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Neural responses to maternal criticism in healthy youth

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Parental criticism can have positive and negative effects on children's and adolescents' behavior; yet, it is unclear how youth react to, understand and process parental criticism. We proposed that youth would engage three sets of neural processes in response to parental criticism including the following: (i) activating emotional reactions, (ii) regulating those reactions and (iii) social cognitive processing (e.g. understanding the parent's mental state). To examine neural processes associated with both emotional and social processing of parental criticism in personally relevant and ecologically valid social contexts, typically developing youth were scanned while they listened to their mother providing critical, praising and neutral statements. In response to maternal criticism, youth showed increased brain activity in affective networks (e.g. subcortical–limbic regions including lentiform nucleus and posterior insula), but decreased activity in cognitive control networks (e.g. dorsolateral prefrontal cortex and caudal anterior cingulate cortex) and social cognitive networks (e.g. temporoparietal junction and posterior cingulate cortex/precuneus). These results suggest that youth may respond to maternal criticism with increased emotional reactivity but decreased cognitive control and social cognitive processing. A better understanding of children's responses to parental criticism may provide insights into the ways that parental feedback can be modified to be more helpful to behavior and development in youth.

Keywords: parental criticism; brain; emotion; cognitive control; social cognitive processing

INTRODUCTION

Parent–child conflict over rules, social conventions and moral standards, such as curfews or appropriate dress, is mildly but pervasively increased during adolescence (Smetana, 1989; Adams and Laursen, 2001; Lichtwarck-Aschoff *et al.*, 2009). As part of this process, parents of adolescents often convey criticism about adolescent behaviors with the hope that youth will understand and adjust their behavior in response to this criticism. Criticism is defined as negative evaluative feedback received from other people in social interactions (Deutsch, 1961; Kamins and Dweck, 1999). Excessive criticism is associated with negative outcomes such as negative emotions, negative self-image and the development of psychopathology (e.g. anxiety and depression) (Harris and Howard, 1984; Hooley and Gotlib, 2000; Sheeber *et al.*, 2001; Jacquez *et al.*, 2004). However, criticism also plays an important role in teaching rules and regulations, shaping appropriate behavior and developing skills in problem-solving and conflict resolution (Harris and Howard, 1984; Smetana, 1989).

Thus, parental criticism appears to be a normal component of parent–child relations during adolescence, with potential for both positive and negative influences. However, the neural mechanisms that mediate the influence of parental criticism on adjustment have not been studied. Here, we take a first step by delineating the neural processes involved in adolescents' response to parental criticism. Examining the neural bases of parental criticism is important because it may help to understand the role of parenting in normal and abnormal development of brain systems associated with affective, cognitive and social processing in adolescence. Brain activity measured while youth listen to criticism may allow us to examine real-time brain responses to parental criticism without interruptions or biases common to self-report measures used in behavioral research (Redelmeier and Kahneman, 1996; Levine and Safer, 2002). Furthermore, this allows us to investigate the role of cognitive control and social cognitive processing in response to parental criticism.

We propose three inter-related neural processes that could be involved in the response to parental criticism in typical adolescents. The first proposed neural process of parental criticism involves having an emotional reaction. Negative emotional reactions to criticism are considered normative (Harris and Howard, 1984; Cuellar *et al.*, 2009) and play a role in motivation to adjust behavior (Campos *et al.*, 1989; Baumeister *et al.*, 2007). Affective networks associated with negative emotional reactions include subcortical–limbic regions such as the amygdala (Dannlowski *et al.*, 2007; Sinke *et al.*, 2010), insula and prefrontal regions such as rostral anterior cingulate cortex (rACC) (Gusnard *et al.*, 2001; Critchley *et al.*, 2004; Lee and Siegle, 2012). Initial evidence suggests that increased activity in affective networks may reflect high levels of perceived criticism (Hooley *et al.*, 2012). We predicted that activity in these areas would be correlated with post-scan ratings of perceived negativity (negative emotion). In previous research with adults, brain activity in affective networks was sustained during the presentation of negative stimuli (Siegle *et al.*, 2002; Hooley *et al.*, 2012) and even more prolonged during subsequent rest periods (Garrett and Maddock, 2006; Hooley *et al.*, 2012). Thus, affective networks would show sustained brain activity in response to maternal criticism and during subsequent rest periods.

The second potential neural process involved in adolescent response to parental criticism is the regulation of the generated emotions. Evidence suggests that adolescents have greater challenges regulating emotions compared with young adults (McRae *et al.*, 2012; Silvers *et al.*, 2012), presumably as a result of protracted development of prefrontal cognitive control systems (Dahl, 2004; Steinberg, 2005) in conjunction with heightened emotional reactivity to negative events during adolescence (Larson and Lampman-Petraitis, 1989; Schneiders *et al.*, 2006). There is no clear separation of brain networks involved in reactivity and regulation as these processes are highly intertwined. That said, structured tests of differential reactions to voluntary regulation compared with passive viewing or experiencing of emotional stimuli suggest additional roles for prefrontal regions such as the dorsolateral prefrontal cortex (DLPFC), ventrolateral PFC, and ACC [caudal ACC (cACC) and rACC] in cognitive control of emotion (Ochsner and

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Gross, 2005; Phillips *et al.*, 2008; Etkin *et al.*, 2011). Although adolescents showed less activity in such 'cognitive control networks' during cognitive reappraisal compared with adults, they show increased activity in these networks during reappraisal compared with during passively viewing neutral pictures (McRae *et al.*, 2012). Thus, youth may have the capacity to recruit cognitive control networks as they attempt to control inappropriate responses to parental criticism despite their protracted development of prefrontal cognitive control systems. We predicted that these areas would be functionally connected with areas in affective networks to interactively manage negative emotional response to parental criticism.

The third potential process involved in responding to parental criticism is having a sense of where the parent is coming from, i.e. understanding others' mental states through mentalizing or perspective taking. Without an understanding of parental intent, the youth would not understand why the parent wants the youth to change and thus might have little motivation to change their behavior. Indeed, negative parent–child relationships have been shown to predict a reduction in social cognitive ability such as empathic concern and perspective taking in adolescence (Soenens *et al.*, 2007; Batanova and Loukas, 2012), suggesting that parental criticism may play an important role in social cognitive processing. Brain regions involved in social cognitive processing ('social cognitive network') include the dorsomedial PFC, posterior superior temporal sulcus (pSTS) and temporoparietal junction (TPJ) (Frith and Frith, 2006; Wang *et al.*, 2006; Blakemore, 2008; Van Overwalle, 2009; Moor *et al.*, 2012). The ventromedial PFC and posterior cingulate cortex (PCC) have also been implicated in thinking about close others' minds as well as self-related processing (Van Overwalle and Baetens, 2009; Murray *et al.*, 2012). Emerging evidence suggests that social cognitive regions are associated with social factors (e.g. relationships with parents and peers) (Belsky and de Haan, 2011; Crone and Dahl, 2012; Somerville, 2013). We thus predicted that activity in these areas would be associated with social factors such as self-reported ratings of parental warmth, characterized as parental positive expressions (e.g. support, affection, praise) toward a child and as a potentially important factor in the development of social competence (Zhou *et al.*, 2002; Laible and Carlo, 2004).

The primary goal of our study was to examine the extent to which healthy youth engage brain regions, previously implicated in negative emotional experience, cognitive control of negative emotion and social cognitive processing, when hearing maternal criticism. A hypothetical model for how relevant brain networks contribute is shown in Figure 5a. This model highlights the three potential domains including negative emotion (e.g. one's own subjective emotions), regulatory function (e.g. cognitive control of emotion) and social processing (e.g. mentalizing or perspective taking). These three domains may be interactive through multiple pathways. Evidence suggests relationships between affective networks subserving emotion reactivity and cognitive control networks (Siegle *et al.*, 2007; Ochsner *et al.*, 2009). Conceptual frameworks also suggest potential relationships between cognitive control and social cognitive networks and between affective and social cognitive networks (Decety and Jackson, 2004; Lee and Siegle, 2012; McRae *et al.*, 2012). Thus, we also propose possible relationships (depicted by bi-directional arrows) between regions subserving different domains of processing of parental criticism.

To examine our primary research question, we adapted an experimental paradigm previously used with adults (Hooley *et al.*, 2005, 2009, 2012). Previous studies with adults demonstrated that individuals who were previously depressed or who perceived their mothers as more critical showed decreased activity in cognitive control networks and increased activity in affective networks in response to maternal criticism (compared with a rest period), compared with healthy adults or with adults who perceived their mothers as less critical (Hooley *et al.*, 2009, 2012). This paradigm has been well-validated and allows us to investigate neural processes involved in maternal criticism in personally relevant (e.g. criticism about oneself delivered by a child or adolescent's own mother's voice) and ecologically valid social contexts (e.g. representing parent–child interactions in everyday life). This work has not been previously extended to youth, and studies with adults have not focused on whether social processing regions were associated with maternal criticism. Furthermore, we examined whether neural activity in response to parental criticism was associated with age. Previous studies have demonstrated age-related linear and non-linear changes in cognitive control and social cognitive networks (Crone *et al.*, 2006; Sebastian *et al.*, 2010, 2011; McRae *et al.*, 2012).

In our study, youth were asked to listen to their own mother make three types of statements: critical, praising and neutral comments during a functional magnetic resonance imaging (fMRI) assessment. We focused on characterizing neural mechanisms associated with maternal criticism by directly comparing brain responses with maternal criticism and neutral statements. Although previous studies with adults have compared brain activity in response to critical comments with brain activity during the rest period (Hooley *et al.*, 2009, 2012), we chose to compare brain activity with critical comments to brain activity during neutral comments in order to identify activity associated with maternal criticism above and beyond general communication. This also allowed us to identify brain regions specifically involved in social cognitive processing, particularly within temporal regions (e.g. pSTS), which are areas of overlap between auditory (Hooley *et al.*, 2009, 2012) and social cognitive processing (Frith and Frith, 2006; Blakemore, 2008) by controlling processing related to listening to the mother's voice (e.g. neutral comments). Although we did not directly compare critical comments with rest periods, we explored brain activity during the subsequent rest period in regions involved in maternal criticism. Thus, we examined the temporal dynamics of brain reactivity to maternal criticism both when youth listen to maternal criticism and when they are subsequently at rest. As mentioned above, we also tested correlations of neural responses to criticism with self-report ratings of perceived negativity (negative emotion), parental warmth and age. Finally, we examined possible inter-relationships between brain networks subserving different domains of processing of maternal criticism.

We hypothesized that affective networks involved in processing negative emotion would be more activated by maternal criticism compared with neutral comments. We predicted that cognitive control networks would be more activated by maternal criticism than by neutral statements which are supposed to be non-emotional and non-demanding of cognitive control (thus, leading to no brain signal changes in these networks). We also predicted that social cognitive networks would be engaged in maternal criticism, but did not specifically predict whether these networks would be more active when hearing criticism compared with neutral statements. Second, we hypothesized that increased brain activity in affective networks particularly subserving negative emotion would be prolonged during the rest period subsequent to maternal criticism. Third, we predicted that self-reported negativity, parental warmth and age would show correlations with brain activity in response to maternal criticism; (i) we predicted positive correlations between perceived negativity and activity in regions of affective networks; (ii) we hypothesized significant relationships between parental warmth and activity in regions of social cognitive networks, without specific hypotheses of their relationships due to limited past research on this issue and (iii) we predicted that there would be linear or non-linear (inverted u-shape) associations between age and neural activity to maternal criticism. Finally, as presented in our model, we also predicted that there would be functional relationships between networks proposed in our model, without specific hypotheses of relationships between these networks. Findings from this study may contribute to a better understanding of roles of criticism in emotional and social processing in youth.

METHODS

Participants

Participants were 32 healthy adolescents [22 women[1], aged 9–17 years ($M = 14.34$, s.d. = 2.04)]. They were recruited from community advertisements, pediatric offices and existing research projects. Exclusion criteria for the study included: (i) current or lifetime DSM-IV (1994) diagnosis for any Axis 1 disorder, (ii) the existence of a major systemic medical illness, (iii) a history of serious head injury and (iv) presence of metal objects in the body. One participant did not complete this task due to an equipment problem and three participants were excluded due to excessive head movement [over 30% of scans with greater than ±5 mm and ±5° movement from a reference image and ±1 mm and ±1° incremental (scan-to-scan) movement]. Twenty-eight typically developing youth [20 women, aged 9–17 years ($M = 14.57$, s.d. = 1.95)] were thus included for our final analysis.

Procedure

Participants provided informed consent using a form approved by the University of Pittsburgh Institutional Review Board. Participants completed two laboratory visits. During the first visit, participants completed a structured diagnostic interview, and the mothers recorded audio clips to be used during the fMRI assessment. The fMRI assessment was completed during their second visit.

Structured diagnostic interviews

On their first visit to the laboratory, each youth and his or her parent(s) were interviewed to determine the youth's mental health history using the Schedule for Affective Disorders and Schizophrenia in School-Age Children—Present and Lifetime version (Kaufman *et al.*, 1997). Parents and youth were interviewed separately, with clinicians integrating data from both informants to arrive at a final diagnosis. All interviews were carried out by trained Bachelor of Arts (BA) level and Master of Arts (MA)-level clinicians. Fifteen percent of interviews were double coded and there were no diagnostic disagreements (kappa = 1.0).

fMRI assessment and debriefing

Participants underwent an fMRI scan. They were asked to lie still as possible during the structural imaging acquisition and then to listen to their mother's audio clips or rest during the functional imaging acquisition. To be able to relate brain activity to subjective reactivity to the comments, after the fMRI assessment, participants were asked to respond to two questions (post-scan emotion ratings): 'How negative was the comment?' and 'How upset did it make you feel?' The rating scale ranged from 1 (not at all) to 10 (very). Participants were carefully debriefed following completion of the scan.

Self-report measure

Parental warmth was assessed by a shortened version of the Child Report of Parent Behavior Inventory (CRPBI) (Schludermann and Schludermann, 1970). Participants responded to each question about their parents' behavior on a three-point scale, ranging from 1 (not like your mother) to 3 (a lot like your mother).

[1] These healthy youth also were recruited as the control group for a study on youth with major depressive disorder in which the female—male ratio is approximately 2 : ;1 because depression is more prevalent in femaleswomen, so the female—male ratio of healthy youth was matched with those of depressed youth.

Stimuli and experimental paradigms

During the fMRI scan, participants were asked to hear their own mother's comments about them. There were two audio clips for critical, praising and neutral comments. Each audio clip lasted for 30 s. To present audio clips as clearly as possible during scanning, the comments were delivered via MRI compatible headphones. We first tested whether participants could hear comments clearly using a sample audio clip recorded by the mother prior to scanning. These audio clips were recorded by the participant's own mother during the first visit. We followed similar procedures used in previous studies (Hooley *et al.*, 2005, 2009) for obtaining audio clips. Each mother was asked to produce two 30 s audio clips describing things that bother her about her child [critical statements beginning with '(Child's name), one thing that bothers me about you is . . .', e.g. not doing chores or attitudes toward family member(s)], two 30 s audio clips describing things that she especially likes about her child [praising statements beginning with '(Child's name), one thing I really like about you is . . .', i.e. sense of humor, being a nice person, willingness to help out and academic and extracurricular achievements] and two 30 s neutral clips (neutral statements: something your child won't find interesting, i.e. grocery shopping, parent work or chores, and weather). Examples of mother's critical and neutral comments are presented in Table 1. To create these clips, each mother was instructed to formulate their critical remarks based on something they have shared with their child on more than one occasion, so that youth would not be exposed to new and potentially disturbing information in the scanner. Praising comments were included to balance critical remarks and to mitigate potential negative effects of critical comments during the scanning.

There was one block each for critical, praising and neutral conditions. Each block (run) consisted of two 30.06 s comment presentations (30 s audio clip with 0.06 s additional duration to match with our TR 1.67 s) and three 30.06 s rest periods. Each began with a 30.06 s rest period, followed by 30.06 s of one's own mother's comment presentation, the second rest period, another comment presentation and then the last rest period. Participants were scanned both when they heard their own mother's comment and when they were at rest. To minimize possible emotional carryover after listening to criticism or praise from parents, the neutral condition block was presented first and the order of two other condition blocks were counterbalanced across participants.

Imaging acquisition and preprocessing

Imaging acquisition

Images were acquired on a 3 T Trio scanner (Siemens, Erlangen, Germany). Thirty-two 3.2 mm slices were acquired parallel to the AC–PC line using a posterior-to-anterior echo planar pulse sequence (T2*-weighted image depicting BOLD signal; Repetition Time (TR) = 1670 ms, Echo Time (TE) = 29 ms, Field of View (FOV) = 205 mm, flip angle = 75). Each image was acquired in 1.67 s, allowing 18 scans per 30.06 s trial consisting of either a 30.06 s comment presentation or rest period. There were three blocks (runs). Each block (run) lasted for 150.3 s (2.505 min). Ninety images (150.3 s/TR = 1.67 s) were collected in each block (run), consequently total 270 images were acquired. High-resolution T1-weighted MPRAGE images (1 mm, axial) were also collected for use in cross-registration.

fMRI data preprocessing

fMRI analyses were conducted using locally developed NeuroImaging Software (NIS) (Fissell *et al.*, 2003) and Analysis of Functional Neuroimaging (AFNI) software (Cox, 1996). Functional imaging data were corrected for motion using 3dVolReg implemented in AFNI using the first image as a reference. Quadratic trends within

Table 1 Examples of critical and neutral comments

Critical comments:
One thing that bothers me about you is that you get upset over minor issues. I could tell you to take your shoes from downstairs. You'll get mad that you have to pick them up and actually walk upstairs, and put them in your room. You'll get mad if I tell you that your room is a little dirty, and it just needs sweeping and dusting. You get upset if your sisters want to do something that you don't agree on, but three of them do, and you don't want to do it. You get upset too easily, and you just need to calm that down
Neutral comments:
We need to concentrate on getting the deck cleaned off. I need to replace the carpeting and power wash the deck, put some paint down on the floor, and obviously put the carpet back. There's a piece of equipment that I need to put together and then the heat lamp needs to be brought to the back, and fill the propane tanks, and paint the steps that are going down into the yard, and we need to paint the steps.

runs were removed and outliers over 1.5 interquartile range from the 25th or 75th percentiles were Winsorized using niscorrect from NIS to remove non-physiological spikes. Data were temporally smoothed using a four-point Gaussian filter and converted to %-change based on the median of all imaging data. Data were co-registered to the Colin-27 Montreal Neurological Institute template using the Automated Image Registration package's (Woods *et al.*, 1993) 32-parameter non-linear automated warping algorithm and spatially smoothed using a 6 mm full width at half maximum filter.

Statistical analyses

Manipulation check: post-scan ratings

Paired-samples *t*-tests were conducted to compare post-scan ratings following maternal critical *vs* neutral comments to ascertain the affective value of the comments.

Whole-brain analyses: neural responses to maternal criticism compared with neutral comments

To examine temporal dynamics of neural responses to maternal critical and neutral comments over time, a random-effects whole-brain voxelwise analysis of variance (ANOVA) was conducted with participant as a random factor, and valence (criticism *vs* neutral) and time (18 scans of 0–30.06 s in each trial of commentary) as fixed factors. This model-free analysis was employed to account for empirical variation in the shape of the hemodynamic response (e.g. sustained activity or early deactivation) rather than relying on hemodynamic responses to have a canonical shape. To control for temporal autocorrelation, brain regions identified from the whole-brain analysis were further subjected to mixed-effects analyses of signal change using valence (criticism *vs* neutral remarks) and time as repeated measures and subject as a random factor, assuming an AR1 covariance structure using restricted maximum-likelihood estimation (REML).

To further understand temporal dynamics of brain activity, we found specific temporal regions (e.g. sustained activity at 21–30 s after the onset of criticism) showing significant differences in time courses between critical and neutral statements by comparing time courses between two conditions at each time point (scan). Guthrie and Buchwald's (1991) method was used to control type I error when point-by-point tests in entire time courses were performed to detect significantly different temporal regions at $P < 0.05$. Thus, temporal regions with significant differences between two conditions represented continuous series of time points that reliably differed in time courses.

The valence × time interaction effect map was thresholded at an uncorrected $P < 0.0001$. To control type 1 error at $P < 0.05$ across the whole brain for each family of tests (i.e. <5% chance that even one voxel was identified in error), voxelwise tests at a given statistical threshold ($P < 0.0001$) were subjected to empirically determine contiguity thresholds based on the spatial autocorrelation of statistical maps using AFNI's AlphaSim program. We used a conservative voxelwise threshold (e.g. $P < 0.0001$) that requires a small number of voxels contiguity to find small regions of our hypothesized brain areas such as amygdala. Thus, both the uncorrected *P* value and contiguity threshold necessary to achieve a corrected brain-wise $P < 0.05$ were reported with each test described below.

Region of Interest (ROI) analysis: brain activity in regions reacting to criticism during the rest period

To further understand whether neural responses to maternal comments last during the rest period, time courses in brain regions (nine functional ROIs shown in Figure 1) identified from the valence × time interaction effect and proposed in our model were extracted during the rest period. Mixed-effects analyses were used to test significant differences in time courses with condition (rest periods after criticism *vs* rest periods after neutral comments) and time as repeated measures and subject as a random factor, assuming an AR1 covariance structure using REML.

Association with perceived negativity, parental warmth and age

We tested associations of neural responses to criticism with affective-social (i.e. perceived negativity and parental warmth) and developmental (i.e. age) factors by correlating post-scan ratings of perceived negativity, parental warmth and age and averaged brain activity across the temporal regions that displayed significant condition (criticism *vs* neutral) differences and were highlighted below the *x* axis of each brain region in Figure 1.

Relationships between brain networks proposed in our model

We proposed bi-directional relationships between brain networks involved in the processing of maternal criticism in our model. These relationships were examined using the psychophysiological interaction analysis (PPI; Friston *et al.*, 1997; O'Reilly *et al.*, 2012) adapted for AFNI (http://afni.nimh.nih.gov/sscc/gangc/CD-CorrAna.html). PPI analysis allowed us to examine significant changes in functional connectivity between brain regions during maternal criticism compared with neutral comments. Our seed brain regions were nine functional ROIs (Figure 1) identified from our primary ANOVA (valence × time) analysis. The time series extracted from each seed brain region was multiplied by experimental conditions (i.e. criticism = 1, neutral condition = −1 and other conditions = 0) to create a PPI variable. For each subject, regression analyses implemented in AFNI's 3dDeconvolve were conducted by entering the physiological variable (time course of seed region), psychological variable (critical *vs* neutral comments) and their interaction (PPI) variable as regressors. To model only critical and neural comments, time points associated with other conditions (i.e. praise and rest periods) were further censored out. The resulting correlation coefficient (*r*) scores were converted to *z* scores through a Fisher's *r* to *z* transformation to perform group analyses using one-sample *t*-tests. To control for multiple comparisons, both the uncorrected *P* value and contiguity thresholds based on the spatial autocorrelation of our functional ROI masks using AFNI's AlphaSim were necessary to achieve a corrected $P < 0.05$. Thus, using an uncorrected threshold of $P < 0.005$, to achieve a corrected type I error of alpha = 0.05 with a small volume correction, cluster sizes (3–31 voxels contiguity) were required.

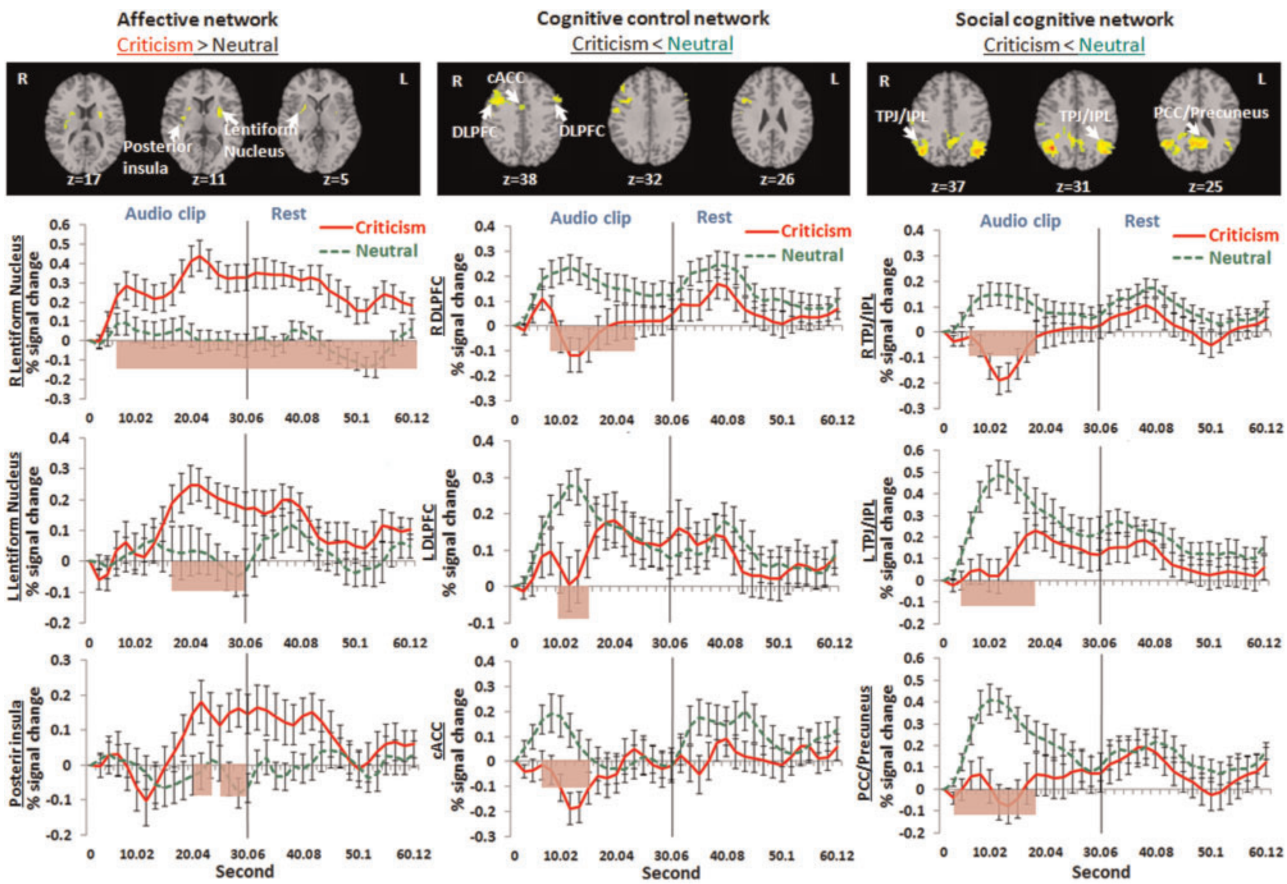

Fig. 1 Neural responses to maternal criticism compared with neutral remarks: time courses in brain regions within affective, cognitive control and social cognitive networks were plotted when hearing own mother's critical and neutral statements (audio clip: 0–30.06 s) and the rest period (30.07–60.12 s). (a) Brain regions in affective networks showed increased and sustained activity when hearing own mother's criticism (bilateral lentiform nucleus and posterior insula) and during the rest period (right lentiform nucleus). (b) Brain regions in cognitive control networks showed decreased activity in response to maternal criticism (bilateral DLPFC and cACC). (c) Brain regions in social cognitive networks showed decreased neural response to maternal criticism (bilateral TPJ/IPL and PCC/precuneus). Significant differences in time courses between critical and neutral statements are highlighted below the x axis (pink: $P < 0.05$). Note. Average activity from the entire ROI was used to plot each time series.

RESULTS

Manipulation check: post-scan ratings of perceived negativity

Paired t-tests were conducted to compare post-scan ratings regarding participants' perceptions of the criticality of their mother's critical and neutral statements. Participants rated their mother's critical remarks (using a 1–10 scale: $M = 5.00$, s.d. = 1.99) as more negative compared with their mother's neutral remarks ($M = 2.29$, s.d. = 1.61; $t(26) = 5.59$, $P < 0.001$, Cohen's $d = 1.25$). They also reported that their mother's critical remarks (using a 1–10 scale: $M = 4.67$, s.d. = 2.26) made them more upset than their mother's neutral remarks ($M = 2.04$, s.d. = 1.43; $t(26) = 5.12$, $P < 0.001$, Cohen's $d = 1.14$).

fMRI results

Neural responses to maternal criticism compared with neutral comments

A valence (criticism *vs* neutral) × time (0–30.06 s) interaction was observed in widespread brain networks ($P < 0.0001$, 10 voxels contiguity; Table 2) including increased activity in the affective network [right lentiform nucleus (putamen): 6.68–30.06 s: $F(1,27) = 15.49$, $P < 0.01$; left lentiform nucleus (putamen): 16.70–30.06 s: $F(1,27) = 12.42$, $P < 0.01$; posterior insula: 20.04–23.38 s: $F(1,27) = 6.47$, $P < 0.05$; 26.72–30.06 s: $F(1,27) = 19.00$, $P < 0.01$] (Figure 1, left column), decreased activity in the cognitive control network [right DLPFC: 8.35–23.38 s: $F(1,27) = 14.73$, $P < 0.01$; left DLPFC: 10.02–15.03 s: $F(1,27) = 11.69$, $P < 0.01$; cACC: 6.68–15.03 s: $F(1,27) = 16.11$, $P < 0.01$] (Figure 1, middle column) and decreased activity throughout the social cognitive processing network [right TPJ extending to inferior parietal lobe (IPL): 6.68–18.37 s: $F(1,27) = 18.17$, $P < 0.01$; left TPJ/IPL: 5.01–18.37 s: $F(1,27) = 21.70$, $P < 0.01$), and PCC/precuneus: 3.34–18.37 s: $F(1,27) = 16.35$, $P < 0.01$] (Figure 1, right column). Other regions outside networks we hypothesized showed significant valence × time interactions (Table 2; illustrated in Figure S1 in our supplementary material).

Brain activity in regions reacting to criticism during the rest period

To examine whether neural responses to criticism lasted during the rest period, we compared neural activity between rest periods after hearing maternal critical and neutral remarks in affective networks associated with criticism described above. Consistent with our hypothesis, increased activity in the affective network was maintained during the subsequent rest period (right lentiform nucleus condition main effect, $F(1,121.23) = 30.75$, $P < 0.01$) (Figure 1, left column).

Association of neural responses to criticism with perceived negativity, parental warmth, and age

Consistent with our first hypothesized process, regarding affective engagement, increased self-reported perceived negativity (negative emotion) was associated with increased and sustained activity in response to maternal criticism in affective network regions (i.e. left lentiform nucleus: 16.70–30.06 s, $r = 0.38$, $P < 0.05$; Figure 2). Consistent with our third hypothesis regarding the role of alleged social processing networks in social information processing, parental warmth was negatively correlated with activity in social cognitive processing regions [decreasing activity in the left TPJ/IPL: 5.01–18.37 s, $r = -0.61$, $P < 0.01$ (Figure 3a) and PCC/precuneus: 3.34–18.37 s, $r = -0.40$, $P < 0.05$ (Figure 3b)]. There were no significant linear or non-linear (quadratic) relationships between age and neural response to maternal criticism in regions associated with affective, cognitive and social cognitive networks (all P values > 0.20).

Table 2 Brain regions showing a valence × time interaction ($P < 0.0001$, 10 voxels contiguity)

Brain region	BA	Size (mm^3)	Talairach coordinates *x*	*y*	*z*	*F* value
Criticism > neutral						
*R lentiform nucleus (putamen)	—	1132	24	4	5	4.53
*L lentiform nucleus (putamen)	—	1132	−24	−1	11	5.3
*R posterior insula	13	720	35	−13	15	4.56
Inferior frontal gyrus	45	241	−54	25	19	5.19
Superior temporal gyrus	38	459	−32	16	−33	4.81
Neutral > criticism						
*R TPJ/IPL	39	29 036	44	−60	33	9.68
*L TPJ/IPL	39	11 752	−42	−61	33	8.36
*PCC/precuneus	31/23	20 163	4	−46	29	6.15
*R DLPFC (MFG)	9	9567	40	13	40	5.81
*L DLPFC (MFG)	8/9	2269	−48	17	36	3.82
*cACC	24	303	4	3	37	3.56
Parahippocampal gyrus	35	621	25	−28	−10	4.42
Parahippocampal gyrus	35/36	1971	−22	−35	−7	4.16
Parahippocampal gyrus	34	443	24	−7	−17	3.73
Parahippocampal gyrus	21	273	40	−17	−13	3.21
Middle frontal gyrus	6	4947	−24	16	56	6.34
Precentral gyrus	6	447	−45	−6	34	3.65

Notes: BA = Brodmann area; *F* value = maximum *F* value in each cluster; R = right; L = left; MFG = middle frontal gyrus.
*Regions inside networks we hypothesized (time courses in these regions are presented in Figure 1; time courses for the other regions are shown in Figure S1 in our supplementary material).

Relationships between brain regions proposed in our model

PPI analyses were employed to examine whether brain networks engaged in processing of maternal criticism were functionally related more during processing of criticism than neutral comments. Consistent with our second hypothesized process, regarding cognitive control of emotion, affective network regions (i.e. left lentiform nucleus and posterior insula) showed a significant increase in functional connectivity with the right DLPFC during maternal criticism compared with neutral comments (Table 3). Of particular interest, youth with more enhanced and sustained activity in response to criticism in the left lentiform nucleus showed less attenuation in the DLPFC (Figure 4). Functional connectivity between cognitive network regions (i.e. bilateral DLPFC) and social cognitive network regions (i.e. bilateral TPJ and PCC) also significantly increased during maternal criticism compared with neutral comments (Table 3). However, significant increases in functional connectivity were not found between affective and social cognitive networks during criticism compared with neutral comments. These PPI results are also summarized in Figure 5b.

DISCUSSION

This study examined neural responses to criticism in typically developing youth using personally relevant and ecologically valid stimuli. Youth were scanned while listening to criticism from their own mothers. In line with our hypotheses, hearing one's own mother's criticism recruited brain regions previously implicated in subjective negative emotions, cognitive control of emotion and social cognitive processing. In response to maternal criticism, healthy youth showed increased activation in an affective network (e.g. lentiform nucleus/putamen and posterior insula). These areas are often specifically associated with processing negative feedback, physical/social pain and negative emotions. However, youth showed decreased activation in a cognitive control network (e.g. DLPFC and cACC) and social cognitive network (e.g. TPJ extending to the IPL and PCC/precuneus). These findings in a typically developing sample of adolescents could suggest that increased affective reactivity, decreased cognitive control and blunted social cognitive processing may be normative in healthy children and adolescents.

Our findings supported our primary hypotheses that criticism from parents is associated with heightened negative responses and difficulty

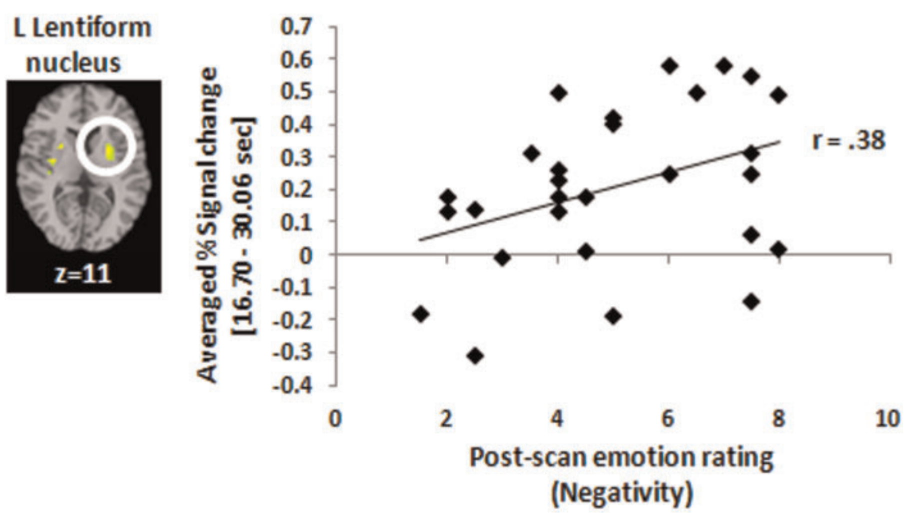

Fig. 2 Associations of neural responses to maternal criticism with self-reported perceived negativity. Self-reported perceived negativity was positively correlated with increased activity to maternal criticism in the left lentiform nucleus. Youth who reported more negative emotional experience with maternal criticism showed more increased lentiform nucleus activity. Note. Average activity from the entire ROI was used for the scatter plot.

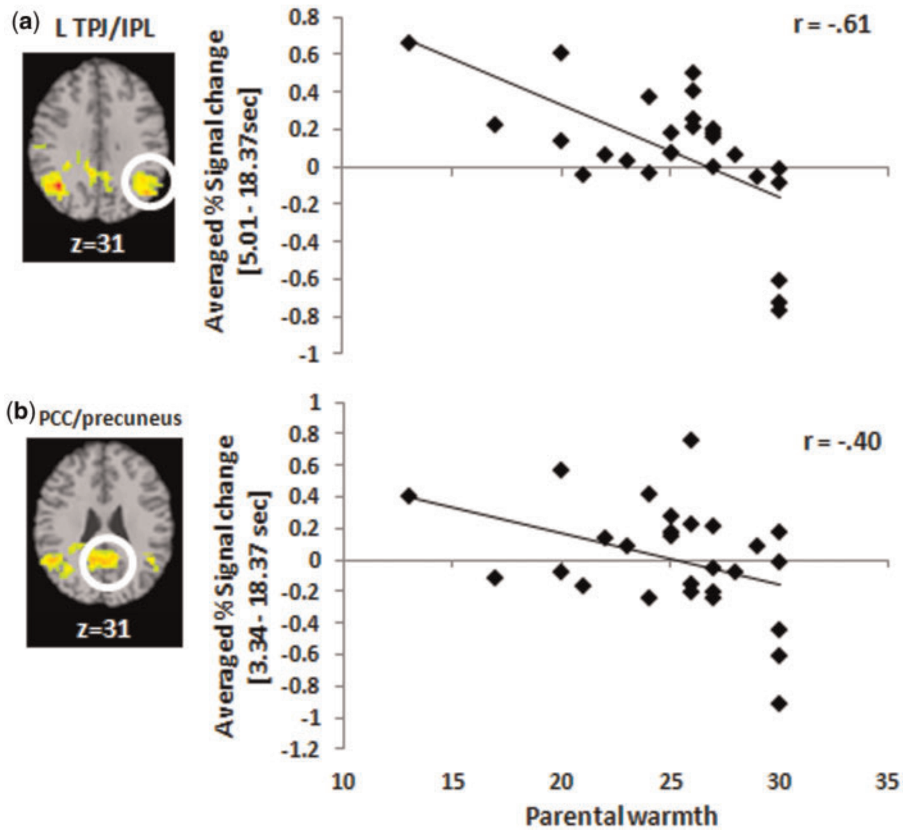

Fig. 3 Associations of neural responses to maternal criticism with parental warmth. Parental warmth was negatively correlated with activity in the left TPJ/IPL (a) and PCC/precuneus (b). Youth who are more accepted and emotionally supported by parents showed more decreased TPJ/IPL and PCC/precuneus activities. Note. Average activity from the entire ROI was used for the scatter plot.

Table 3 Results from PPI analysis during maternal criticism compared with neutral comments ($P < 0.005$, small volume correction)

Seed region	Correlate	BA	Size (mm^3)	Talairach coordinates			*t* value	Correlation coefficient (*r*)	
				x	*y*	*z*		Criticism >	Neutral
Affective network									
L lentiform nucleus	R DLPFC	6/9	231	51	0	36	3.48	0.36	0.05
R lentiform nucleus	—								
R posterior insula	R DLPFC	6/9	693	52	1	38	3.44	0.48	0.32
Cognitive control network									
R DLPFC	R TPJ	39	264	40	−68	26	4.04	0.48	0.19
L DLPFC	R TPJ	39	627	36	−66	27	4.14	0.45	0.24
cACC	—								
Social cognitive network									
R TPJ/IPL	R DLPFC	6/9	231	52	0	36	4.14	0.47	0.28
L TPJ/IPL	R DLPFC	6/9	330	51	−2	35	3.51	0.36	0.15
	L DLPFC	9	264	−49	4	47	4.3	0.47	0.38
PCC	R DLPFC	6/9	330	51	4	37	3.91	0.42	0.13
	R DLPFC	6/9	165	40	7	41	3.78	0.50	0.38
	L DLPFC	9	297	−49	4	44	3.78	0.43	0.30

Notes: BA = Brodmann area; R = right; L = left.

regulating negative emotions. These results are also consistent with the previous study with adults that showed increased activity in affective networks and decreased activity in cognitive control networks in individuals with high levels of perceived criticism (Hooley *et al.*, 2012). Within the affective network, the lentiform nucleus (putamen) and posterior insula are associated with processing of negative emotions (Luo *et al.*, 2004; Kessler *et al.*, 2011; Duerden *et al.*, 2013; Mazza *et al.*, 2013). The lentiform nucleus and posterior insula have also been implicated in emotional aspects of negative feedback (Dobryakova and Tricomi, 2013; Becker *et al.*, 2014) and physical/social pain (Salomons *et al.*, 2007; Kross *et al.*, 2011), respectively. Increased and sustained activity in the affective network may thus reflect enhanced emotional responses to negative feedback and social pain associated with maternal criticism. Consistent with our hypothesis, enhanced activity in the lentiform nucleus was positively correlated with perceived negativity of maternal criticism. Furthermore, increased lentiform nucleus activity was maintained during the subsequent rest period following criticism, consistent with sustained emotional information processing associated with processes such as rumination (Siegle *et al.*, 2002; Brosschot *et al.*, 2006).

In contrast, cognitive control network regions (DLPFC and cACC) were less active in response to maternal criticism, possibly indicating a lack of youth's regulatory function in parent–child conflict. The first phrase ['(Child's name), one thing that bothers me about you is'] of critical comments likely highlights the personal relevance of the criticism, possibly increasing difficulty reappraising negative emotional information conveyed by criticism. Thus, decreased activity in the cognitive control network may be related to reduced regulatory control abilities in adolescents compared with adults, but we do not yet have data to support this claim in this study.

Cognitive reappraisal requires several cognitive processes such as working memory, semantic memory and response selection (Ochsner and Gross, 2008). Thus, youth may fail to activate cognitive control networks, consequently leading to difficulty maintaining cognitive processing (e.g. thinking about alternative interpretation) of maternal

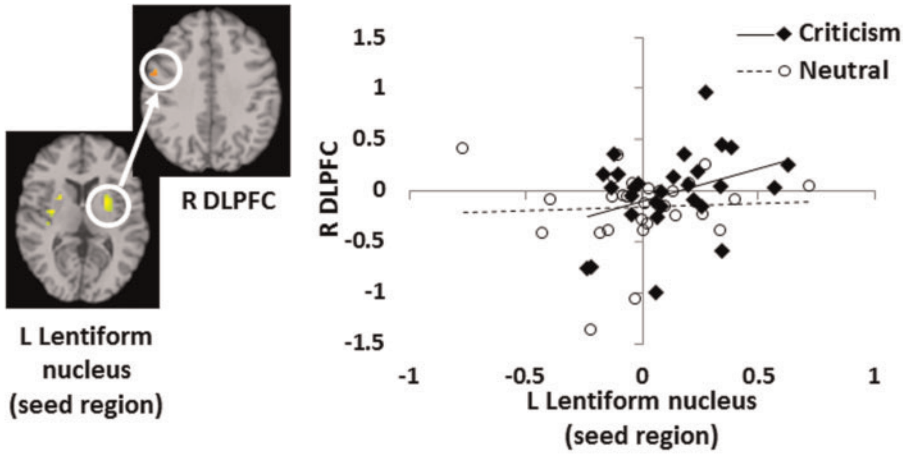

Fig. 4 PPI results depicting functional connectivity between left lentiform nucleus and right DLPFC. The lentiform nucleus showed greater functional connectivity with the right DLPFC in response to maternal criticism ($r = .36$) compared with neutral comments ($r = .05$). Note. Average activity from the entire ROI was used for the scatter plot.

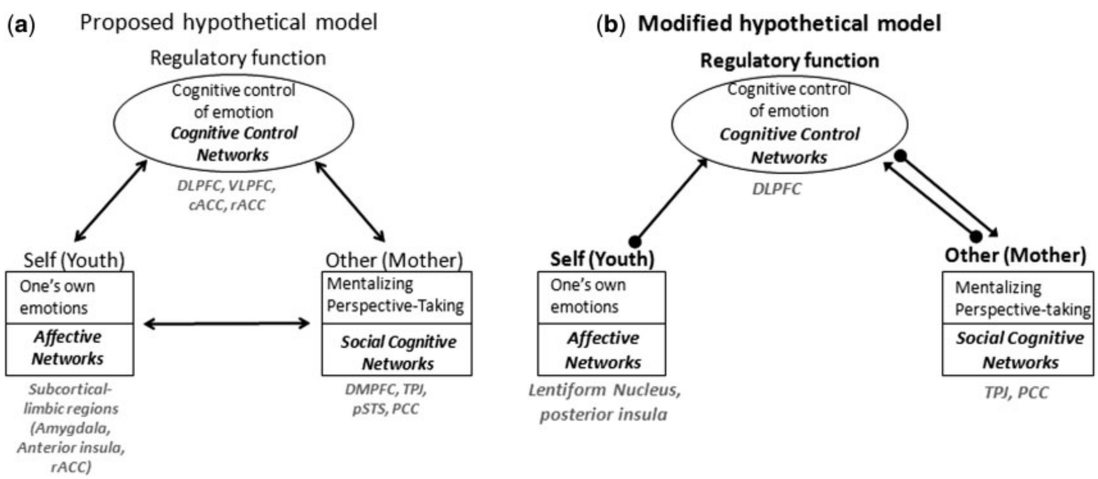

Fig. 5 A proposed hypothetical model of brain networks involved in processing of maternal criticism and their relationships between regions. (a) We proposed a priori brain networks associated with three domains (emotion, regulatory function and social cognitive processing of parental criticism) and possible interactive relationships between these regions depicted by bi-directional arrows. (b) A modified hypothetical model based on our findings: we found that some proposed brain regions were involved in the processing of maternal criticism, e.g. increased activity in subcortical–limbic regions such as lentiform nucleus and posterior insula and decreased activity in cognitive control regions (DLPFC and cACC) and social brain regions (TPJ/IPL and PCC/precuneus). We also found significantly increased functional connectivity between affective (i.e. left lentiform nucleus and posterior insula) and cognitive control networks (i.e. right DLPFC) and between cognitive control networks (i.e. DLPFC) and social cognitive networks (i.e. TPJ and PCC) during maternal criticism compared with neutral comments, indicating these networks may be inter-related in processing of negative feedback in social interactive contexts. Note. Oval arrows indicate seed brain regions.

criticism. Another possible explanation is that decreased activity in cognitive control networks may be associated with detachment from criticism. Youth may detach themselves from maternal criticism by minimizing cognitive control processing related to criticism (e.g. stop thinking about criticism) because they may know that criticism hurts them. Unexpectedly, youth showed increased activity in these cognitive control networks when they heard non-emotional neutral comments. Increased activity from the onset of neutral comments may indicate that youth are able to be engaged in cognitive processing (e.g. attention and memory) of neutral comments.

As hypothesized, maternal criticism was also associated with activity in brain regions subserving social cognitive processing (TPJ/IPL and PCC/precuneus). The TPJ/IPL and PCC/precuneus are involved in understanding others' mind via perspective taking or mentalizing (Van Overwalle, 2009; Lee and Siegle, 2012; Murray *et al.*, 2012). The most intriguing finding is decreased TPJ/IPL and PCC/precuneus responses to maternal criticism compared with previous neutral statements, suggesting that youth shut down social processing (e.g. mentalizing or perspective taking), possibly to not think about their parents' mental states. It is also possible that decreased activity in the PCC/precuneus, previously implicated in self-related processing, may be associated with reduced self-related processing in response to personally relevant critical remarks. Thus, youth may not link parental criticism to their self-image or self-concept. This result was not expected, but provides important neural data on how youth socially process criticism from parents. Furthermore, the decrement in brain activity in regions involved in mentalizing or perspective taking could help to explain the high frequency of maladaptive conflict resolution in parent–adolescent dyads (Laursen and Collins, 1994; Steinberg and Silk, 2002), such as youth's disengagement (e.g. walking away). For example, youth may not listen to their parents' criticism, thereby leading parents to deliver harsher criticism in the future.

Alternatively, less active social cognitive processing of maternal criticism could reflect adaptive and flexible social adjustment in certain situations. Evidence suggests that disengagement may be an effective short-term strategy for controlling negative emotions (Rice *et al.*, 2007). It has been also suggested that there are exceptional situations in which less understanding of others' mental states has a positive effect on relationships with close people (Ickes and Simpson, 1997; Simpson *et al.*, 2011). Thus, diminished neural response in social cognitive networks may be associated with brief disengagement from such negative feedback to protect their feeling and relationships with parents. In line with this alternative idea, decreased activity in response to maternal criticism in social cognitive networks was negatively associated with parental warmth. Youth who are more accepted and emotionally supported by parents showed decreased activity to maternal criticism in social cognitive processing regions, suggesting that they may be more motivated to reduce social cognitive processing to protect themselves and relationships with parents. This result may indicate healthy youth's flexible engagement in social cognitive processing in specific social situations.

In contrast to our hypothesis, no age-related changes were found in affective, cognitive control or social brain networks. This may be due in part to dynamic changes in parent–child conflictual relationships across adolescence. For example, parent–child conflicts are the most frequent in early adolescence (Allison and Schultz, 2004), but conflict intensity increases from early adolescence to mid-adolescence (Laursen *et al.*, 1998). Perhaps, neural engagement in processing of maternal criticism may be more affected by affective social factors (e.g. parental warmth and perceived negativity of criticism) rather than age. It is also worthy to note that age-related brain changes were often found in previous studies (Crone *et al.*, 2006; McRae *et al.*, 2012) which compared neural activity in different age groups (e.g. children, adolescence and young adults) rather than different stages (e.g. early, mid and late) within adolescence. Furthermore, there were only a few subjects in late childhood/early adolescence (e.g. 9–11 years old range), which may have limited our ability to detect age-related changes in brain activity in response to maternal criticism. Future research may be needed to clarify age effects on neural response to parental criticism in adolescence.

As hypothesized, there were significant functional relationships between affective network regions (left lentiform nucleus and posterior insula) and cognitive control network regions (DLPFC) in response to maternal criticism compared with neutral comments. In line with these results, brain regions in affective networks are also anatomically connected with regions in cognitive control networks (Beckmann *et al.*, 2009; Haber and Knutson, 2010; Starr *et al.*, 2011). Enhanced functional connectivity between affective and DLPFC may represent increased interactive processes to deal with negative emotional responses to maternal criticism. We also found increased functional connectivity during maternal criticism between cognitive control networks (DLPFC) and social brain networks (TPJ and PCC), which are known to be anatomically inter-connected (Petrides, 2005; Hoshi, 2006). More decreased DLPFC activity in response to maternal criticism was associated with more decreased activity in the TPJ and PCC, indicating possible reciprocal interactions between cognitive control and social cognitive function in processing of maternal criticism.

We should note that three inter-related neural processes were examined here by considering activity in the networks of brain regions often associated with each type of process. This approach is necessarily an oversimplification as (i) observation of activity cannot be used to infer causal roles for these regions and (ii) existing data suggest that most of the regions have many functions (Lindquist and Barrett, 2012), and thus separation of different brain structures is not strictly possible. That said, a strong literature suggests that co-activation of clusters of regions is at least mildly associated with different processes (Laird *et al.*, 2011), and without a guiding framework, interpretation of brain function at the level of whole-brain analysis would be largely impossible. Thus, we tentatively relied on reverse inference regarding the putative general function of brain networks here to help organize our results.

There are several other limitations to this study. First, it is unclear whether the neural responses (e.g. decreased TPJ/IPL activity) we reported are unique to maternal criticism or criticism in general without using a comparison condition, such as criticism from unfamiliar parents. We also used audio clips recorded by mothers, but future research should examine whether adolescents respond similarly to paternal criticism. Second, our participants passively listened to critical and neutral comments during the scanning; therefore, we can only infer that their attention was focused on processing the comments. This experimental design without explicit tasks/manipulations or behavioral measures (e.g. emotion regulation tasks, mentalizing tasks or manipulation of non-social *vs* social conditions) also does not allow for direct tests of specific functions, especially in cognitive control networks and social cognitive networks. Future research could investigate task-related brain functions using specific explicit tasks or experimental manipulations. For example, using explicit emotion regulation tasks (e.g. reappraisal) or social cognitive tasks (e.g. mentalizing) may allow future research to examine whether adolescents engage emotion regulation and social cognition and recruit the corresponding brain networks in response to parental criticism. Third, there might be possible order or emotional carryover effects because neutral statements were presented prior to critical statements in all participants and praise statements were also presented prior to critical statements in about half of the participants. However, findings of time courses during the rest period suggest that possible emotional carryover effects disappear during the subsequent rest period. Fourth, individual differences in dispositions such as child's temperaments, as well as individual differences in parent–child relationships, could mediate or moderate neural responses to maternal criticism. Fifth, we used only two 30 sec audio clips in each condition due to experimental constraints in the use of more ecologically valid and personally relevant maternal criticism. Finally, it should be noted that we did not examine the extent to which healthy youth show behavioral adjustments in response to criticism and whether brain networks engaged in processing of maternal criticism mediate the subsequent behavioral adjustments. One recent study showed that advice on risky choice from an expert decreased choice of risk taking and increased activity in cognitive control networks in adolescents (Engelmann *et al.*, 2012). Criticism (or negative feedback) from parents may have similar impacts on behavioral and neural changes in adolescents, which is an important area for future research.

Despite these limitations, our study elucidated neural responses to maternal criticism in typically developing youth. A major strength of our study is the use of audio clips containing participants' own mothers' criticism, a proxy of real parent–child interactions in family contexts. Our findings provide insights into a better understanding of how youth process criticism from parents. Criticism, as negative evaluative feedback, is associated with increased activity in affective networks possibly reflecting increased negative emotional experience, but decreased activity in networks associated with cognitive control and social cognitive processing. Our main findings suggest that adolescents may be sensitive to negative emotional aspects of criticism, and typically decrease both cognitive control processes and social cognitive processes (e.g. mentalizing or perspective taking), when receiving maternal critical feedback. Despite possible negative impacts of parental criticism, parents still need to criticize their children's behaviors in order to teach rules and regulations. Our findings may have implications for parenting. Parents may benefit from understanding that when they criticize their adolescents, adolescents may experience a strong negative emotional reaction, may have difficulty cognitively controlling this emotion and may also find it challenging to understand the parent's perspective or mental state. Future research may reveal potential differences in neural response to parental criticism in youth with affective or behavioral disorders compared with healthy youth.

SUPPLEMENTARY DATA

Supplementary data are available at *SCAN* online.

Conflict of Interest

At the time this research was done, Dr. Siegle was an unpaid consultant for TrialIQ. The other authors report no conflicts of interest.

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