



Unraveling how the adolescent brain deals with criticism using dynamic causal modeling

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ABSTRACT

Sensitivity to criticism, which can be defined as a negative evaluation that a person receives from someone else, is considered a risk factor for the development of psychiatric disorders in adolescents. They may be more vulnerable to social evaluation than adults and exhibit more inadequate emotion regulation strategies such as rumination. The neural network involved in dealing with criticism in adolescents may serve as a biomarker for vulnerability to depression. However, the directions of the functional interactions between the brain regions within this neural network in adolescents are still unclear. In this study, 64 healthy adolescents (aged 14 to 17 years) were asked to listen to a series of self-referential auditory segments, which included negative (critical), positive (praising), and neutral conditions, during fMRI scanning. Dynamic Causal Modeling (DCM) with Parametric Empirical Bayesian (PEB) analysis was performed to map the interactions within the neural network that was engaged during the processing of these segments. Three regions were identified to form the interaction network: the left pregenual anterior cingulate cortex (pgACC), the left dorsolateral prefrontal cortex (DLPFC), and the right precuneus (preCUN). We quantified the modulatory effects of exposure to criticism and praise on the effective connectivity between these brain regions. Being criticized was found to significantly inhibit the effective connectivity from the preCUN to the DLPFC. Adolescents who scored high on the Perceived Criticism Measure (PCM) showed less inhibition of the preCUN-to-DLPFC connectivity when being criticized, which may indicate that they required more engagement of the Central Executive Network (which includes the DLPFC) to sufficiently disengage from negative self-referential processing. Furthermore, the inhibitory connectivity from the DLPFC to the pgACC was strengthened by exposure to praise as well as criticism, suggesting a recruitment of cognitive control over emotional responses when dealing with positive and negative evaluative feedback. Our novel findings contribute to a more profound understanding of how criticism affects the adolescent brain and can help to identify potential biomarkers for vulnerability to develop mood disorders before or during adulthood.

1. Introduction

Adolescence is a crucial developmental period during which the incidence of psychiatric illnesses increases, including mood and anxiety disorders (Chen et al., 2022; Lamblin et al., 2017; Paus et al., 2008). Neurodevelopmental changes that occur during adolescence (such as the

relatively early maturation of the limbic system) could make youngsters prone to higher emotional responsiveness and heightened sensitivity to external stimuli, including social feedback. At the same time, their ability to effectively regulate their emotions (which is related to the maturation of other brain regions, such as the prefrontal cortex) may not develop at the same speed, creating a potential window of susceptibility

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to depression (Crone and Dahl, 2012; Yurgelun-Todd, 2007). Therefore, negative social experiences can have a powerful impact on adolescents, as they are more vulnerable to social evaluation than adults.

Criticism, an all-too-familiar and salient example of a negative social experience, can be defined as a negative (social) evaluation that a person receives from someone else (Hooley et al., 2005). Several studies have suggested that people who are sensitive to criticism may also be vulnerable to psychiatric disorders (Burcusa and Iacono, 2007; Hooley et al., 2012). For instance, an association between high parental criticism and/or rejection and current as well as future symptoms of depression in minors has been established (Nelemans et al., 2014; Thompson and Berenbaum, 2009). Thus, repeated exposure to high levels of criticism can make adolescents vulnerable to developing mental health problems, including depression (Lee et al., 2015; Silk et al., 2017; Thapar et al., 2022).

Intriguingly, the *perception* of criticism (i.e., how much criticism is getting through to someone) may be related to vulnerability to criticism at the brain level (Hooley and Miklowitz, 2017; Hooley et al., 2012). There is evidence that people who score high on perceived criticism have difficulty engaging inhibitory control over negative information (Masland and Hooley, 2015). In a social interaction context, higher sensitivity to rejection has been shown to prospectively predict higher levels of rumination (Pearson et al., 2011). As a form of social rejection, criticism can thus induce ruminative thoughts (De Raedt et al., 2017), which need to be regulated to prevent maladaptive emotional responses (Vanderhasselt et al., 2015), and affect a person's mood. Increases in negative mood states and decreases in positive mood states have been observed after exposure to criticism in adults and adolescents (Aupperle et al., 2016; Baeken et al., 2018; Dedoncker et al., 2019; Hooley et al., 2012). These mood state disturbances also point to the need for adequate emotion regulation (Butterfield et al., 2021; Hooley et al., 2009; Lee et al., 2015; Vandermeer et al., 2022).

During adolescence, brain regions involved in emotion regulation, including the limbic system and prefrontal cortex, undergo protracted structural and functional development (Ahmed et al., 2015). Prior neuroimaging studies of brain development in childhood and adolescence provide evidence that this development is characterized by a reduction of short-range connectivity and a strengthening of long-range connectivity (Supekar et al., 2009; Váša et al., 2020). Since long-range connections tend to be concentrated on association cortical areas involved in higher-order cognitive functions, these results suggested that primary sensory and motor areas mature earlier in childhood, whereas association areas show a relatively protracted maturation, extending into adolescence and early adulthood. Moreover, it has been suggested that their ongoing brain development renders adolescents less able to successfully regulate their emotions, putting them at greater risk for anxiety and depressive disorders (Powers and Casey, 2015). Therefore, the neural correlates of mood and ruminative state changes that occur during exposure to criticism, as well as the engagement of brain areas involved in emotion regulation, could serve as biomarkers for vulnerability to mood disorders.

Studies investigating the neural mechanisms involved in dealing with criticism in adolescents collectively point to the role of specific brain regions associated with affective salience (e.g., amygdala and anterior cingulate cortex; ACC), emotion regulation (e.g., dorsolateral prefrontal cortex; DLPFC), and self-referential processing (e.g., precuneus; preCUN) (Aupperle et al., 2016; Butterfield et al., 2021; Hooley et al., 2009; Lee et al., 2015). For instance, Lee et al. (2015) examined the neural processes of parental criticism in healthy adolescents by measuring their brain activity while they listened to critical, praising, and neutral comments. They found that healthy adolescents showed increased activity in brain regions associated with the processing of emotional experiences (e.g., ACC), and decreased activity in brain regions associated with cognitive control (e.g., DLPFC) and self-referential processing (e.g., preCUN) when hearing auditory criticism, relative to neutral comments. van Houtum et al. (2022) presented mock parental

social feedback words to healthy adolescent about their personality and found increased activity in the ACC (specifically the pregenual ACC), and decreased activity in the DLPFC and precuneus in adolescents receiving mock parental critical feedback words (e.g., 'unreliable') compared to praising feedback words (e.g., 'sweet'). Furthermore, some research has indicated that the developmental mismatch between the prefrontal and limbic regions during adolescence may result in less effective regulation and heightened emotional reactivity in adolescents (Ahmed et al., 2015). Taken together, these findings suggest that increased emotional responsiveness, weaker cognitive control, and decreased self-referential processing may be normal responses to criticism during adolescence.

It has been suggested that both positive and negative emotions are regulated through (indirect) top-down connections with the limbic system, including the ACC (Disner et al., 2011). The ACC is considered an important area in the interplay between affective and cognitive regulatory processes (Carnevali et al., 2018). The dorsal ACC (dACC) is thought to be primarily involved in cognitive regulatory processes, while the rostral ACC (rACC), comprised of the pregenual ACC (pgACC) and subgenual ACC (sgACC), is thought to be more involved in emotion regulation (Bush et al., 2000). More specifically, the sgACC appears to be strongly implicated in experiencing emotions (Abend et al., 2019; Masten et al., 2011; Scharnowski et al., 2020) and in the pathogenesis of mood disorders (Chai et al., 2016; Drevets et al., 1997), while the pgACC appears to be more involved in the processing of the emotional aspects of pain (Edes et al., 2019), as well as engaging in social interactions (Van Mao et al., 2017).

The pgACC is considered a hub for integrating emotion and cognition in order to guide emotion regulation through its projections to several cortical regions, such as the DLPFC and preCUN (Marusak et al., 2016; Tang et al., 2019). As a part of the Central Executive Network (CEN), the DLPFC is thought to be critically important to higher-level cognitive control, and it has been shown to be implicated in the processing of criticism in both adults and adolescents. In addition, differences in activation of this key cognitive control area during exposure to auditory criticism have been revealed between adults with vs. without a history of depression, and adults with high vs. low perceived criticism (Hooley et al., 2009; Hooley et al., 2012). Furthermore, increased functional connectivity (FC) between the DLPFC and the preCUN has been found in healthy adolescents during exposure to auditory critical comments, compared with neutral ones (Lee et al., 2015). The preCUN is defined as a hub of the Default Mode Network (DMN) implicated in self-referential processing (Andrews-Hanna et al., 2014). Experimental findings have shown that rumination is associated with a decrease in inhibition of DMN activity (Bartova et al., 2015), particularly the active state of the preCUN (Cooney et al., 2010; Zhou et al., 2020). Yoon et al. (2023) extended these findings of an association between the preCUN activity and adults' individual differences in rumination by demonstrating similar patterns in adolescent girls: they also ruminated more in the context of social rejection (i.e., receiving a negative social evaluation), suggesting possible developmental stabilities in self-referential processing from late adolescence to adulthood.

Despite the previous studies providing evidence for the involvement of the ACC, DLPFC, and preCUN in the neural response to exposure to criticism, it is still unclear *how* these brain regions interact with one another when exposed to criticism. Dynamic Causal Modeling (DCM) is a Bayesian approach used to study brain interaction: DCM provides a framework to understand how one area of the brain influences another, and how this is affected by external stimuli (i.e., experimental manipulation). In the context of neuroimaging, DCM is an analytical method used to model and infer the causal interactions between different brain regions (Zeidman et al., 2019a). In other words, DCM models are based on assumptions about neural processes. The causality in DCM refers to causal interactions among hidden neuronal states: (i) how the present state of one neuronal population causes dynamics (i.e., rate of change) in another via synaptic connections, and (ii) how these interactions change

under the influence of external perturbations (i.e., experimental manipulations) or endogenous brain activity. Thus, DCM allows for testing a generative model of brain responses by quantifying the effective connectivity between brain areas and how this connectivity changes under task-dependent modulation (Friston, 2009; Stephan et al., 2010). Moreover, the Parametric Empirical Bayesian (PEB) is used as a supplement to DCM, which allows for exploring the relationship between brain connectivity and individual differences in behavioral measurements (Friston et al., 2016; Zeidman et al., 2019b).

Therefore, the goal of our study was to detect how effective connectivity in the neural network – which comprises three regions of interest (ROI): the ACC (and its subdivisions), the DLPFC, and the preCUN – are affected by exposure to criticism and/or praise in healthy adolescents through DCM. To investigate these interactions, we used self-referential auditory segments with a negative (critical), positive (praising), and neutral valence. Data analyses were focused on the block of time during the presentation of the auditory comments. We expected that critical and/or praising auditory segments would have a significant modulatory effect on the effective connectivity in the neural network. In addition, given that exposure to criticism can affect one's mood state and trigger ruminative thoughts, and that the perception of criticism appears to affect the ability to engage inhibitory control over negative emotional information, we explored whether the individual differences in perceived criticism, mood state changes, and/or ruminative state changes could affect the modulatory effects of exposure to criticism or praise on the effective connectivity between our ROIs.

2. Materials and methods

2.1. Participants

Ninety-six healthy adolescents were recruited from several high schools in Ghent (Belgium) and through social media. Dutch-speaking participants aged between 14 and 17 years old were included in the study. Participants were assessed by a child and adolescent psychiatrist using the Dutch versions of the Structured Clinical Interview for DSM-5 Junior Edition (SCID-5-Junior) (Wante et al., 2021), the Psychotic Disorders section of the Kiddie-Schedule for Affective Disorders and Schizophrenia for School-Age Children (K-SADS-PL) (Kaufman et al., 1997), and the Scale for Suicidal Ideation (SSI) (Beck et al., 1979). Additionally, participants' depressive symptoms were assessed with the Children's Depression Inventory (CDI) (Kovacs, 1992). Participants were excluded if they (i) had a mood disorder (currently or previously) based on the SCID-5-Junior; (ii) were at high risk for suicide; (iii) were currently receiving psychotropic medication; (iv) had a significant intellectual disability (screened using Raven's Standard Progressive Matrices); (v) had a neurological disorder (currently or previously); or (vi) in case of a contra-indication for magnetic resonance imaging (MRI). This study was approved by the Ghent University Hospital (UZ Gent) Medical Ethics Committee (reference number 2018/0852) and was carried out in accordance with the Declaration of Helsinki (2004). Written informed consent was obtained from all participating adolescents and their parents. Participants received 40 euros as compensation for participating in this study. This study protocol has also been described in previous publications (Bonduelle et al., 2021; Bonduelle et al., 2023).

A total of 32 participants were excluded due to a major depressive disorder ($n = 2$), technical issues during image acquisition ($n = 3$), excessive head movement during functional magnetic resonance imaging (fMRI) scanning ($n = 7$), and excessive distortion of images because of wearing braces ($n = 20$). Analyses were conducted on the remaining 64 participants (aged 14 to 17 years, $Mean = 16.53$ y, $SD = 1.03$), with 42 girls and 22 boys. See Table S1 in the Supplementary Materials for additional information regarding the demographic characteristics of our study sample.

2.2. Experimental paradigm

Participants were asked to listen attentively to a series of auditory comments presented through non-ferrous gradient-damping headphones during the fMRI scan. All participants heard the same comments, voiced by a female voice actor (intending to mimic a maternal voice). They were instructed to imagine that they were listening to someone who knew them very well talking to them, and to focus their gaze on a fixation cross via a reverse mirror inside the scanner. The comments included three emotional valences: negative (criticism), positive (praise), and neutral. Each comment lasted 30 seconds and was interspersed with 30 seconds of silence. The participants first heard two neutral comments followed by two positive ones, and then another two neutral comments followed by two negative ones (see Fig. 1). This specific order was chosen in accordance with the affective contrast theory (Manstead et al., 1983), which states that the impact of an emotional experience (e.g., being criticized) is contingent on the level of contrast with a preceding emotional state (e.g., being praised). State questionnaires measuring the effects of being criticized were administered at the end of the sequence. The comments were based on those used in other studies with adult participants (Hooley et al., 2005; Hooley et al., 2012), but were adapted in order to be broadly applicable and relevant to adolescents within a family context, in concertation with the original experiment's lead investigator (J. M. Hooley). These comments always started with a sentence that indicated how a mock parental figure felt about the participant (e.g., "One of the things I really like about you is..."; or "One of the things that bothers me about you is..."). Below, we provide an example of a neutral, praising, and critical comment, respectively:

Neutral: "One of the things you did last week was to go out for a walk. It was a clear day. You walked from the house to the nearest corner shop – a distance of about half a mile. When you got there, you looked for a magazine. Then you waited in line to pay for it and also bought a pack of gum at the counter. The whole trip took less than an hour."

Praising: "One thing I really like about you is the way you pay attention to the people you are with. You really seem to be able to make the people around you feel good. Part of it is that you are a good listener. But you also have a really warm personality and a genuine interest in other people. It's a great combination and it makes people feel really happy to be around you."

Critical: "One of the things that bothers me about you is how bad you are at dealing with negative feedback. If someone says anything even remotely critical of you, you tend to get very defensive. You are far from a perfect person – even if that is how you like to see yourself. I really wish you would listen when other people tell you what bothers them rather than getting all hostile and trying to defend yourself."

The full list of available comments can also be found in the Supplementary Materials.

2.3. Behavioral assessments

2.3.1. Perceived criticism

To assess the participants' sensitivity to criticism, we used the Perceived Criticism Measure (PCM; Hooley et al., 1989; Hooley et al., 2017). Participants were asked to rate the question "How critical are your significant others – such as your family members or close friends – of you in general?" on an 11-point scale, ranging from 0 ("not critical at all") to 10 ("very critical indeed"), prior to the scan session. We chose an 11-point scale instead of the original 10-point scale (from 1 to 10) to match a ratio scale (with an absolute zero point) more closely, as discussed in our previous publications (Bonduelle et al., 2021; Bonduelle et al., 2023). A higher score indicates higher perceived criticism (range: 0–10).

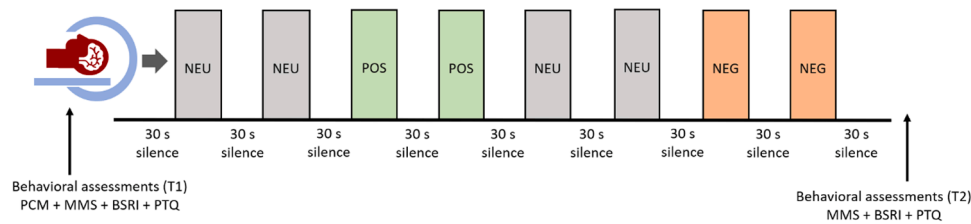


Fig. 1. Experimental paradigm. Participants were exposed to a standardized set of auditory comments during the fMRI scan. They first heard two neutral comments followed by two positive ones (praise), and then another two neutral comments followed by two negative ones (criticism). Each comment lasted 30 seconds and was interspersed with 30 seconds of silence. Behavioral assessments were completed before and after exposure to the auditory comments. Abbreviations: NEU, neutral; POS, positive; NEG, negative; T1, pre-experiment; T2, post-experiment; PCM, Perceived Criticism Measure; MMS, Momentary Mood States; BSRI, Brief State Rumination Inventory; PTQ, Perseverative Thinking Questionnaire.

2.3.2. Momentary mood states

To evaluate temporary changes in mood states before versus after exposure to criticism, we used six Momentary Mood State (MMS) scales measuring fatigue, vigor, anger, tension, sadness, and cheerfulness. These MMS scales are part of the Profile of Mood States (McNair et al., 1992). Participants were asked how they felt “at that moment” by providing a rating on an 11-point scale ranging from 0 (“not at all”) to 10 (“very much”). The Total Mood Disturbance Score (TMDS) was calculated by summing all of the MMS scales, after reverse-scoring the “vigor” and “cheerfulness” scales; as such, higher scores on all of the MMS scales (TMDS range: 0–60) indicated more negative affect.

2.3.3. Ruminative state

To obtain a state measure of ruminative thoughts, the 8-item Brief State Rumination Inventory (BSRI; Marchetti et al., 2018) and the 15-item Perseverative Thinking Questionnaire (PTQ; Ehrling et al., 2011) were completed. The BSRI’s items were designed to capture maladaptive state rumination (Nolen-Hoeksema et al., 2008). Participants were presented with eight individual statements regarding their repetitive negative thoughts at the time of answering (e.g., “Right now, it is hard for me to shut off negative thoughts about myself”). All items were rated using an 11-point scale ranging from 0 (“completely disagree”) to 10 (“completely agree”). The BSRI total score was calculated by summing all items. Higher scores indicated a more ruminative state (range: 0–80). The PTQ was used to assess different aspects of rumination: 1) repetitiveness, 2) intrusiveness, 3) difficulty of disengagement, 4) unproductivity, and 5) capturing mental capacity. Participants were instructed to respond to statements about how often they thought about negative experiences or problems (e.g., “The same thoughts keep going through my mind again and again”) in the past few minutes and rate each item on a scale ranging from 1 (“never”) to 5 (“almost always”). The PTQ total score was calculated by summing all items. In this study, the PTQ was used to assess *state* rumination, measuring ruminative thoughts “at that moment”, instead of *trait* rumination (i.e., the habitual tendency to ruminate). Thus, higher scores indicated higher state rumination (range: 15–75).

Mood and ruminative states were assessed at two different time points (T1: pre-experiment; T2: post-experiment). Delta scores (post-minus pre-experiment scores) were calculated to assess changes in mood and ruminative states after exposure to criticism. Perceived criticism, a trait measure, was only assessed pre-experiment (see Fig. 1).

2.4. MRI data acquisition

All MRI data were acquired using a 64-channel head coil on a Siemens MAGNETOM 3T Prisma MRI scanner (Siemens, Erlangen, Germany) at UZ Gent, Belgium. The functional data were obtained using a single-shot gradient-echo echo-planar imaging (EPI) sequence with the following parameters: repetition time (TR) = 2500 ms; echo time (TE) = 35 ms; voxel size = $3.5 \times 3.5 \times 3$ mm³; flip angle = 80°; field of view (FOV) = 224 mm × 224 mm; data matrix = 64 × 64; slice thickness = 3

mm with 17 % gap; 42 slices in interleaved ascending order, and 220 volumes acquired in about 9 minutes (only the time-series of the experiment were extracted and used for analysis). High resolution brain structural images were obtained using a T1-weighted (T1w) 3D Magnetization-Prepared Rapid Gradient Echo (MPRAGE) sequence with TR = 2250 ms, TE = 4.18 ms, flip angle = 9°, slice thickness = 1 mm, FOV = 256 mm × 256 mm, data matrix = 256 × 256, voxel size = $1 \times 1 \times 1$ mm³, and 176 sagittal slices.

2.5. MRI data preprocessing

The MRI data preprocessing was performed using fMRIPrep v20.2.1 (Esteban et al., 2020). Briefly, the T1w image was corrected for intensity non-uniformity with N4BiasFieldCorrection (ANTs 2.3.3; Tustison et al., 2010), skull-stripped, and used as a reference throughout the workflow. Then, for each of the BOLD runs per participant, a reference volume and its skull-stripped version were generated using a custom methodology of fMRIPrep. The BOLD reference was co-registered (six degrees of freedom) to the T1w reference using bbregister (Freesurfer; Greve and Fischl, 2009). Head-motion parameters with respect to the BOLD reference were estimated before any spatiotemporal filtering using mcflirt (FSL 5.0.9; Jenkinson et al., 2002). After that, the BOLD runs were slice-timing corrected using 3dTshift from AFNI 20160207 (Cox and Hyde, 1997), and resampled into MNI152NLin2009cAsym standard space, generating a preprocessed, spatially normalized BOLD run. Framewise displacement (FD) (Jenkinson et al., 2002; Power et al., 2014) was calculated based on the preprocessed BOLD. In addition, a set of physiological noise regressors were extracted for anatomical component-based noise correction (aCompCor; Behzadi et al., 2007). For more details on the pipeline, please see the section corresponding to the workflow documentation of fMRIPrep (<https://fmripred.readthedocs.io/en/latest/workflows.html>). Afterwards, a spatial smoothing with a Gaussian kernel at a full-width-at-half-maximum (FWHM) of 6 mm was applied to the preprocessed BOLD time-series using the CONN toolbox (www.nitrc.org/projects/conn, Whitfield-Gabrieli and Nieto-Castanon, 2012). In addition, preprocessed BOLD time-series were denoised using the regression of potential confounding effects characterized by the top five CompCor noise components from white matter, the top five CompCor noise components from cerebrospinal fluid mask, motion parameters and their first derivatives, and outlier scans, followed by a high-pass filtering of 0.01 Hz. If participants had a mean FD greater than 2 mm during fMRI scanning, they were excluded ($n = 7$) from analyses.

2.6. General linear model analysis of fMRI data

As we wanted to explore the effects of the auditory comments on brain activation patterns first, data analyses were performed by using SPM12 (<http://www.fil.ion.ucl.ac.uk/spm/software/spm12/>). The first-level analysis was conducted by building a General Linear Model (GLM) including three different experimental conditions (praising, criticizing, and neutral comments) and six head motion parameters as

regressors. To examine the main effect of emotional valence, a within-subject one-way ANOVA design was performed in a second-level group analysis across negative, positive, and neutral conditions. Age, gender, and mean FD were added as covariates. The significance threshold was set at $p < .05$ after a false discovery rate (FDR) correction, with a minimum cluster size of 30 voxels. Post-hoc contrast analyses were performed to characterize different activation patterns between each of the conditions. Age, gender, and mean FD were added as covariates. For the post-hoc analyses, one-sample t -tests were implemented for individual contrast images to compare the positive and negative conditions to each other and to the neutral condition. The significant statistical parametric map thresholded with $p < .05$ after a FDR correction, with a minimum cluster size of 30 voxels. Brain regions with significant differences in the F -contrast across all experimental conditions, and criticism vs. neutral, praise vs. neutral, and criticism vs. praise contrasts, are shown in the Fig. S1 (see Supplementary Materials). The detailed information for these brain regions are listed in the Table S2, S3, and S4 (see Supplementary Materials).

2.7. DCM with PEB analysis

To analyze causal interactions between brain regions involved in dealing with criticism in healthy adolescents, we performed a DCM analysis using SPM12. In the present study, the DLPFC and preCUN were selected as ROIs, given that these ROIs are related to the neural processes known to be involved after exposure to criticism in adolescents (Lee et al., 2015), and exhibited significant activation in the GLM analysis. In addition, we included the pgACC as a third ROI, because the significant activation within the ACC in the GLM analysis was only located in the pgACC.

According to the results of the group-level GLM analysis, the peak coordinates of the main effect of the task (under three experimental conditions) within these ROIs were located in the left pgACC, the left DLPFC, and the right preCUN. Therefore, we included these brain regions as ROIs in the DCM model (Fig. 2a). After identifying the ROI peak coordinates at the group level, the peak coordinates of each ROI for each subject were constrained to be a maximum of 10 mm from the group-level peak (left pgACC [-6, 50, 9]; left DLPFC [-9, 36, 58]; right preCUN [8, -52, 13]). Each ROI was identified as including all voxels located within a sphere centered on the individual subject's peak with a 5 mm radius. This allows for each subject to have slightly different loci of responses (Zeidman et al., 2019a). Then, the time series were extracted for each ROI using the first eigenvariate as summary statistics, and adjusted using an F -contrast involving all experimental effects.

The DCM was set up to model the entire experiment using three matrices: (i) matrix A, with intrinsic connections between and within the regions, which represents the average effective connectivity under the experimental manipulation; (ii) matrix B, with modulatory connections that are modulated by the experimental condition, which measures how

much the connectivity strength changes due to different experimental conditions; and (iii) matrix C, the driving input to the system, which stimulates the activity in the ROIs. Specifically, a full DCM model was set up (Fig. 2b) to include (i) bidirectional connections between the ROIs and self-connections in matrix A; (ii) modulatory effects of different experimental conditions (i.e., praise and criticism) on the between-region connections in matrix B, to assess how these experimental conditions alter the effective connectivity between the ROIs; and (iii) all the experimental conditions combined as one driving input for the left pgACC in matrix C, since this brain region is involved in emotion perception of external stimuli (Disner et al., 2011).

To estimate DCM parameters at the group level, we performed a Parametric Empirical Bayes (PEB) analysis (Zeidman et al., 2019b) in order to (i) estimate the group means of connectivity strengths (i.e., 'commonalities') across subjects; (ii) test the relationship between individual differences in behavioral measurements (i.e., between-subject differences) and modulatory connections. Specifically, it integrates the individual-level Dynamic Causal Models (DCMs) with a group-level General Linear Model (GLM), forming a Bayesian hierarchical framework. This framework allows for capturing both the shared connectivity patterns across the group and the unique variations related to individual behavioral measurements. For example, researchers might use PEB to study the effect of a particular medication on brain connectivity. By performing DCM with PEB analysis on brain scans from a group of patients, PEB can reveal the average effect of the medication on brain connectivity and also how this effect differs from person to person, considering individual characteristics such as age or prior health conditions. In our study, to investigate whether individual differences in perceived criticism, changes in mood states, and/or changes in ruminative states would influence the modulatory connections, the behavioral measurements (including the PCM score and delta scores of the TMDs, BSRI total scores, and PTQ total scores) were included as regressors in the PEB design matrix, respectively. Age and gender were included as covariates.

After having specified and estimated the PEB models, we performed an automatic search procedure called 'Bayesian model reduction' (BMR) to prune away any parameters (i.e., connections) that did not contribute to the model evidence, and compare model evidence among the full and reduced models. A Bayesian model average (BMA) was then used to compute the group average of connectivity parameters across models, weighted by the models' posterior probabilities (Pp). We considered connectivity parameters as significant when their Pp was greater than 95 % (i.e., strong evidence of the parameters being present vs. absent).

Although our hypotheses were about changes in effective connectivity between ROIs due to praise and criticism (matrix B), it is important to present these results in the context of the average effective connectivity across experimental conditions (matrix A). Therefore, we specified and estimated a separate PEB model for the average connectivity of matrix A, and performed an automatic search over reduced models.

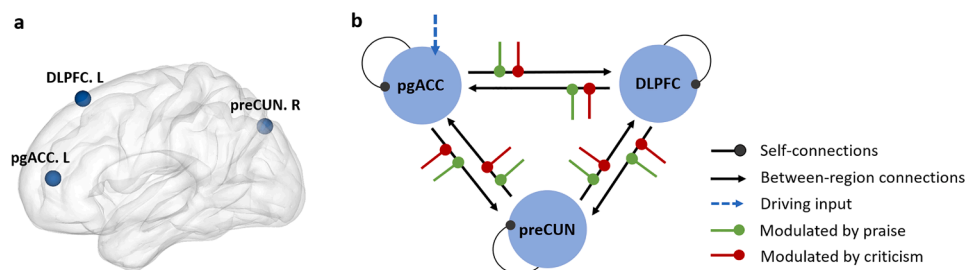


Fig. 2. The network architecture implemented for the DCM. (a) The location of the selected regions of interest (ROIs): the left pgACC, left DLPFC, and right preCUN. (b) Schematic of the model specification in the DCM model. The light blue circles represent the nodes (ROIs) comprising the model: "pgACC" stands for the left pgACC, "DLPFC" for the left DLPFC, and "preCUN" for the right preCUN. The model includes the bidirectional connections between the ROIs and self-connections in matrix A, modulation of between-region connections by criticism and praise in matrix B, and driving input from the left pgACC in matrix C. Abbreviations: pgACC, pregenual anterior cingulate cortex; DLPFC, dorsolateral prefrontal cortex; preCUN, precuneus; L (R), left (right) hemisphere.

3. Results

3.1. Behavioral assessments

Behavioral assessments were analyzed using the Statistical Package for the Social Science (SPSS) version 28 (IBM, Chicago). To investigate the mood and ruminative state changes after exposure to criticism, a paired sample *t*-test was used to examine differences between TMDS, BSRI total scores, and PTQ total scores before and after exposure to criticism. The significance level was set at $p < .05$, two-tailed, for all analyses. Table 1 lists the mood and ruminative states before and after exposure to criticism. We found that the TMDS increased significantly after exposure to criticism ($t = 6.39$, $p < .001$), indicating that the adolescents experienced more negative affect after being criticized. In addition, we found that both the BSRI and PTQ total scores increased significantly after exposure to criticism ($t = 5.07$, $p < .001$; $t = 3.77$, $p < .001$), suggesting that adolescents ruminate more after being criticized.

3.2. DCM results

The intrinsic connections and modulatory connections of the neural architecture are listed in Table 2 and 3 respectively. Fig. 3 shows the effective connectivity parameters and modulatory connectivity parameters (with $P_p > 95\%$) in the DCM model. Positive values of the *intrinsic* connections indicate excitation of these connections; negative values indicate inhibition. Positive values of the *modulatory* connections indicate an excitatory effect on the effective connectivity under a particular experimental condition; negative values indicate inhibition under that experimental condition.

Our intrinsic connections analyses showed that the self-connections of the pgACC (-0.19 Hz, $P_p = 100\%$), DLPFC (-0.64 Hz, $P_p = 100\%$), and preCUN (-0.87 Hz, $P_p = 100\%$) were inhibitory. There was also strong evidence that showed that the pgACC-to-DLPFC (0.21 Hz, $P_p = 100\%$) and preCUN-to-DLPFC (0.13 Hz, $P_p = 100\%$) connections were excitatory, whereas the DLPFC-to-pgACC connection (-0.1 Hz, $P_p = 100\%$) was inhibitory.

Of most interest are the modulatory effects of the experimental conditions (exposure to praise or to criticism). We found that exposure to criticism modulated the preCUN-to-DLPFC connection (-0.49 Hz, $P_p = 100\%$) by decreasing the intrinsic excitation of this connection. In other words, exposure to criticism appeared to weaken the excitatory connection from the preCUN to the DLPFC. We also found that both praise (0.31 Hz, $P_p = 100\%$) and criticism (0.23 Hz, $P_p = 100\%$) modulated the DLPFC-to-pgACC connection by increasing the intrinsic inhibition of this connection. That is, both exposure to praise and to criticism appeared to strengthen the inhibitory connection from the DLPFC to the pgACC.

Furthermore, the inhibitory modulation of the preCUN-to-DLPFC connection by exposure to criticism was negatively associated with the participants' sensitivity to criticism (i.e., PCM score) (-0.21 Hz, $P_p = 100\%$). That is, higher perceived criticism was associated with a weaker inhibitory effect of exposure to criticism on the intrinsic excitation of the preCUN-to-DLPFC connection. However, the associations between individual differences in delta scores of the TMDS, BSRI total scores, and/or PTQ total scores on the one hand and modulatory connections on the

Table 2

Averaged connectivity parameters of intrinsic connections (matrix A) in DCM with PEB.

To ↓ From →	pgACC	DLPFC	preCUN
pgACC	-0.19*	-0.1*	-0.05
DLPFC	0.21*	-0.64*	0.13*
preCUN	0.04	-0.02	-0.87*

Notes: The asterisk symbol indicates the connectivity with a posterior probability (P_p) greater than 95 %. Positive values of connection strengths indicate excitation of the connections; negative values indicate inhibition. Abbreviations: pgACC, pregenual anterior cingulate cortex; DLPFC, dorsolateral prefrontal cortex; preCUN, precuneus.

Table 3

Averaged connectivity parameters of modulatory connections (matrix B) in DCM with PEB.

Connections	Commonalities	
	praise	criticism
pgACC → DLPFC	0	0
pgACC → preCUN	0	0
DLPFC → pgACC	0.31*	0.23*
DLPFC → preCUN	0	0
preCUN → pgACC	0	0
preCUN → DLPFC	-0.09	-0.49*

Notes: "Commonalities" represents the averaged strength of modulatory connectivity. The asterisk symbol indicates a connectivity with a posterior probability greater than 95 %. Positive values of modulatory connections indicate an excitatory effect on the effective connectivity under a specific experimental condition; negative values indicate an inhibitory effect under that condition. Abbreviations: pgACC, pregenual anterior cingulate cortex; DLPFC, dorsolateral prefrontal cortex; preCUN, precuneus.

other did not meet the threshold of statistical significance.

Additional exploratory moderation analyses with individual depressive symptom scores (CDI) did not significantly affect this preCUN-to-DLPFC connection either ($p > 0.05$) (see Supplementary Material).

4. Discussion

In the current study, we performed DCM analysis to examine how specific brain regions interact when dealing with praise and criticism in healthy adolescents. Specifically, we assessed how the effective connectivity between regions associated with emotional experiences (i.e., pgACC), emotion regulation through cognitive control (i.e., DLPFC), and self-referential thinking (i.e., preCUN) changed when exposed to praise and criticism. The DCM analyses revealed that the preCUN-to-DLPFC connection was not modulated by praise, but only by criticism (-0.49 Hz), which was negatively associated with the PCM score (-0.21 Hz). That is, the intrinsic excitatory connection from the preCUN to the DLPFC (0.13 Hz) was inhibited (i.e., became less excitatory) by exposure to criticism. This inhibitory effect was less pronounced in participants who were more sensitive to criticism (i.e., those with higher PCM scores). Moreover, the intrinsic inhibitory DLPFC-to-pgACC connection (-0.10 Hz) was enhanced by both praise (0.31 Hz) and criticism (0.23

Table 1

Behavioral variables of mood and ruminative states before and after experiment

	TMDS			BSRI total			PTQ total		
	Mean (SD)	<i>t</i>	<i>p-value</i>	Mean (SD)	<i>t</i>	<i>p-value</i>	Mean (SD)	<i>t</i>	<i>p-value</i>
pre	16.52 (7.66)	6.39	<.001	16.30 (13.15)	5.07	<.001	11.03 (10.79)	3.77	<.001
post	21.84 (6.83)			24.20 (15.07)			15.27 (12.33)		

Notes: A paired sample *t*-test was used to detect significant differences in TMDS, BSRI total scores, and PTQ total scores before and after exposure to criticism. Abbreviations: TMDS, Total Mood Disturbance Score; BSRI, Brief State Rumination Inventory; PTQ, Perseverative Thinking Questionnaire; pre, before the experiment; post, after the experiment; SD, standard deviation.

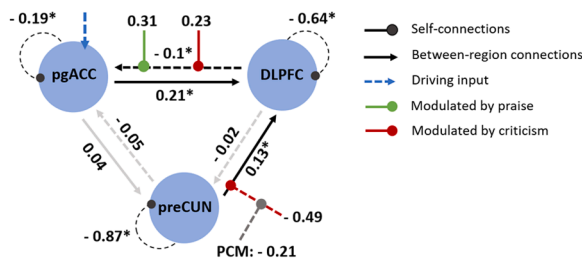


Fig. 3. The group-average DCM with PEB. The schematic illustrates the intrinsic connections and modulatory connections in the DCM model. The full lines indicate connections with a positive value (excitation), while the dotted lines indicate connections with a negative value (inhibition). For the *intrinsic* connections (matrix A), the black arrows represent connections with a posterior probability (Pp) greater than 95 %, while the light gray arrows represent connections with a Pp lower than 95 %. The asterisk symbol indicates an *intrinsic* connection with a Pp greater than 95 %. For the *modulatory* connections (matrix B), only those with a posterior probability greater than 95 % are presented. The “PCM: -0.21” represents the amount to which individual differences in modulatory effects on connectivity are explained by the participants’ sensitivity to criticism (i.e., by their PCM score). Abbreviations: pgACC, pregenual anterior cingulate cortex; DLPFC, dorsolateral prefrontal cortex; preCUN, pre-cuneus; PCM, Perceived Criticism Measure.

H_z), which implies that the connection from the DLPFC to the pgACC became more inhibitory during exposure to both praise and criticism.

First, our healthy adolescent participants reported a significant increase in mood disturbance and in ruminative thoughts after being criticized, indicating that the experimental manipulation was successful in inducing a more disturbed mood state and a more ruminative state. This finding is consistent with our hypotheses and aligns with previous studies on adult and adolescent samples demonstrating decreased positive mood states, increased negative mood states (Aupperle et al., 2016; Baeken et al., 2018; Dedoncker et al., 2019; van Schie et al., 2018; Vanderhasselt et al., 2015), and increased ruminative thinking after exposure to criticism (De Raedt et al., 2017; Kaiser et al., 2015).

Second, our DCM analyses showed that the intrinsic excitatory preCUN-to-DLPFC connection was inhibited (i.e., this connection became less excitatory) when adolescents were dealing with critical comments. This indicates that healthy adolescents responded to negative evaluative feedback by inhibiting the excitatory preCUN-to-DLPFC connection. The preCUN is an important node of the DMN, and is commonly implicated in self-referential processing and rumination (Davey et al., 2016; Utevsky et al., 2014; Zhou et al., 2020). On the other hand, the DLPFC is part of the Central Executive Network (CEN), which is related to cognitive control processes (Barch, 2013; Menon and D’Esposito, 2022). Interactions between the DMN and the CEN, which are critical for cognitive and emotional regulation, have been demonstrated in previous studies (Gotlieb et al., 2022; Lydon-Staley et al., 2019). The interplay between the DLPFC and the DMN is well-known to be linked to cognitive control over emotions and self-referential processing (Liu et al., 2022; Miller et al., 2015). An increased FC between the posterior cingulate cortex (PCC)/preCUN and the DLPFC has also been shown in healthy adolescents after exposure to criticism (Lee et al., 2015), indicating an interaction between self-referential processes and cognitive control. On the other hand, other studies have linked *lower* FC between the CEN and DMN to more adaptive emotion behavior (Banihashemi et al., 2023). Our current effective connectivity findings add to these observations: exposure to criticism inhibited the excitatory connection from the preCUN to the DLPFC in our healthy adolescent population. As such, inhibition of this preCUN-to-DLPFC connection appears to be a normative neural response to negative evaluative feedback in adolescents.

Importantly, when adolescents who scored higher on the PCM (i.e., those who were more sensitive to criticism) were exposed to criticism, the degree of modulatory inhibition of the intrinsic excitatory preCUN-

to-DLPFC connection decreased. This implies that adolescents who were more sensitive to criticism may have inhibited effective connectivity from regions involved in self-referential processing (i.e., preCUN) to regions involved in cognitive control (i.e., DLPFC) to a lesser extent than those who were not as sensitive to criticism. One possible interpretation is that this could have allowed them to engage the CEN (involved in cognitive control) relatively more to counteract negative evaluative feedback. Previous studies suggested that high levels of perceived criticism are considered a predictor of high levels of rumination (Pearson et al., 2011), as well as a risk factor for developing psychopathology (e.g., anxiety and depressive disorders) in both adults and adolescents (Hooley et al., 2005; Hooley and Miklowitz, 2017). It has been demonstrated that individuals who score high on the PCM have more difficulty exercising attentional control in the context of negative emotional information (e.g., criticism) (Masland and Hooley, 2015). In addition, previous studies found that both adolescent and adult individuals with higher levels of rumination may allocate more cognitive resources to negative evaluative feedback than those with lower levels of rumination, which interferes with the performance of tasks that demand cognitive resources (Kaiser et al., 2015; Yoon et al., 2023). Taken together, our findings may indicate that adolescents who were more sensitive to criticism required more engagement of the CEN to sufficiently disengage from negative evaluative feedback, showing a similar pattern as individuals with higher levels of rumination. Moreover, the connectivity between the DLPFC and the preCUN has been identified as a neural biomarker related to depression. In this perspective, our findings may indicate that a lower extent of modulatory inhibition on the intrinsic excitatory preCUN-to-DLPFC connection (as observed in those adolescents of our sample who were more sensitive to criticism) could be a potential biomarker for heightened risk for the development of mood and anxiety disorders.

Of note, no modulatory (inhibitory or excitatory) effect on the intrinsic preCUN-to-DLPFC connection was observed during exposure to praising audio segments. This may be explained by an overall increased sensitivity to criticism during adolescence, resulting in stronger emotional responses to negative than to positive or neutral verbal feedback. Lamblin et al. (2017) suggested that feelings in response to negative feedback are particularly salient for adolescents. Rodman et al. (2017) also revealed that relative to adults, adolescents (including healthy ones) may internalize negative feedback to a greater extent, leaving them more vulnerable to such feedback.

Our DCM analyses also revealed that the intrinsic inhibitory connection from the DLPFC to the pgACC was strengthened when healthy adolescents were exposed to both praise and criticism. This finding may provide insights into the neural mechanisms involved in processing both positive and negative evaluative feedback in the adolescent brain. As mentioned, the DLPFC (as a part of the CEN) is implicated in cognitive control and plays an important role in emotion regulation (Kohn et al., 2014; Ochsner and Gross, 2005). On the other hand, the pgACC is primarily involved in emotional self-regulation and integrating emotional and cognitive information (Shafritz et al., 2006). It has been shown to contribute to inhibitory processing of emotional stimuli (Cui et al., 2023; Etkin et al., 2011; Eugene et al., 2010), and it also serves as a connectional hub which receives projections from the (pre-)frontal cortex (such as the DLPFC) (Tang et al., 2019). It has been suggested that the pgACC can be activated by emotional experiences, both with a positive and a negative valence (Bjork et al., 2017; Lindquist et al., 2016). It has been proposed that in people who are vulnerable for depression, prolonged processing of emotional experiences could be maintained by impaired top-down cognitive control (by brain areas such as the DLPFC) over limbic areas (via the ACC) (De Raedt and Koster, 2010; Disner et al., 2011). Our finding of an enhanced intrinsic inhibitory DLPFC-to-pgACC connection may reflect the healthy adolescent brain’s adaptive response to both positive and negative evaluative information by suppressing emotional responses and facilitating cognitive control processes.

Although our healthy adolescents reported a significant increase in mood disturbance and in ruminative thoughts after the experiment, we did not find statistically significant associations between the changes in mood or ruminative states (i.e., Δ TMDS, Δ PTQ and Δ BSRI scores) and the modulatory effects of exposure to praise or criticism on the effective connectivity between each pair of ROIs within the neural architecture (i.e., the pgACC, DLPFC, and preCUN). This may seem unexpected, given that these regions are known to be associated with ruminative and/or mood changes. However, the relative size of those ruminative or mood changes appears not to be correlated with the changes in effective connectivity between our ROIs. This might be explained in part by the fact that our sample consisted of non-depressed adolescents, rather than (depressed) adults. For instance, connectivity between the DLPFC and the preCUN has been identified as a neural biomarker related to rumination in adult depression (Benschop et al., 2021; Ichikawa et al., 2020; Taylor et al., 2022), but that may not apply to non-depressed and/or younger brains. Furthermore, the timing and frequency of our mood and rumination assessments may not have been optimal: the TMDS, BSRI, and PTQ were assessed before and after the entire experimental protocol, but not before and after each block of praising, neutral or critical audio segments. As such, we may have missed the actual mood and/or ruminative state changes that occurred during and/or immediately after each block of audio segments, which is when our fMRI scans were performed.

There are several other limitations and strengths with regard to the present study that merit being addressed. Some of these have already been discussed in previous publications (Bonduelle et al., 2021; Bonduelle et al., 2023). This study included an extensive mental health assessment and recruited a relatively large and homogeneous sample ($n = 64$) of healthy (non-depressed) adolescents within a specific age range (14 to 17 years old), which can be considered as a major strength of this study. Concerning study limitations, first, our DCM analyses are constructed based on *a priori* selected ROIs. Although this selection was based on literature findings and was supported by our activation results (see Fig. S1) to define a model space, other ROIs related to emotional and cognitive processing could have been involved as well. Next, the adolescents were all exposed to the same series of auditory segments, which were designed to be broadly applicable within a typical parent-to-adolescent interaction, rather than individually tailored praise or criticism expressed by one of the participants' own parents. This standardized experimental set-up (which was very similar to some other studies, such as Chou et al., 2023) may well have tempered the adolescents' emotional responses (Bonduelle et al., 2021; Silk et al., 2017), but is also less likely to have caused variation between the participants due to the specific content or tone of the segments. We did not ask our participants who they imagined was giving them feedback; future studies could include this question. As mentioned above, mood and ruminative states were only assessed before and after the entire experiment, with criticism as the last auditory script. These state changes were not assessed before and/or after exposure to emotionally neutral or positive (praising) comments to minimize the time spent in the MRI scanner and any involuntary head movement. As two critical segments were played at the end, it is assumed that changes in mood and ruminative states are (largely) due to these negative comments. However, we cannot know whether these changes would have been different if we had not played the neutral and positive comments before, and cannot compare the mood and ruminative states in each experimental condition. Moreover, the effects on the participants' ruminative state could have been more apparent in the silent periods following the auditory comments, as ruminative thoughts may have especially occurred (or increased) during those periods (Chou et al., 2023). Lastly, although we controlled for age and gender, there were more girls than boys in our sample. Indeed, there is evidence of gender (and age) differences regarding neural mechanisms underlying emotional processing following negative social evaluation and vulnerability to depressive symptoms (Bangasser and Cuarenta, 2021; García-García et al., 2016;

Lungu et al., 2015). It could be of interest to further investigate the influence of gender and age in future studies.

5. Conclusions

To our knowledge, this is the first study using DCM to examine how three key brain regions involved in emotional reactivity, self-referential processing and emotion regulation through cognitive control interact when dealing with praise or criticism in a healthy adolescent sample. Our results indicated that the intrinsic inhibitory connectivity from the DLPFC to the pgACC was strengthened during exposure to both praise and criticism, pointing to a recruitment of cognitive control and emotion regulation in response to both positive and negative evaluative feedback. However, only exposure to criticism weakened the intrinsic excitatory connectivity from the preCUN to the DLPFC. Importantly, adolescents who were more sensitive to criticism (i.e., higher PCM scores) exhibited less inhibitory modulation of their excitatory preCUN-to-DLPFC connectivity during exposure to criticism. These findings provide better insights into the healthy adolescent's neural response to criticism, offering a deeper comprehension of this dynamic, which may hold promise for identifying biomarkers that could signal a predisposition to mood disorders in adolescents, either currently or as they transition into adulthood. Future research should verify whether similar effective connectivity patterns are present in clinical adolescent samples and whether these persist into adulthood.

Compliance with ethical standards

The study protocol involving human participants was approved by the UZ Gent Medical Ethics Committee. Written informed consent was obtained from each participant's parents/legal guardian before the study.

CRedit authorship contribution statement

Qinyuan Chen: Conceptualization, Formal analysis, Validation, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. **Sam Luc Bart Bonduelle:** Conceptualization, Investigation, Writing – review & editing. **Guo-Rong Wu:** Conceptualization, Supervision, Writing – review & editing. **Marie-Anne Vanderhasselt:** Writing – review & editing. **Rudi De Raedt:** Conceptualization, Supervision, Writing – review & editing. **Chris Baeken:** Conceptualization, Supervision, Resources, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no competing financial interests.

Data availability

Due to the requirements of the institutional ethics, the datasets generated and analyzed in the current study are only made available via a request to the corresponding author, with the need a formal data sharing agreement.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.neuroimage.2024.120510](https://doi.org/10.1016/j.neuroimage.2024.120510).

References

- Abend, R., Sar-el, R., Gonen, T., Jalon, I., Vaisvaser, S., Bar-Haim, Y., Hendler, T., 2019. Modulating emotional experience using electrical stimulation of the medial-prefrontal cortex: a preliminary tDCS-fMRI study. *Neuromodulation* 22 (8), 884–893. <https://doi.org/10.1111/ner.12787>.
- Ahmed, S.P., Bittencourt-Hewitt, A., Sebastian, C.L., 2015. Neurocognitive bases of emotion regulation development in adolescence. *Dev. Cogn. Neurosci.* 15, 11–25. <https://doi.org/10.1016/j.dcn.2015.07.006>.
- Andrews-Hanna, J.R., Smallwood, J., Spreng, R.N., 2014. The default network and self-generated thought: component processes, dynamic control, and clinical relevance. *Ann. N.Y. Acad. Sci.* 1316 (1), 29–52. <https://doi.org/10.1111/nyas.12360>.
- Aupperle, R.L., Morris, A.S., Silk, J.S., Criss, M.M., Judah, M.R., Eagleton, S.G., Alvarez, R.P., 2016. Neural responses to maternal praise and criticism: relationship to depression and anxiety symptoms in high-risk adolescent girls. *Neuroimage Clin.* 11, 548–554. <https://doi.org/10.1016/j.nicl.2016.03.009>.
- Baeken, C., Dedoncker, J., Remue, J., Wu, G.R., Vanderhasselt, M.A., De Witte, S., De Raedt, R., 2018. One MRI-compatible tDCS session attenuates ventromedial cortical perfusion when exposed to verbal criticism: the role of perceived criticism. *Hum. Brain Mapp.* 39 (11), 4462–4470. <https://doi.org/10.1002/hbm.24285>.
- Bangasser, D.A., Cuarenta, A., 2021. Sex differences in anxiety and depression: circuits and mechanisms. *Nat. Rev. Neurosci.* 22 (11), 674–684. <https://doi.org/10.1038/s41583-021-00513-0>.
- Banihashemi, L., Schmithorst, V.J., Bertocci, M.A., Samolyk, A., Zhang, Y., Lima Santos, J.P., Phillips, M.L., 2023. Neural network functional interactions mediate or suppress white matter-emotional behavior relationships in infants. *Biol. Psychiatry* 94 (1), 57–67. <https://doi.org/10.1016/j.biopsych.2023.03.004>.
- Barch, D.M., 2013. Brain network interactions in health and disease. *Trend. Cognit. Sci.* 17 (12), 603–605. <https://doi.org/10.1016/j.tics.2013.09.004>.
- Bartova, L., Meyer, B.M., Diers, K., Rabl, U., Scharinger, C., Popovic, A., Pezawas, L., 2015. Reduced default mode network suppression during a working memory task in remitted major depression. *J. Psychiatr. Res.* 64, 9–18. <https://doi.org/10.1016/j.jpsychires.2015.02.025>.
- Beck, A.T., Kovacs, M., Weissman, A., 1979. Assessment of suicidal intention: the scale for suicide ideation. *J. Consult. Clin. Psychol.* 47, 343–352. <https://doi.org/10.1037/0022-006X.47.2.343>.
- Behzadi, Y., Restom, K., Liu, J., Liu, T.T., 2007. A component based noise correction method (CompCor) for BOLD and perfusion based fMRI. *Neuroimage* 37 (1), 90–101. <https://doi.org/10.1016/j.neuroimage.2007.04.042>.
- Benschop, L., Poppa, T., Medani, T., Shahabi, H., Baeken, C., Leahy, R.M., Vanderhasselt, M.A., 2021. Electrophysiological scarring in remitted depressed patients: elevated EEG functional connectivity between the posterior cingulate cortex and the subgenual prefrontal cortex as a neural marker for rumination. *J. Affect. Disord.* 281, 493–501. <https://doi.org/10.1016/j.jad.2020.12.081>.
- Bjork, J. M., Straub, L. K., Provost, R. G., & Neale, M. C. J. C. t. o. i. p. (2017). The ABCD study of neurodevelopment: identifying neurocircuit targets for prevention and treatment of adolescent substance abuse. 4, 196–209.
- Bonduelle, S.L.B., Chen, Q., Wu, G.R., Braet, C., De Raedt, R., Baeken, C., 2021. Exposure to criticism modulates left but not right amygdala functional connectivity in healthy adolescents: individual influences of perceived and self-criticism. *Front. Psychiatry* 12, 673805. <https://doi.org/10.3389/fpsy.2021.673805>.
- Bonduelle, S.L.B., De Raedt, R., Braet, C., Campforts, E., Baeken, C., 2023. Parental criticism affects adolescents' mood and ruminative state: self-perception appears to influence their mood response. *J. Exp. Child. Psychol.* 235, 105728. <https://doi.org/10.1016/j.jecp.2023.105728>.
- Burcusa, S.L., Iacono, W.G., 2007. Risk for recurrence in depression. *Clin. Psychol. Rev.* 27 (8), 959–985. <https://doi.org/10.1016/j.cpr.2007.02.005>.
- Bush, G., Luu, P., Posner, M.I., 2000. Cognitive and emotional influences in anterior cingulate cortex. *Trend. Cognit. Sci.* 4 (6), 215–222. [https://doi.org/10.1016/s1364-6613\(00\)01483-2](https://doi.org/10.1016/s1364-6613(00)01483-2).
- Butterfield, R.D., Silk, J.S., Lee, K.H., Siegle, G.S., Dahl, R.E., Forbes, E.E., Ladouceur, C. D., 2021. Parents still matter! Parental warmth predicts adolescent brain function and anxiety and depressive symptoms 2 years later. *Dev. Psychopathol.* 33 (1), 226–239. <https://doi.org/10.1017/s0954579419001718>.
- Carnevali, L., Koenig, J., Sgoifo, A., Ottaviani, C., 2018. Autonomic and brain morphological predictors of stress resilience. *Front. Neurosci.* 12. <https://doi.org/10.3389/fnins.2018.00228>.
- Chai, X.Q.J., Hirshfeld-Becker, D., Biederman, J., Uchida, M., Doehrmann, O., Leonard, J.A., Whitfield-Gabrieli, S., 2016. Altered intrinsic functional brain architecture in children at familial risk of major depression. *Biol. Psychiatry* 80 (11), 849–858. <https://doi.org/10.1016/j.biopsych.2015.12.003>.
- Chen, J., Tam, A., Kebets, V., Orban, C., Ooi, L.Q.R., Asplund, C.L., Yeo, B.T.T., 2022. Shared and unique brain network features predict cognitive, personality, and mental health scores in the ABCD study. *Nat. Commun.* 13 (1), 2217. <https://doi.org/10.1038/s41467-022-29766-8>.
- Chou, T., Deckersbach, T., Dougherty, D.D., Hooley, J.M., 2023. The default mode network and rumination in individuals at risk for depression. *Soc. Cogn. Affect. Neurosci.* 18 (1). <https://doi.org/10.1093/scan/nsad032>.
- Cooney, R.E., Joormann, J., Eugène, F., Dennis, E.L., Gotlib, I.H., 2010. Neural correlates of rumination in depression. *Cogn. Affect. Behav. Neurosci.* 10 (4), 470–478. <https://doi.org/10.3758/cabn.10.4.470>.
- Cox, R.W., Hyde, J.S., 1997. Software tools for analysis and visualization of fMRI data. *NMR Biomed.* 10 (4–5), 171–178. [https://doi.org/10.1002/\(sici\)1099-1492\(199706/08\)10:4/5<171::Aid-nbm453>3.0.Co;2-I](https://doi.org/10.1002/(sici)1099-1492(199706/08)10:4/5<171::Aid-nbm453>3.0.Co;2-I).
- Crone, E.A., Dahl, R.E., 2012. Understanding adolescence as a period of social-affective engagement and goal flexibility. *Nat. Rev. Neurosci.* 13 (9), 636–650. <https://doi.org/10.1038/nrn3313>.
- Cui, H.L., Zhang, Y.Y., Zhao, Y.J., Zhao, Y., Ding, Q., Chen, R.Q., Voon, V., 2023. Mechanisms underlying capsulotomy for refractory obsessive-compulsive disorder: neural correlates of negative affect processing overlap with deep brain stimulation targets. *Mol. Psychiatry*. <https://doi.org/10.1038/s41380-023-01989-1>.
- Davey, C.G., Pujol, J., Harrison, B.J., 2016. Mapping the self in the brain's default mode network. *Neuroimage* 132, 390–397. <https://doi.org/10.1016/j.neuroimage.2016.02.022>.
- De Raedt, R., Koster, E.H., 2010. Understanding vulnerability for depression from a cognitive neuroscience perspective: a reappraisal of attentional factors and a new conceptual framework. *Cogn. Affect. Behav. Neurosci.* 10 (1), 50–70. <https://doi.org/10.3758/cabn.10.1.50>.
- De Raedt, R., Remue, J., Loeys, T., Hooley, J.M., Baeken, C., 2017. The effect of transcranial direct current stimulation of the prefrontal cortex on implicit self-esteem is mediated by rumination after criticism. *Behav. Res. Ther.* 99, 138–146. <https://doi.org/10.1016/j.brat.2017.10.009>.
- Dedoncker, J., Vanderhasselt, M.A., Remue, J., De Witte, S., Wu, G.R., Hooley, J.M., Baeken, C., 2019. Prefrontal tDCS attenuates medial prefrontal connectivity upon being criticized in individuals scoring high on perceived criticism. *Brain Imaging Behav.* 13 (4), 1060–1070. <https://doi.org/10.1007/s11682-018-9927-8>.
- Disner, S.G., Beevers, C.G., Haigh, E.A., Beck, A.T., 2011. Neural mechanisms of the cognitive model of depression. *Nat. Rev. Neurosci.* 12 (8), 467–477. <https://doi.org/10.1038/nrn3027>.
- Drevets, W.C., Price, J.L., Simpson, J.R., Todd, R.D., Reich, T., Vannier, M., Raichle, M. E., 1997. Subgenual prefrontal cortex abnormalities in mood disorders. *Nature* 386 (6627), 824–827. <https://doi.org/10.1038/386824a0>.
- Edes, A.E., McKie, S., Szabo, E., Kokonyei, G., Pap, D., Zsombok, T., Juhasz, G., 2019. Increased activation of the pregenual anterior cingulate cortex to citalopram challenge in migraine: an fMRI study. *Bmc Neurol.* 19 (1). <https://doi.org/10.1186/s12883-019-1478-0>.
- Ehring, T., Zetsche, U., Weidacker, K., Wahl, K., Schönfeld, S., Ehlers, A., 2011. The perseverative thinking questionnaire (PTQ): validation of a content-independent measure of repetitive negative thinking. *J. Behav. Ther. Exp. Psychiatry* 42 (2), 225–232. <https://doi.org/10.1016/j.jbtep.2010.12.003>.
- Esteban, O., Ciric, R., Finc, K., Blair, R.W., Markiewicz, C.J., Moodie, C.A., Gorgolewski, K.J., 2020. Analysis of task-based functional MRI data preprocessed with fMRIPrep. *Nat. Protoc.* 15 (7), 2186–2202. <https://doi.org/10.1038/s41596-020-0327-3>.
- Etkin, A., Egner, T., Kalisch, R., 2011. Emotional processing in anterior cingulate and medial prefrontal cortex. *Trend. Cognit. Sci.* 15 (2), 85–93. <https://doi.org/10.1016/j.tics.2010.11.004>.
- Eugene, F., Joormann, J., Cooney, R.E., Atlas, L.Y., Gotlib, I.H., 2010. Neural correlates of inhibitory deficits in depression. *Psychiatry Res. Neuroimag.* 181 (1), 30–35. <https://doi.org/10.1016/j.psychres.2009.07.010>.
- Friston, K., 2009. Causal modelling and brain connectivity in functional magnetic resonance imaging. *PLoS Biol.* 7 (2), e33. <https://doi.org/10.1371/journal.pbio.1000033>.
- Friston, K., Litvak, V., Oswal, A., Razi, A., Stephan, K.E., van Wijk, B.C.M., Zeidman, P., 2016. Bayesian model reduction and empirical Bayes for group (DCM) studies. *Neuroimage* 128, 413–431. <https://doi.org/10.1016/j.neuroimage.2015.11.015>.
- García-García, I., Kube, J., Gaebler, M., Horstmann, A., Villringer, A., Neumann, J., 2016. Neural processing of negative emotional stimuli and the influence of age, sex and task-related characteristics. *Neurosci. Biobehav. Rev.* 68, 773–793. <https://doi.org/10.1016/j.neubiorev.2016.04.020>.
- Gotlib, R., Yang, X.F., Immordino-Yang, M.H., 2022. Default and executive networks' roles in diverse adolescents' emotionally engaged construals of complex social issues. *Soc. Cogn. Affect. Neurosci.* 17 (4), 421–429. <https://doi.org/10.1093/scan/nsab108>.

- Greve, D.N., Fischl, B., 2009. Accurate and robust brain image alignment using boundary-based registration. *Neuroimage* 48 (1), 63–72. <https://doi.org/10.1016/j.neuroimage.2009.06.060>.
- Hooley, J.M., Gruber, S.A., Parker, H.A., Guillaumot, J., Rogowska, J., Yurgelun-Todd, D.A., 2009. Cortico-limbic response to personally challenging emotional stimuli after complete recovery from depression. *Psychiatry Res.* 172 (1), 83–91. <https://doi.org/10.1016/j.psychres.2009.02.001>.
- Hooley, J.M., Gruber, S.A., Scott, L.A., Hiller, J.B., Yurgelun-Todd, D.A., 2005. Activation in dorsolateral prefrontal cortex in response to maternal criticism and praise in recovered depressed and healthy control participants. *Biol. Psychiatry* 57 (7), 809–812. <https://doi.org/10.1016/j.biopsych.2005.01.012>.
- Hooley, J.M., Miklowitz, D.J., 2017. Perceived criticism in the treatment of a high-risk adolescent. *J. Clin. Psychol.* 73 (5), 570–578. <https://doi.org/10.1002/jclp.22454>.
- Hooley, J.M., Siegle, G., Gruber, S.A., 2012. Affective and neural reactivity to criticism in individuals high and low on perceived criticism. *PLoS One* 7 (9), e44412. <https://doi.org/10.1371/journal.pone.0044412>.
- Hooley, J.M., Teasdale, J.D., 1989. Predictors of relapse in unipolar depressives: expressed emotion, marital distress, and perceived criticism. *J. Abnorm. Psychol.* 98 (3), 229–235. <https://doi.org/10.1037//0021-843x.98.3.229>.
- Ichikawa, N., Lisi, G., Yahata, N., Okada, G., Takamura, M., Hashimoto, R.I., Okamoto, Y., 2020. Primary functional brain connections associated with melancholic major depressive disorder and modulation by antidepressants. *Sci. Rep.* 10 (1) <https://doi.org/10.1038/s41598-020-60527-z>.
- Jenkinson, M., Bannister, P., Brady, M., Smith, S., 2002. Improved optimization for the robust and accurate linear registration and motion correction of brain images. *Neuroimage* 17 (2), 825–841. [https://doi.org/10.1016/s1053-8119\(02\)91132-8](https://doi.org/10.1016/s1053-8119(02)91132-8).
- Kaiser, R.H., Andrews-Hanna, J.R., Metcalfe, C.A., Dimidjian, S., 2015. Dwell or decenter? Rumination and decentering predict working memory updating after interpersonal criticism. *Cognit. Therapy Res.* 39 (6), 744–753. <https://doi.org/10.1007/s10608-015-9697-1>.
- Kaufman, J., Birmaher, B., Brent, D., Rao, U., Flynn, C., Moreci, P., Ryan, N., 1997. Schedule for affective disorders and schizophrenia for school-age children present and lifetime version (K-SADS-PL): initial reliability and validity data. *J. Am. Acad. Child Adolescent Psychiatry* 36 (7), 980–988. <https://doi.org/10.1097/00004583-199707000-00021>.
- Kohn, N., Eickhoff, S.B., Scheller, M., Laird, A.R., Fox, P.T., Habel, U., 2014. Neural network of cognitive emotion regulation - An ALE meta-analysis and MACM analysis. *Neuroimage* 87, 345–355. <https://doi.org/10.1016/j.neuroimage.2013.11.001>.
- Kovacs, M., 1992. *Children's Depression Inventory*. Multi-Health Systems, Inc, North Tonawanda, NY.
- Lamblin, M., Murawski, C., Whittle, S., Fornito, A., 2017. Social connectedness, mental health and the adolescent brain. *Neurosci. Biobehav. Rev.* 80, 57–68. <https://doi.org/10.1016/j.neubiorev.2017.05.010>.
- Lee, K.H., Siegle, G.J., Dahl, R.E., Hooley, J.M., Silk, J.S., 2015. Neural responses to maternal criticism in healthy youth. *Soc. Cogn. Affect. Neurosci.* 10 (7), 902–912. <https://doi.org/10.1093/scan/nsu133>.
- Lindquist, K.A., Satpute, A.B., Wager, T.D., Weber, J., Barrett, L.F., 2016. The brain basis of positive and negative affect: evidence from a meta-analysis of the human neuroimaging literature. *Cerebral Cortex* 26 (5), 1910–1922. <https://doi.org/10.1093/cercor/bhv001>.
- Liu, G., Zhang, N., Teoh, J.Y., Egan, C., Zeffiro, T.A., Davidson, R.J., Quevedo, K., 2022. Self-compassion and dorsolateral prefrontal cortex activity during sad self-face recognition in depressed adolescents. *Psychol. Med.* 52 (5), 864–873. <https://doi.org/10.1017/s0033291720002482>.
- Lungu, O., Potvin, S., Tikász, A., Mendrek, A., 2015. Sex differences in effective fronto-limbic connectivity during negative emotion processing. *Psychoneuroendocrinology* 62, 180–188. <https://doi.org/10.1016/j.psypneuro.2015.08.012>.
- Lydon-Staley, D.M., Kuehner, C., Zamosc, V., Huffziger, S., Kirsch, P., Bassett, D.S., 2019. Repetitive negative thinking in daily life and functional connectivity among default mode, fronto-parietal, and salience networks. *Transl. Psychiatry* 9. <https://doi.org/10.1038/s41398-019-0560-0>.
- Manstead, A.S., Proffitt, C., Smart, J.L., 1983. Predicting and understanding mothers' infant-feeding intentions and behavior: testing the theory of reasoned action. *J. Pers. Soc. Psychol.* 44 (4), 657–671. <https://doi.org/10.1037//0022-3514.44.4.657>.
- Marchetti, I., Mor, N., Chiorri, C., Koster, E.H.W., 2018. The brief state rumination inventory (BSRI): validation and psychometric evaluation. *Cognit. Therapy Res.* 42 (4), 447–460. <https://doi.org/10.1007/s10608-018-9901-1>.
- Marusak, H.A., Thomason, M.E., Peters, C., Zundel, C., Elrahal, F., Rabinak, C.A., 2016. You say 'prefrontal cortex' and I say 'anterior cingulate': meta-analysis of spatial overlap in amygdala-to-prefrontal connectivity and internalizing symptomatology. *Transl. Psychiatry* 6. <https://doi.org/10.1038/tp.2016.218>.
- Masland, S.R., Hooley, J.M., 2015. Perceived criticism: a research update for clinical practitioners. *Clin. Psychol.-Sci. Practice* 22 (3), 211–222. <https://doi.org/10.1111/cpsp.12110>.
- Masten, C.L., Eisenberger, N.I., Borofsky, L.A., McNealy, K., Pfeifer, J.H., Dapretto, M., 2011. Subgenual anterior cingulate responses to peer rejection: a marker of adolescents' risk for depression. *Dev. Psychopathol.* 23 (1), 283–292. <https://doi.org/10.1017/s0954579410000799>.
- McNair, D.M., Lorr, M., Droppleman, L.F., 1992. *Profile of Mood States: Manual*. EdITS.
- Menon, V., D'Esposito, M., 2022. The role of PFC networks in cognitive control and executive function. *Neuropsychopharmacology* 47 (1), 90–103. <https://doi.org/10.1038/s41386-021-01152-w>.
- Miller, C.H., Hamilton, J.P., Sacchet, M.D., Gotlib, I.H., 2015. Meta-analysis of functional neuroimaging of major depressive disorder in youth. *Jama Psychiatry* 72 (10), 1045–1053. <https://doi.org/10.1001/jamapsychiatry.2015.1376>.
- Nelemans, S.A., Hale 3rd, W.W., Branje, S.J., Hawk, S.T., Meeus, W.H., 2014. Maternal criticism and adolescent depressive and generalized anxiety disorder symptoms: a 6-year longitudinal community study. *J. Abnorm. Child Psychol.* 42 (5), 755–766. <https://doi.org/10.1007/s10802-013-9817-x>.
- Nolen-Hoeksema, S., Wisco, B.E., Lyubomirsky, S., 2008. Rethinking rumination. *Perspect. Psychol. Sci.* 3 (5), 400–424. <https://doi.org/10.1111/j.1745-6924.2008.00088.x>.
- Ochsner, K.N., Gross, J.J., 2005. The cognitive control of emotion. *Trend. Cognit. Sci.* 9 (5), 242–249. <https://doi.org/10.1016/j.tics.2005.03.010>.
- Paus, T., Keshavan, M., Giedd, J.N., 2008. Why do many psychiatric disorders emerge during adolescence? *Nat. Rev. Neurosci.* 9 (12), 947–957. <https://doi.org/10.1038/nrn2513>.
- Pearson, K.A., Watkins, E.R., Mullan, E.G., 2011. Rejection sensitivity prospectively predicts increased rumination. *Behav. Res. Ther.* 49 (10), 597–605. <https://doi.org/10.1016/j.brat.2011.06.004>.
- Power, J.D., Mitra, A., Laumann, T.O., Snyder, A.Z., Schlaggar, B.L., Petersen, S.E., 2014. Methods to detect, characterize, and remove motion artifact in resting state fMRI. *Neuroimage* 84, 320–341. <https://doi.org/10.1016/j.neuroimage.2013.08.048>.
- Powers, A., Casey, B., 2015. The adolescent brain and the emergence and peak of psychopathology. *J. Infant, Child, Adolesc. Psychotherapy* 14 (1), 3–15.
- Rodman, A.M., Powers, K.E., Somerville, L.H., 2017. Development of self-protective biases in response to social evaluative feedback. *Proc. Natl. Acad. Sci. U.S.A.* 114 (50), 13158–13163. <https://doi.org/10.1073/pnas.1712398114>.
- Scharnowski, F., Nicholson, A.A., Pichon, S., Rosa, M.J., Rey, G., Eickhoff, S.B., Koush, Y., 2020. The role of the subgenual anterior cingulate cortex in dorsomedial prefrontal-amygdala neural circuitry during positive-social emotion regulation. *Hum. Brain Mapp.* 41 (11), 3100–3118. <https://doi.org/10.1002/hbm.25001>.
- Shafritz, K.M., Collins, S.H., Blumberg, H.P., 2006. The interaction of emotional and cognitive neural systems in emotionally guided response inhibition. *Neuroimage* 31 (1), 468–475. <https://doi.org/10.1016/j.neuroimage.2005.11.053>.
- Silk, J.S., Lee, K.H., Elliott, R.D., Hooley, J.M., Dahl, R.E., Barber, A., Siegle, G.J., 2017. Mom-I don't want to hear it': brain response to maternal praise and criticism in adolescents with major depressive disorder. *Soc. Cogn. Affect. Neurosci.* 12 (5), 729–738. <https://doi.org/10.1093/scan/nsx014>.
- Stephan, K.E., Penny, W.D., Moran, R.J., den Ouden, H.E.M., Daunizeau, J., Friston, K.J., 2010. Ten simple rules for dynamic causal modeling. *Neuroimage* 49 (4), 3099–3109. <https://doi.org/10.1016/j.neuroimage.2009.11.015>.
- Supekar, K., Musen, M., Menon, V., 2009. Development of large-scale functional brain networks in children. *PLoS Biol.* 7 (7), e1000157. <https://doi.org/10.1371/journal.pbio.1000157>.
- Tang, W., Jbabdi, S., Zhu, Z.Y., Cottaar, M., Grisot, G., Lehman, J.F., Haber, S.N., 2019. A connectional hub in the rostral anterior cingulate cortex links areas of emotion and cognitive control. *eLife* 8. <https://doi.org/10.7554/eLife.43761>.
- Taylor, J.E., Yamada, T., Kawashima, T., Kobayashi, Y., Yoshihara, Y., Miyata, J., Motegi, T., 2022. Depressive symptoms reduce when dorsolateral prefrontal cortex-precuneus connectivity normalizes after functional connectivity neurofeedback. *Sci. Rep.* 12 (1) <https://doi.org/10.1038/s41598-022-05860-1>.
- Thapar, A., Eyre, O., Patel, V., Brent, D., 2022. Depression in young people. *Lancet* 400 (10352), 617–631. [https://doi.org/10.1016/s0140-6736\(22\)01012-1](https://doi.org/10.1016/s0140-6736(22)01012-1).
- Thompson, R.J., Berenbaum, H., 2009. The association between rejection and depression in the context of women's relationships with their parents. *J. Soc. Person. Rel.* 26 (2–3), 327–339. <https://doi.org/10.1177/0265407509106721>.
- Tustison, N.J., Avants, B.B., Cook, P.A., Zheng, Y., Egan, A., Yushkevich, P.A., Gee, J.C., 2010. N4ITK: improved N3 bias correction. *IEEE Trans. Med. Imaging* 29 (6), 1310–1320. <https://doi.org/10.1109/tmi.2010.2046908>.
- Utevsky, A.V., Smith, D.V., Huettel, S.A., 2014. Precuneus is a functional core of the default-mode network. *J. Neurosci.* 34 (3), 932–940. <https://doi.org/10.1523/jneurosci.4227-13.2014>.
- van Houtum, L., Will, G.J., Wever, M.C.M., Janssen, L.H.C., van Schie, C.C., Tollenaar, M.S., Elzinga, B.M., 2022. Adolescents' affective and neural responses to parental praise and criticism. *Dev. Cogn. Neurosci.* 54, 101099. <https://doi.org/10.1016/j.dcn.2022.101099>.
- Van Mao, C., Araujo, M.F.P., Nishimaru, H., Matsumoto, J., Tran, A.H., Hori, E., Nishijo, H., 2017. Pregenual anterior cingulate gyrus involvement in spontaneous social interactions in primates-evidence from behavioral, pharmacological, neuropsychiatric, and neurophysiological findings. *Front. Neurosci.* 11. <https://doi.org/10.3389/fnins.2017.00034>.
- van Schie, C.C., Chiu, C.D., Rombouts, S., Heiser, W.J., Elzinga, B.M., 2018. When compliments do not hit but critiques do: an fMRI study into self-esteem and self-knowledge in processing social feedback. *Soc. Cogn. Affect. Neurosci.* 13 (4), 404–417. <https://doi.org/10.1093/scan/nsy014>.
- Vanderhasselt, M.A., Remue, J., Ng, K.K., Mueller, S.C., De Raedt, R., 2015. The regulation of positive and negative social feedback: a psychophysiological study. *Cogn. Affect. Behav. Neurosci.* 15 (3), 553–563. <https://doi.org/10.3758/s13415-015-0345-8>.
- Vandermeer, M.R.J., Liu, P., Ali, O.M., Daooust, A.R., Joannisse, M.F., Barch, D.M., Hayden, E.P., 2022. Children's neural reactivity to maternal praise and criticism: associations with early depressive symptoms and maternal depression. *Dev. Psychopathol.* <https://doi.org/10.1017/s0954579422000840>.
- Vásá, F., Romero-García, R., Kitzbichler, M.G., Seidlitz, J., Whitaker, K.J., Vaghi, M.M., Bullmore, E.T., 2020. Conservative and disruptive modes of adolescent change in human brain functional connectivity. *Proc. Natl. Acad. Sci. U. S. A.* 117 (6), 3248–3253. <https://doi.org/10.1073/pnas.1906144117>.
- Wante, L., Braet, C., Bögels, S., & Roelofs, J. (2021). SCID-5 Junior: gestructureerd klinisch interview voor DSM-5 stoornissen bij kinderen en adolescenten.

- Whitfield-Gabrieli, S., Nieto-Castanon, A., 2012. Conn: a functional connectivity toolbox for correlated and anticorrelated brain networks. *Brain Connect.* 2 (3), 125–141. <https://doi.org/10.1089/brain.2012.0073>.
- Yoon, L., Keenan, K.E., Hipwell, A.E., Forbes, E.E., Guyer, A.E., 2023. Hooked on a thought: Associations between rumination and neural responses to social rejection in adolescent girls. *Dev. Cogn. Neurosci.* 64, 101320 <https://doi.org/10.1016/j.dcn.2023.101320>.
- Yurgelun-Todd, D., 2007. Emotional and cognitive changes during adolescence. *Curr. Opin. Neurobiol.* 17 (2), 251–257. <https://doi.org/10.1016/j.conb.2007.03.009>.
- Zeidman, P., Jafarian, A., Corbin, N., Seghier, M.L., Razi, A., Price, C.J., Friston, K.J., 2019a. A guide to group effective connectivity analysis, part 1: First level analysis with DCM for fMRI. *Neuroimage* 200, 174–190. <https://doi.org/10.1016/j.neuroimage.2019.06.031>.
- Zeidman, P., Jafarian, A., Seghier, M.L., Litvak, V., Cagnan, H., Price, C.J., Friston, K.J., 2019b. A guide to group effective connectivity analysis, part 2: Second level analysis with PEB. *Neuroimage* 200, 12–25. <https://doi.org/10.1016/j.neuroimage.2019.06.032>.
- Zhou, H.X., Chen, X., Shen, Y.Q., Li, L., Chen, N.X., Zhu, Z.C., Yan, C.G., 2020. Rumination and the default mode network: meta-analysis of brain imaging studies and implications for depression. *Neuroimage* 206, 116287. <https://doi.org/10.1016/j.neuroimage.2019.116287>.