685  | 0.000999987 | Right anterior cingulate / paracingulate gyri, BA 24    |
| 58, -2, 18 | 2.682  | 0.000999987 | Right postcentral gyrus, BA 48                          |
| 46, -18, 44 | 2.674  | 0.000999987 | Right precentral gyrus, BA 4                            |
| -52, 12, 2 | 2.656  | 0.000999987 | Left inferior frontal gyrus, opercular part, BA 48      |
| 38, 24, 24 | 2.647  | 0.000999987 | Right inferior frontal gyrus, triangular part, BA 48    |
| -2, 60, 16 | 2.644  | 0.000999987 | Left superior frontal gyrus, medial, BA 10              |
| -8, 6, 36  | 2.62   | 0.000999987 | Left median cingulate / paracingulate gyri, BA 24       |
| -16, -6, 24 | 2.581  | 0.000999987 | Left caudate nucleus                                    |
| -50, -12, 32 | 2.551  | 0.003000021 | Left postcentral gyrus, BA 3                            |
| -42, -42, 16 | 2.529  | 0.000999987 | Left superior longitudinal fasciculus III               |
| 52, -26, 42 | 2.489  | 0.000999987 | Right postcentral gyrus, BA 3                           |
| 38, -42, 38 | 2.462  | 0.029999971 | (undefined), BA 40                                     |
| -50, -6, 28 | 2.46   | 0.003000021 | Left precentral gyrus, BA 4                            |
| 44, 6, 30  | 2.439  | 0.000999987 | Right precentral gyrus, BA 44                           |
| 52, -40, 38 | 2.433  | 0.032999992 | Right supramarginal gyrus, BA 40                        |
| 0, 38, 20  | 2.43   | 0.000999987 | Left anterior cingulate / paracingulate gyri, BA 24      |
| -40, -78, -4 | 2.422  | 0.000999987 | Left inferior occipital gyrus, BA 19                    |
| 26, 38, 30  | 2.416  | 0.000999987 | Right middle frontal gyrus, BA 46                       |
| -56, 12, 24 | 2.405  | 0.004999995 | Left inferior frontal gyrus, opercular part, BA 44      |
| -28, 42, 24 | 2.405  | 0.009000003 | Left middle frontal gyrus, BA 46                        |
| -8, 14, 6  | 2.402  | 0.000999987 | Left caudate nucleus, BA 25                            |
| -2, 36, 38  | 2.362  | 0.000999987 | Left superior frontal gyrus, medial, BA 9              |
| 30, 60, 6  | 2.351  | 0.003000021 | Right middle frontal gyrus, BA 10                       |
| 14, 48, 36  | 2.33   | 0.000999987 | Right superior frontal gyrus, dorsolateral, BA 9        |
| -2, 24, 46  | 2.311  | 0.000999987 | Left supplementary motor area, BA 8                     |
| Coordinates | Z Score | p Value     | Region                                      |
|-------------|---------|-------------|---------------------------------------------|
| -10,44,14   | -2.306  | 0.000999987 | Left anterior cingulate / paracingulate gyri, BA 32 |
| 22,48,32    | -2.3    | 0.000999987 | Right middle frontal gyrus                  |
| -48,18,42   | -2.288  | 0.003000021 | Left postcentral gyrus, BA 4                |
| -2,32,42    | -2.287  | 0.000999987 | Left superior frontal gyrus, medial, BA 8   |
| -18,36,38   | -2.283  | 0.000999987 | Left superior longitudinal fasciculus I     |
| 4,22,-4     | -2.238  | 0.000999987 | Right olfactory cortex, BA 25               |
| 50,68,20    | -2.237  | 0.000999987 | Right middle temporal gyrus, BA 39          |
| -50,60,18   | -2.217  | 0.000999987 | Left middle temporal gyrus, BA 39           |
| 26,58,0     | -2.201  | 0.003000021 | Right superior frontal gyrus, dorsolateral, BA 11 |
| -40,12,24   | -2.16   | 0.004999995 | Left frontal inferior longitudinal fasciculus |
| -42,16,42   | -2.157  | 0.003000021 | Left postcentral gyrus, BA 6                |
| -26,22,44   | -2.045  | 0.032999992 | Left middle frontal gyrus, BA 9             |
| 24,58,14    | -2.004  | 0.003000021 | Right superior frontal gyrus, dorsolateral, BA 10 |
| 58,20,14    | -1.986  | 0.000999987 | Right inferior frontal gyrus, opercular part, BA 48 |
| 22,56,20    | -1.976  | 0.001999974 | Right superior frontal gyrus, dorsolateral, BA 46 |
| -22,78,-26  | -1.95   | 0.000999987 | Left cerebellum, crus I                      |
| 8,-70,-20   | -1.95   | 0.000999987 | Right cerebellum, hemispheric lobule VI     |
| 8,-82,30    | -1.95   | 0.000999987 | Right cerebellum, crus II                   |
| -24,-62,-34 | -1.95   | 0.000999987 | Left cerebellum, hemispheric lobule VI      |
| -2,-74,-22  | -1.95   | 0.000999987 | Cerebellum, vermic lobule VII               |
| -4,-84,-16  | -1.95   | 0.000999987 | Left cerebellum, crus I, BA 17             |
| 32,-66,-20  | -1.95   | 0.000999987 | Right cerebellum, hemispheric lobule VI, BA 19 |
| -24,-44,-18 | -1.95   | 0.001999974 | Left fusiform gyrus, BA 37                 |
| 16,-70,-22  | -1.95   | 0.000999987 | Right cerebellum, hemispheric lobule VI, BA 18 |
| 34,-56,-28  | -1.95   | 0.000999987 | Right cerebellum, hemispheric lobule VI, BA 37 |
| -30,-66,-22 | -1.95   | 0.000999987 | Left cerebellum, hemispheric lobule VI, BA 19 |
| 0,-70,-16   | -1.95   | 0.000999987 | Cerebellum, vermic lobule VI                |
| -16,-70,-22 | -1.95   | 0.000999987 | Left cerebellum, hemispheric lobule VI, BA 18 |
| -12,-76,-34 | -1.95   | 0.000999987 | Left cerebellum, crus II                    |
| -32,-16,-18 | -1.95   | 0.000999987 | Left hippocampus, BA 20                     |
| -30,-70,-14 | -1.95   | 0.000999987 | Left fusiform gyrus, BA 19                 |
| 30,-60,-34  | -1.95   | 0.000999987 | Right cerebellum, crus I                    |
| 28,-76,-28  | -1.949  | 0.000999987 | Right cerebellum, crus I, BA 19            |
| 10,-82,-22  | -1.949  | 0.000999987 | Right cerebellum, crus I, BA 18             |
| -10,-84,-18 | -1.949  | 0.000999987 | Left cerebellum, crus I, BA 18              |
| -26,18,48   | -1.948  | 0.032999992 | Left middle frontal gyrus, BA 8             |
| -16,-54,-12 | -1.948  | 0.000999987 | Left cerebellum, hemispheric lobule IV / V, BA 19 |
| -44,-54,-8  | -1.948  | 0.005999982 | Left inferior temporal gyrus, BA 37         |
| -18,-68,-28 | -1.948  | 0.000999987 | Left cerebellum, crus I, BA 19              |
| -20,-62,-12 | -1.948  | 0.000999987 | Left lingual gyrus, BA 19                  |
| X, Y, Z  | T   | p    | Region                                      |
|---------|------|------|---------------------------------------------|
| -46,-50,-14 | -1.948 | 0.001999974 | Left inferior temporal gyrus, BA 20        |
| 42,-58,-28   | -1.948 | 0.000999987 | Right cerebellum, crus I, BA 37           |
| -46,-62,-14  | -1.948 | 0.003000021 | Left inferior occipital gyrus, BA 37      |
| 8,-58,-38    | -1.947 | 0.032999992 | Cerebellum, vermic lobule IX               |
| -24,-74,-16  | -1.946 | 0.000999987 | Left fusiform gyrus, BA 18                |
| -36,-60,-28  | -1.945 | 0.000999987 | Left cerebellum, crus I, BA 37           |
| 8,-68,-30    | -1.945 | 0.001999974 | Right cerebellum, hemispheric lobule VIII |
| 28,-66,-16   | -1.94  | 0.001999974 | Right fusiform gyrus, BA 19               |
| -32,52,10    | -1.938 | 0.01700002  | Left middle frontal gyrus, BA 10          |
| 30,-20,54    | -1.922 | 0.000999987 | (undefined), BA 4                         |
| 14,-78,34    | -1.922 | 0.000999987 | Right cuneus cortex, BA 19                |
| 0,-68,34     | -1.922 | 0.000999987 | Left precuneus                            |
| 4,-68,38     | -1.922 | 0.000999987 | Right precuneus, BA 7                     |
| -28,-54,52   | -1.922 | 0.032000005 | Left inferior parietal (excluding supramarginal and angular) gyri, BA 7 |
| -6,-70,38    | -1.922 | 0.000999987 | Left precuneus, BA 7                      |
| -26,-60,56   | -1.922 | 0.032000005 | Left superior parietal gyrus, BA 7        |
| 24,-64,56    | -1.921 | 0.015999973 | Right superior parietal gyrus, BA 7       |
| 4,-14,56     | -1.92  | 0.003000021 | Right supplementary motor area, BA 6      |
| 30,42,-14    | -1.919 | 0.010999978 | Right middle frontal gyrus, orbital part, BA 11 |
| 0,-62,-30    | -1.918 | 0.001999974 | Cerebellum, vermic lobule VIII            |
| -14,-40,-14  | -1.918 | 0.018000007 | Left cerebellum, hemispheric lobule IV / V|
| 38,58,-4     | -1.912 | 0.01700002  | Right middle frontal gyrus, orbital part, BA 10 |
| 24,-24,54    | -1.908 | 0.001999974 | Right hand superior U tract               |
| 18,-74,44    | -1.903 | 0.003000021 | Right precuneus, BA 19                    |
| 34,56,-6     | -1.902 | 0.018000007 | Right middle frontal gyrus, orbital part, BA 47 |
| 46,10,-26    | -1.901 | 0.010999978 | Right temporal pole, superior temporal gyrus, BA 20 |
| 28,-72,44    | -1.9  | 0.003000021 | Right superior occipital gyrus, BA 7      |
| -54,-54,32   | -1.893 | 0.010999978 | Left angular gyrus, BA 39                |
| -18,24,46    | -1.891 | 0.033999979 | Left frontal superior longitudinal        |
| 12,-88,-14   | -1.877 | 0.005999982 | Right lingual gyrus, BA 18                |
| 40,-54,40    | -1.868 | 0.010999978 | Right inferior parietal (excluding supramarginal and angular) gyri, BA 40 |
| -6,-12,56    | -1.865 | 0.003000021 | Left supplementary motor area, BA 6       |
| 26,-40,-28   | -1.853 | 0.010999978 | Right cerebellum, hemispheric lobule IV / V, BA 37 |
| -38,-52,-28  | -1.835 | 0.005999982 | Left cerebellum, hemispheric lobule VI, BA 37 |
| 34,-48,60    | -1.834 | 0.018000007 | Right superior parietal gyrus, BA 2       |
| 48,-20,50    | -1.814 | 0.003000021 | Right postcentral gyrus, BA 4             |
| 32,-52,54    | -1.809 | 0.015999973 | Right inferior parietal (excluding supramarginal and angular) gyri, BA 7 |
| -4,-38,60    | -1.798 | 0.018000007 | Left precuneus, BA 5                      |
| 42,50,-6     | -1.79  | 0.018000007 | Right middle frontal gyrus, orbital part, BA 46 |
| X, Y, Z   | T   | p    | Region                                      |
|----------|-----|------|---------------------------------------------|
| 6,24,46  | -1.785 | 0.005999982 | Right supplementary motor area, BA 8     |
| -52,-54,26 | -1.773 | 0.010999978 | Left angular gyrus, BA 22                |
| 50,-32,54 | -1.705 | 0.035000026 | Right postcentral gyrus, BA 2            |
| -52,-44,-8 | -1.694 | 0.035000026 | Left arcuate network, long segment       |
Table S3. Heterogeneity statistics for the areas reported for the meta-analysis of brain activation to emotion in FEP patients versus healthy controls.

| Coordinates   | Region                                | SDM-Z | Estimate $I^2$ | Estimate $Q^2$ | Estimate $H^2$ |
|---------------|---------------------------------------|-------|---------------|---------------|---------------|
| -38,2,-10     | Left insula, BA 48                    | -4.655| 0             | 0.77148       | 1.00000       |
| -26,-2,-14    | Left amygdala, BA 34                  | -4.027| 0             | 0.90438       | 1.00000       |
| 28,-38,4      | Right hippocampus, BA 37              | -3.95 | 0             | 1.35795       | 1.00000       |
| -18,-10,-12   | Left hippocampus                      | -4.093| 0             | 1.38875       | 1.00000       |
| 0,40,4        | Left anterior cingulate / paracingulate gyri | -3.611| 0             | 1.23011       | 1.00000       |
| 10,46,2       | Right anterior cingulate / paracingulate gyri, BA 10 | -3.184| 0             | 1.32822       | 1.00000       |
| -42,-72,14    | Left middle occipital gyrus, BA 37    | -3.565| 0             | 1.26232       | 1.00000       |

Figure S1. The $I^2$ heterogeneity statistic distribution from the meta-analysis of brain activation to emotion in FEP patients versus healthy controls.

(A) Whole-brain distribution of the $I^2$ statistic. $I^2$ increases from blue to cyan. Transparent areas have an $I^2$ value of 0. (B) The distribution of the $I^2$ statistic in the meta-analysis.
Combined meta-analysis of brain activation to emotion in FEP and CHRp compared to healthy controls.

A combined meta-analysis of t-maps of brain activation to emotional versus neutral stimuli in FEP patients and individuals at CHRp compared to healthy controls showed significantly decreased activation in a large widespread cluster (Z = -(4.253-1.406), k = 77,082, p_{TFCE} < 0.05). The cluster comprised peaks in several brain regions classically involved in emotion processing, such as the left insula (x = -38, y = -4, z = -12, Z = -3.932, p_{TFCE} = 0.000999987), left amygdala (x = -22, y = 2, z = -18, Z = -2.769, p_{TFCE} = 0.000999987), right amygdala (x = 22, y = -2, -12, Z = -3.275, p_{TFCE} = 0.000999987), right hippocampus (x = 32, y = -18, z = -16, Z = -3.523, p_{TFCE} = 0.000999987), left hippocampus (x = -20, y = -8, z = -12, Z = -4.031, p_{TFCE} = 0.000999987), anterior cingulate (x = -4, y = 38, z = 4, Z = -2.974, p_{TFCE} = 0.000999987), and occipital cortex (x = -28, y = -82, z = 18, Z = -3.542, p_{TFCE} = 0.000999987) (Fig. S2).

Figure S2. Results of a combined meta-analysis of group-comparison t-maps in both FEP and CHRp populations compared to healthy controls. Results shown on a standard template at p_{TFCE} < 0.001 for display purposes. Decreasing Z value displayed with increasing warm colours (green, yellow, red).
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