The development of emotion regulation: an fMRI study of cognitive reappraisal in children, adolescents and young adults

Kateri McRae,[1] James J. Gross,[2] Jochen Weber,[3] Elaine R. Robertson,[2] Peter Sokol-Hessner,[4] Rebecca D. Ray,[5] John D.E. Gabrieli,[6] and Kevin N. Ochsner[3]

[1]University of Denver, Department of Psychology, Denver, CO, [2]Stanford University, Department of Psychology, Stanford, CA, [3]Columbia University, Department of Psychology, New York, NY, [4]California Institute of Technology, Division of Humanities and Social Sciences, Pasadena, CA, [5]University of Wisconsin, Madison, Departments of Radiology and Psychiatry, Madison, WI and [6]Massachusetts Institute of Technology, Department of Brain and Cognitive Sciences, Cambridge, MA, USA

The ability to use cognitive reappraisal to regulate emotions is an adaptive skill in adulthood, but little is known about its development. Because reappraisal is thought to be supported by linearly developing prefrontal regions, one prediction is that reappraisal ability develops linearly. However, recent investigations into socio-emotional development suggest that there are non-linear patterns that uniquely affect adolescents. We compared older children (10–13), adolescents (14–17) and young adults (18–22) on a task that distinguishes negative emotional reactivity from reappraisal ability. Behaviorally, we observed no age differences in self-reported emotional reactivity, but linear and quadratic relationships between reappraisal ability and age. Neurally, we observed linear age-related increases in activation in the left ventrolateral prefrontal cortex, previously identified in adult reappraisal. We observed a quadratic pattern of activation with age in regions associated with social cognitive processes like mental state attribution (medial prefrontal cortex, posterior cingulate cortex, anterior temporal cortex). In these regions, we observed relatively lower reactivity-related activation in adolescents, but higher reappraisal-related activation. This suggests that (i) engagement of the cognitive control components of reappraisal increases linearly with age and (ii) adolescents may not normally recruit regions associated with mental state attribution, but (iii) this can be reversed with reappraisal instructions.

Keywords: reappraisal; emotion regulation; development; social; cognitive

INTRODUCTION

Emotion regulation is a crucial, adaptive skill in adulthood. One of the most flexible and effective types of emotion regulation is the capacity to cognitively reappraise events by interpreting them in ways that change our emotional responses to them (Gross and Thompson, 2007; Giuliani and Gross, 2009). While increasing attention has been paid to reappraisal in adults, little is known about how this adaptive ability develops over the course of adolescence.

Reappraisal in adulthood

In adults, reappraisal is one of the most commonly used emotion regulation strategies, and greater reappraisal use is associated with greater positive affect, greater well-being, diminished negative affect and fewer depressive symptoms (Gross and John, 2003). Behavioral studies instructing adults to use reappraisal have shown that it can be used

effectively to modulate several aspects of emotional responding, including self-reported negative and positive affect (Gross, 1998; Giuliani et al., 2008; Kober et al., 2010), peripheral physiology (Ray et al., 2010), neural indicators of emotional responding (Schaefer et al., 2002; Ochsner et al., 2004; Hajcak and Nieuwenhuis, 2006; Urry et al., 2006; Kim and Hamann, 2007) and economic decisions thought to be influenced by affect (Sokol-Hessner et al., 2009; van't Wout et al., 2010).

Reappraisal is a cognitively complex regulatory strategy that involves keeping the goal to reappraise in working memory; generating alternative (re)appraisals by retrieving from semantic memory information regarding the causes, significance and potential outcomes of the emotional situation; selecting among these possible reappraisals; maintaining the selected appraisal in working memory and finally monitoring the extent to which one is successful in changing one's affective state (Ochsner and Gross, 2008). As such, reappraisal depends on well-studied cognitive abilities, such as working memory, attention and response selection that engages lateral prefrontal and parietal regions (Ochsner and Gross, 2008; Kalisch, 2009). This has led to the conceptualization of reappraisal as closely related to cognitive abilities such as working memory (Schmeichel et al., 2008).

In addition to engaging cognitive control processes, reappraisal also involves representing the mental states of the self and others (as one attends to one's own emotional state or rethinks those of others during the reappraisal process; Ochsner *et al.*, 2004; Ochsner *et al.*, 2009; McRae *et al.*, in press). Although reappraisal is largely considered a cognitive regulatory skill, it is possible that developmental changes in these social processes, like representing another's mental state, are just as important in supporting reappraisal ability. These processes typically engage a network of regions centered on the medial prefrontal cortex (mPFC), and also includes the posterior cingulate cortex, superior temporal sulcus and the temporal poles. These regions are thought to support the ability to attribute mental states to the self and others, which underlies many complex social cognitive abilities, such as self-referential judgments, mentalizing, perspective taking and empathy (Amodio and Frith, 2006; Frith and Frith, 2006; Singer, 2006; Lieberman, 2007; Olson *et al.*, 2007; Olsson and Ochsner, 2008; Adolphs, 2009; Carrington and Bailey, 2009;).

Reappraisal in late childhood and adolescence

The ability to reappraise may be particularly important for adolescents, given the number of novel social and emotional situations that they must navigate, but very little behavioral or functional imaging work has directly focused on the development of reappraisal abilities. Adolescents use cognitive emotion regulation strategies, including reappraisal, less frequently than adults (Garnefski *et al.*, 2002), so it follows that reappraisal is used more and more frequently over the course of development. In addition, behavioral studies of emotion regulation habits in children or adolescents indicate that some emotion regulation strategies, like reappraisal, are more adaptive than others, just as they are in adults (Silk *et al.*, 2007; Garnefski *et al.*, 2009; Carthy *et al.*, 2010). What remains unclear, however, is how the ability to reappraise changes over the course of development.

To date, the majority of imaging research relevant to understanding the neural bases of reappraisal in children and adolescents comes from structural studies of the development of control systems and functional studies of conventional cognitive control tasks. Structural development of prefrontal regions, and the cognitive control abilities they support, is thought to increase sharply over the course of adolescent development (Lewis and Stieben, 2004; Barnea-Goraly *et al.*, 2005; Bunge and Wright, 2007). According to most accounts, there are linear improvements across development in terms of performance on classic cognitive control tasks (e.g. working memory, response inhibition, selection attention), using both emotional and neutral stimuli, and increased activation of the lateral prefrontal regions thought to support these tasks (Perlman and Pelphrey, 2011). This suggests that there should be linear improvements in reappraisal ability through adolescence.

While these studies may characterize the prefrontal control systems involved in reappraisal, they fail to examine the social cognitive processes that also are engaged during reappraisal. This is important because social cognitive abilities, such as mental state attribution, are unlike cognitive control abilities in that they may not improve linearly across development through childhood, adolescence and into adulthood. Long-standing views of child development have focused upon the idea that adolescents might process affect differently than either older children or young adults (Hall, 1904; Casey *et al.*, 2010), which predicts quadratic rather than linear patterns of socio-affective development. In keeping with this, neuroimaging studies of the development of social–cognitive processes in adolescents indicate that they engage medial prefrontal cortices to a greater extent than adults (Blakemore, 2008; Burnett *et al.*, 2009; Pfeifer *et al.*, 2009). Together, these data suggest that the social cognitive processes that are often part of successful reappraisal may be engaged to a greater degree in adolescents than either children or adults.

Recognizing the importance of the issue, three studies have taken initials steps toward studying the neural correlates of reappraisal using developmental samples. Results from these studies have failed to identify regions in which reappraisal-related activation changes with age. Two such studies observed significant activation during the reappraisal of sadness in several prefrontal regions that are also activated during reappraisal in adults (Levesque *et al.*, 2003, 2004), and the other did not observe any age-related changes during the down-regulation of negative affect (Pitskel *et al.*, 2011). Interpretation of these data is clouded, however, by the facts that none of these studies differentiated between linear and non-linear changes with age, and more importantly, that they all used small samples with relatively restricted age ranges. The first two studies examined children and adults in separate analyses, never directly comparing the groups (Levesque *et al.*, 2003, 2004); and a third examined adolescents only up to the age of 17 years, and therefore could not fully characterize the developmental trajectory through young adulthood (Pitskel *et al.*, 2011). Therefore, these studies could not identify the potentially separable contributions of linear and non-linear developmental trajectories in the processes of interest.

The present study

It is unknown whether the development of reappraisal ability proceeds linearly, like the development of core cognitive abilities, or in a non-linear fashion with respect to adolescents, like the development of social cognitive abilities such as mental state attribution. To address this issue, the present study used a cross-sectional design to examine the development of emotion regulation in older children, adolescents and young adults. Participants were scanned while completing a reappraisal task that has been well validated in adults and allows for the separation of emotion regulation ability from baseline emotional reactivity (Ochsner *et al.*, 2002; Ochsner

et al., 2004; Urry et al., 2006; Kim and Hamann, 2007; McRae et al., 2008; Wager et al., 2008; McRae et al., 2010). This allowed us to test for both linear and non-linear patterns in the relationships between age, behavioral indices of reappraisal success and brain activation during reappraisal.

METHODS

Participants

Thirty-eight participants between the ages of 10 and 22 completed the experimental procedure and were compensated for their time. Of these, 21 were female (mean age = 16.75, s.d. = 3.64) and 17 were male (mean age = 16.10, s.d. = 4.11). Although all analyses treated age as a continuous variable, for clarity of presentation, figures are displayed in groups of older children (10–13; $N = 12$), adolescents (14–17; $N = 10$) and young adults (18–23; $N = 16$). Potential participants were excluded if they were (i) left-handed, (ii) below 10 or above 23 years of age, (iii) not native English speakers, (iv) had a current or past diagnosis of neurological or psychiatric disorder, (v) had a history of head trauma, (vi) were pregnant, (vii) currently used psychoactive medication or (viii) had any non-MRI compatible conditions (e.g. metal in body, tattoo on face or neck, medicine delivery patch). Participants provided written consent (or written assent and parental consent) in compliance with the Institutional Review Board guidelines at Stanford University. Data from a subset of the young adult participants in this sample have been reported elsewhere, combined with data not reported here to investigate gender differences in emotion regulation (McRae et al., 2008).

Emotion regulation task

The trial structure was identical to several previous investigations of cognitive reappraisal (e.g. Ochsner et al., 2004). At the start of each trial, an instruction word was presented in the middle of the screen ('decrease' or 'look'; 4 s), a picture was presented (negative if instruction was decrease (regulation instruction), negative or neutral if instruction was look (non-regulation instruction; 8 s), followed by a self-report rating of the strength of negative affect (on a scale from 1 to 4, where 1 was labeled 'weak' and 4 was labeled 'strong'; 4 s) and then the word 'relax' (4 s). Responses were made on a 4-button button box using the participant's dominant (right) hand. The combinations of instruction and picture produce three trial types: decrease negative (reappraisal), look negative (non-regulation) and look neutral (non-emotional).

A total of 72 trials (24 of each trial type) were administered in four runs to children and adolescents, and 90 trials (30 of each trial type) were administered to adults. Different numbers of trials were given to allow parents to screen all 60 eligible negative pictures and exclude up to 12 pictures, creating different sets of pictures for each child and adolescent. Adults were given all 90 pictures so that a wide variety of pictures could be selected post hoc for the purpose of being retroactively compared to any idiosyncratic picture set created for a child or adolescent. We used two different procedures to retroactively select pictures to include for the adults. First, we randomly removed 12 trials for each adult to compare adults with adolescents and children using the same number of trials. Behavioral data from this analysis show the same relationship with age reported here and is included in supplementary material. Our second goal in retroactive picture selection was to make child, adolescent and adult performance on the task as comparable as possible, as our main focus is to compare activation in regions of interest during the successful regulation of emotion. To equate performance, we removed reappraisal trials for which the highest rating of negative affect was reported, as well as look negative trials for which the lowest rating of negative affect was reported, and trials that showed inconsistent patterns with age. Although we were not able to fully equate performance across age, as even with the most favorable selection of trials children and adolescents failed to reach the level of reappraisal success that adults achieved, analyses of behavioral and fMRI data here reflect this performance matching attempt and only include 16 trials per condition for each subject. Therefore, the behavioral performance we report here is somewhat biased to be more similar across age, but this selection process increases the interpretability of the fMRI data by excluding, for example, pictures for which more children failed to complete the task compared to adults.

Stimuli were presented and button responses collected using Psyscope software (Cohen et al., 1993) running on a Macintosh G3 computer. An LCD projector displayed stimuli on a screen mounted on a custom head coil fitted with a bite-bar to limit head motion. Picture stimuli were taken from the International Affective Picture System (Lang et al., 2001) as well as from a set of similar pictures that had been previously used in research with children (Cordon et al., unpublished data). Negative pictures had mean normative valence ratings of 2.55, and mean arousal ratings of 5.86. Neutral images had mean valence ratings of 4.94 and mean arousal ratings of 2.92.[1] Pictures were randomized into different picture presentation orders to reduce the effect of idiosyncratic assignment of picture to instruction and picture order. Within each order, pictures were counterbalanced across conditions such that normative valence and arousal ratings did not differ between them. Instruction and picture types were pseudo-randomized with the constraint that no more than three of any trial type or picture type followed each other sequentially.

---

[1] The IAPS images were 2200, 2205, 2440, 2493, 2516, 2800, 2840, 3030, 3051, 3160, 3180, 3230, 3250, 3500, 3530, 6150, 6210, 6211, 6250, 6260, 6300, 6312, 6370, 6510, 6830, 6831, 7002, 7004, 7009, 7025, 7050, 7090, 7100, 7211, 7233, 7235, 7950, 8230, 9007, 9050, 9140, 9181, 9210, 9420, 9421, 9430, 9440, 9470, 9490, 9570, 9571, 9600, 9611, 9620, 9910, 9921 and the following images from an additional set: 17, 18, 33, 34, 37, 43 and 81 (Cordon et al., unpublished).

Procedure

After reading an overview of the task, participants completed a practice session during which the experimenter showed sample negative and neutral images not used in the experiment. For the regulation (decrease) trials, the experimenter prompted the participant to narrate aloud his or her self-generated re-interpretation of the image. Three types of re-interpretations were suggested: (i) It is not real (e.g. it is just a scene from a movie, they are just pretending), (ii) Things will improve with time (e.g. whatever is going wrong will resolve over time) and (iii) Things are not as bad as they appear to be (e.g. the situation looks worse than it is, it could be a lot worse, at least it is not me in that situation). If, during training, a participant's responses suggested that they were using a non-cognitive strategy (such as expressive suppression or averting their attention from the emotional aspects of the picture) the experimenter offered corrective instructions and re-directed the participant to use one of the three strategies mentioned above.

Imaging parameters

Twenty-five axial slices (4 mm thick, 1 mm skip) were collected at a 3T (GE Signa LX Horizon Echospeed) scanner with a T2* sensitive gradient echo spiral-in-out pulse sequence (TR = 2.00, TE = 30 ms, 60° flip angle, 24-cm field of view, 64 × 64 data acquisition matrix), which has been shown to effectively reduce signal dropout at high field strengths. Evaluation of signal dropout in medial temporal and orbitofrontal regions revealed that signal retained was equal to or better than previous reports using this sequence (Preston *et al.*, 2004).

Data analysis

For the behavioral data, mean negative affect ratings were calculated for the look negative, look neutral and decrease negative conditions. After confirming main effects of reactivity (look negative > look neutral) and regulation (look negative > decrease negative), we computed reactivity and regulation scores for each participant using simple differences between mean ratings for the conditions. To assess the relationship of age to reactivity and regulation, difference scores were regressed against a set of first- and second-order (linear and quadratic) age regressors using multiple linear regression in Statistical Package for the Social Sciences version 19 (SPSS; Chicago, IL, USA).

For subject-level analyses of the fMRI data, each participant's sequential functional volumes were realigned to the first scan and default SPM2 settings were used to warp the mean functional image to fit a standardized template (16 non-linear iterations; SPM2; Wellcome Department of Imaging Neuroscience, University College London, UK). Normalized images were resampled into 2 mm × 2 mm × 2 mm voxels. Finally, images were smoothed with a 6-mm full-width at half maximum Gaussian kernel. Preprocessed images were entered into a standard

multiple regression (ordinary least squares) in NeuroElf (http://neuroelf.net), which included regressors for the conditions of interest (cue and picture onsets for look neutral, look negative and decrease negative conditions). The 8-s picture period was modeled as a boxcar convolved with a canonical HRF. The GLM also included regressors for the condition of no interest (the affect rating portion of the trial), motion parameters[2] and temporal filter regressors with a cut-off of 160 s. Results reported here focus upon the contrasts between conditions during the picture-viewing period, as differential effects from the cue period were not significant at whole-brain corrected levels.

To assess random-effects across participants of all ages, one-sample *t*-tests were computed with NeuroElf for the look negative > look neutral (Emotional Reactivity) and the decrease negative > look negative (Emotion Regulation) contrasts. For these contrasts, we utilized height and cluster size thresholding after establishing FWE thresholds using the alphasim procedure (Forman *et al.*, 1995) at a significance level of $P < 0.005$, FWE $P < 0.05$ at 57 voxels. To assess the relationship of different neural responses to age, contrast maps were regressed against a set of first- and second-order (linear and quadratic) age regressors using multiple linear regression.

Because we were searching the whole brain for correlations with contrasts of conditions (look negative > look neutral and look negative > decrease negative), we used a whole-brain masking procedure to restrict identified voxels to those with an interpretable pattern of activation. In particular, we were interested in voxels that showed relationships with age in the specific condition of interest (usually the first term in the contrast), and not in the comparison condition (the second term in the contrast; for previous use of a similar technique, see McRae *et al.*, 2010). For all correlational analyses, we used a mask of the voxels that showed a significant linear relationship with the first term in the contrast. So, for decrease negative > look negative, we used a mask of voxels that showed a significant correlation of age with beta weights in the decrease negative condition ($P < 0.05$ uncorrected) and then report voxels within that mask that show a significant correlation between age and contrast activations (decrease negative > look negative) at a more stringent, extent-corrected threshold ($P < 0.005$, FWE $P < 0.05$). For the quadratic relationship with age in the decrease negative > look negative contrast, we were interested in voxels showing the quadratic relationship due to an underlying quadratic relationship with both the first and the second terms of the contrast, so we reported these contrasts with each mask separately. ROIs, such as those displayed in the figures, were defined functionally by an 8-mm sphere around peak activation voxels. Local maxima (activation or correlation peaks) are given whenever values within a cluster were found to be not connected to the

already considered (central) mass in a higher values first watershed searching algorithm.

RESULTS

Self-reported negative affect

Whole-group main effects

Considering all participants, significantly greater negative affect was reported for negative than neutral pictures in the look condition [$t(38) = 23.03$, $P < 0.001$], confirming that a negative affective response was induced by the negative images. Lower negative affect was reported for decrease (reappraise) trials than look negative trials [$t(38) = 7.23$, $P < 0.001$], confirming that the reappraisal instruction resulted in the successful reduction of negative affect.

Effects of age

We did not observe a significant relationship between emotional reactivity (look negative-look neutral difference) and age, with either the linear regressor ($\beta = 0.129$, $P = 0.441$) or the quadratic regressor ($\beta = 0.162$, $P = 0.335$). For emotion regulation, we observed a significant relationship between reappraisal success (look negative-decrease negative difference) and age with the linear regressor ($\beta = 0.446$, $P < 0.004$) as well with the quadratic regressor ($\beta = 0.356$, $P < 0.014$). These relationships were driven entirely by a significant negative relationship between negative affect during the decrease negative trials ($\beta = -0.490$, $P < 0.002$, linear; $\beta = -0.328$, $P < 0.020$, quadratic) and not by a significant relationship during the look negative trials ($\beta = 0.072$, $P = 0.662$, linear; $\beta = 0.135$, $P = 0.424$, quadratic) (Figure 1).

Neural responses

Whole-group main effects

Consistent with prior work in adults, with all participants included, we observed strong significant activations related to emotional reactivity (look negative > look neutral contrast) in the insula, visual cortex and several subcortical regions (including the amygdala). Full whole-brain results can

be found in Supplementary Table S1. Also consistent with prior work in adults, we observed significant activations due to reappraisal (decrease negative > look negative contrast) in bilateral prefrontal, parietal and temporal regions (Figure 2). Significant down-regulation (look negative > decrease negative) also was observed in several regions previously reported as down-regulated during reappraisal. We did not observe this effect in an *a priori* region of interest, the amygdala, even with a targeted ROI analysis. Full whole-brain results can be found in Supplementary Tables S2 and S3.

Effects of gender

When gender was included as a predictor in our model, we did not observe any significant main effects, nor any interactions with gender.

Linear effects of age

We did not observe age-related differences in our *a priori* region of interest, the amygdala, even with a targeted ROI analysis. However, for emotional reactivity, in our whole-brain analysis, we did observe a linear effect of age in two regions: a positive relationship with the fusiform gyrus and a negative relationship with the ventromedial prefrontal cortex (Table 1). With respect to emotion regulation, we observed linear increases in activation with age in a left ventrolateral PFC region, the left inferior frontal gyrus (BA 45) (Figure 3 and Table 2).

Quadratic effects of age

For emotional reactivity, we observed a quadratic pattern of activation in multiple regions, such that older children and young adults engaged these regions more strongly during the look negative condition than the look neutral condition, compared with the adolescents. These regions included several prefrontal regions, bilateral superior temporal gyrus, the left insula, left parahippocampal gyrus and regions in both anterior and posterior cingulate cortices (Table 3). For emotion regulation, we observed a quadratic pattern of activation in multiple regions that are typically engaged during
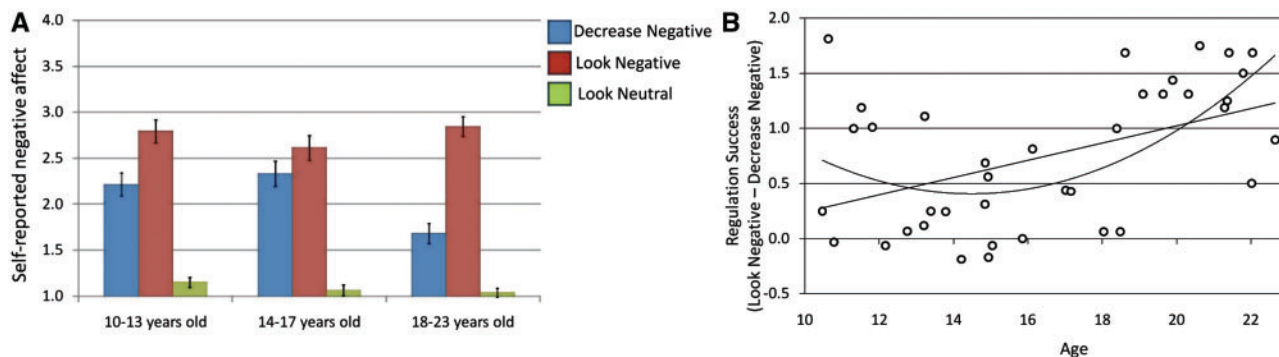

Fig. 1 Self-reported negative affect in response to the three experimental conditions (decrease negative, look negative and look neutral) by age group (**A**) and reappraisal success scores (look negative-decrease negative) by age (**B**). All analyses were done with age as a continuous variable, but we display results by age group for descriptive purposes.
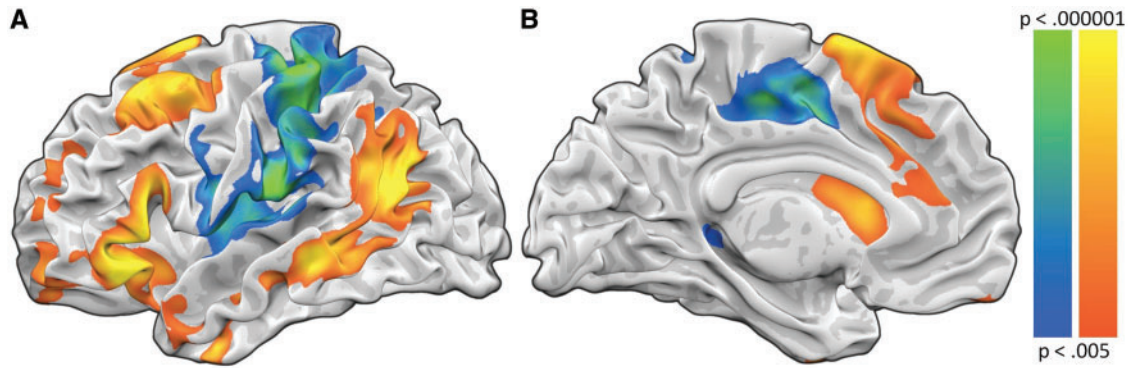
Fig. 2 Left lateral (**A**) and medial (**B**) renderings of the main effects of reappraisal (decrease negative > look negative) in all participants, thresholded at a FWE corrected $P < 0.05$. Warm colors represent regions that with positive values for the comparison (decrease negative > look negative), cool colors represent regions with negative values (look negative > decrease negative).

Table 1 Linear effects of age in the emotional reactivity contrast (look negative > look neutral)

Cluster peak	Voxels	Mean r	Region	BA
−41 −38 −18	123	0.5252 (0.3026)	Left fusiform gyrus	20
−3 50 −16	220	−0.4865 (−0.4043)	Left medial frontal gyrus	11

Peak statistics in parens reflect the analysis including all trials. Peaks are identified with Talairach coordinates. B.A. = Brodmann Area.
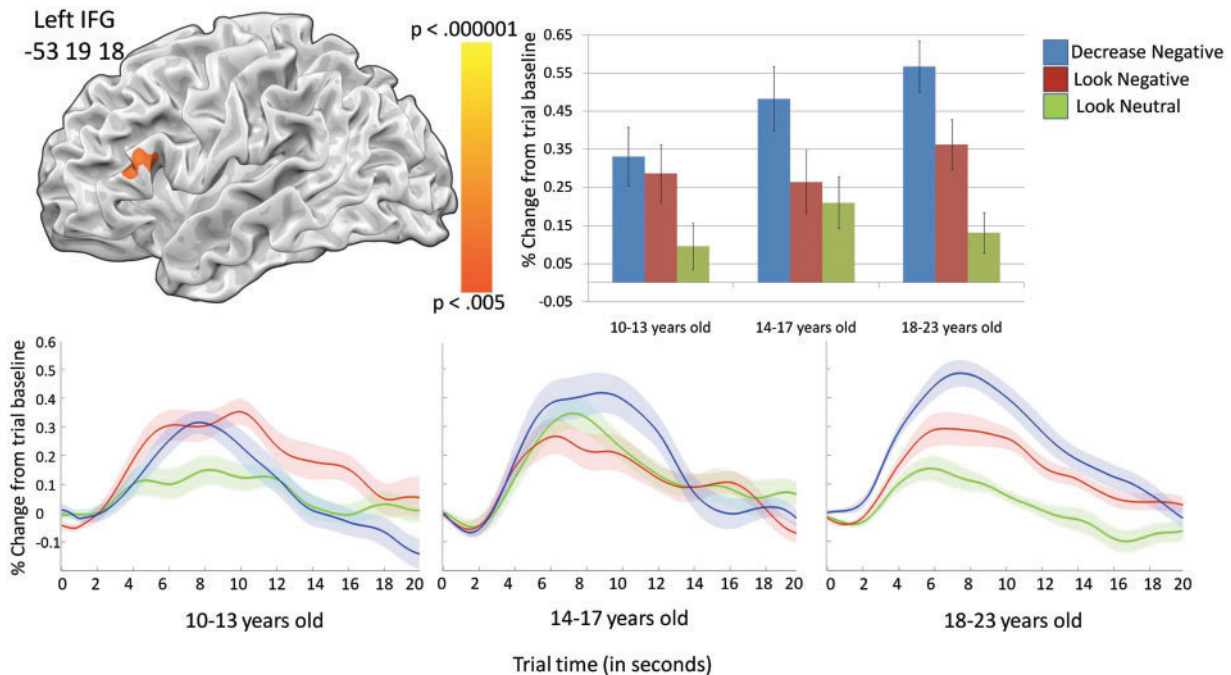

Fig. 3 Left inferior frontal gyrus activation identified in the linear relationship between age and the decrease negative > look negative contrast (top left), mean parameter estimates for the identified cluster by age group for descriptive purposes (top right) and time courses shown by age group from the identified cluster (bottom). Time courses were interpolated using a windowed-sinc interpolation to a 100-ms resolution and are shown for descriptive purposes only. Values shown here were computed by using the value at the onset of each trial (± 2 s) as baseline for that trial and averaging across conditions and participants. Standard error is represented in error bars (top left) and in the light 'halo' around each dark-colored mean time course (bottom). The peak is identified with Talairach coordinates.

Table 2 Linear effects of age in the emotion regulation contrast (decrease negative > look negative)

Cluster Peak	voxels	mean r	Region	B.A.
−53 19 18	95	0.4700 (0.2871)	Left inferior frontal gyrus	45

Peak statistics in parens reflect the analysis including all trials. Peaks are identified with Talairach coordinates.

Table 3 Quadratic effects of age in the emotional reactivity contrast (look negative > look neutral)

Cluster peak	Subcluster peak	voxels	mean r	Region	B.A.
39 −33 2		193	0.4865 (0.3613)	Right subgyral	
	39 −33 2	141	0.4794 (0.3607)	Right subgyral	
	56 −32 9	52	0.5059 (0.3646)	Right superior temporal gyrus	42
−40 −28 2		128	0.4798 (0.3371)	Left insula	22
	−40 −28 2	109	0.4725 (0.3455)	Left insula	22
	−37 −37 9	19	0.5221 (0.3052)	Left superior temporal gyrus	41
22 28 42		243	0.4712 (0.3687)	Right middle frontal gyrus	8
−35 −32 −20		115	0.4639 (0.3060)	Left parahippocampal gyrus	36
	−35 −32 −20	80	0.4561 (0.2938)	Left parahippocampal gyrus	36
	−23 −40 −18	27	0.4847 (0.3684)	Left culmen	
6 −45 −8		59	0.4548 (0.3941)	Right cerebellar lingual	
33 3 40		61	0.4481 (0.2560 ns)	Right middle frontal gyrus	6
	33 3 40	48	0.4502 (0.2475 ns)	Right middle frontal gyrus	6
	42 7 47	13	0.4403 (0.2821)	Right middle frontal gyrus	6
−25 −32 70		60	0.4501 (0.4250)	Left postcentral gyrus	3
	−25 −32 70	32	0.4573 (0.4386)	Left postcentral gyrus	3
	−28 −36 52	15	0.4503 (0.3978)	Left postcentral gyrus	40
	−33 −45 49	13	0.4319 (0.4229)	Left superior parietal lobule	7
−15 24 32		90	0.4473 (0.2620 ns)	Left cingulate gyrus	32
	−15 24 32	52	0.4452 (0.2343 ns)	Left cingulate gyrus	32
	−25 19 49	16	0.4522 (0.3164)	Left middle frontal gyrus	8
	−26 31 39	22	0.4485 (0.2850)	Left middle frontal gyrus	8
7 −9 33		66	0.4501 (0.3667)	Right cingulate gyrus	24
	7 −9 33	32	0.4547 (0.3469)	Right cingulate gyrus	24
	−4 12 31	34	0.4458 (0.3853)	Left cingulate gyrus	24
6 −29 32		70	0.4415 (0.3580)	Right cingulate gyrus	31
	6 −29 32	30	0.4376 (0.3601)	Right cingulate gyrus	31
	3 −43 27	40	0.4444 (0.3564)	Right cingulate gyrus	31

Higher r values indicate greater contrast values in adolescents than older children and young adults. Peak statistics in parens reflect the analysis including all trials, with ns = not significant at $P < .05$. Peaks are identified with Talairach coordinates.

reappraisal in adults, such that adolescents engaged these regions more during reappraisal than either of the other two groups. The quadratic relationship in one of these regions, the posterior cingulate, was driven by a quadratic pattern in the decrease negative condition. The relationship between age and the other regions was driven by a quadratic pattern in the look negative condition. These regions include regions associated with social cognition such as mental state attribution, including the medial prefrontal cortex, the posterior cingulate cortex and the temporal poles (Table 4 and Figure 4).

DISCUSSION

This study is the first to report the neural correlates of cognitive reappraisal used as an emotion regulation strategy by older children, adolescents and young adults. Two key findings were obtained. First, we found a strong linear increase in cognitive reappraisal ability with age, which was accompanied by linear increases in the activation of a region of the left ventrolateral prefrontal cortex previously associated with reappraisal in adults (Ochsner and Gross, 2005, 2008). Second, we found a non-linear relationship between age and reappraisal ability, which was accompanied by activation in regions associated with mental state attribution (Frith and

Frith, 1999; Mitchell *et al.*, 2005; Olsson and Ochsner, 2008). This non-linear relationship took the form of lower levels of activation during emotional reactivity and greater levels of activation during successful reappraisal in the adolescents (14–17) compared to the older children and young adults.

Taken together, these data indicate that although reappraisal ability tracks linearly with age in some prefrontal regions, adolescents may process the emotional value of stimuli differently than either children or adults, as evidenced by lesser engagement of regions implicated in social processing during unregulated responding, but increased engagement of these regions when reappraising.

Development impacts emotion regulation, not emotional reactivity

The vast majority of previous work on emotional development has not been able to separate potential age-related differences in one's emotional reaction from the effects of regulation strategies that modulate emotional responding. We used a validated experimental paradigm that allows for the separation of emotional reactivity and deliberate emotion regulation, and so we were able to examine the relationship between age, emotional reactivity and emotion regulation, as indexed by reappraisal ability.

Table 4 Quadratic effects of age in the emotion regulation contrast (decrease negative > look negative) masked with the quadratic relationship between age and decrease negative (a) and look negative (b)

A. Cluster peak		Voxels	mean r	Region	BA
	0 −43 30	95	−0.5066 (−0.1576 ns)	Left cingulate gyrus	31

B. Cluster peak	Subcluster Peak	Voxels	mean r	Region	BA
−19 34 44		1974	−0.4999 (−0.3311)	Left middle frontal gyrus	8
	−19 34 44	966	−0.4948 (−0.3113)	Left middle frontal gyrus	8
	−15 54 34	148	−0.5298 (−0.3917)	Left superior frontal gyrus	9
	22 28 47	231	−0.5354 (−0.3776)	Right superior frontal gyrus	8
	26 36 44	18	−0.6281 (−0.5242)	Right superior frontal gyrus	8
	−34 21 47	118	−0.5047 (−0.3726)	Left middle frontal gyrus	8
	−36 7 50	46	−0.5732 (−0.2956)	Left middle frontal gyrus	6
	11 4 10	76	−0.4687 (−0.2615 ns)	Right anterior cingulate	32
	−30 4 42	11	−0.5591 (−0.3262)	Left middle frontal gyrus	6
	−22 60 −1	29	−0.4641 (−0.3367)	Left superior frontal gyrus	10
	−29 40 12	64	−0.4590 (−0.3146)	Left middle frontal gyrus	10
	−21 38 −18	41	−0.4611 (−0.2158)	Left middle frontal gyrus	11
	−44 38 −2	51	−0.4551 (−0.2373 ns)	Left middle frontal gyrus	47
	−13 8 24	20	−0.4623 (−0.1489 ns)	Left caudate	
	−45 53 −1	32	−0.4735 (−0.2707 ns)	Left middle frontal gyrus	10
	−4 60 9	43	−0.4676 (−0.2634 ns)	Left medial frontal gyrus	10
	−29 57 24	11	−0.4475 (−0.0687 ns)	Left superior frontal gyrus	10
−47 −73 34		361	−0.5101 (−0.2768)	Left angular gyrus	39
	−47 −73 34	278	−0.4981 (−0.2595 ns)	Left angular gyrus	39
	−44 −65 42	56	−0.5946 (−0.3464)	Left inferior parietal lobule	39
	−48 −58 18	27	−0.4586 (−0.2469 ns)	Left superior temporal gyrus	22
−30 −82 −19		1057	−0.4847 (−0.3084)	Left declive	
	−30 −82 −19	243	−0.4955 (−0.3112)	Left declive	
	32 −80 −18	640	−0.4748 (−0.2918)	Right declive	
	19 −89 −19	23	−0.5852 (−0.3832)	Right declive	
	6 −84 −13	16	−0.5495 (−0.3379)	Right lingual gyrus	18
	35 −69 −26	19	−0.5199 (−0.3390)	Right uvula	
	−32 −66 −34	60	−0.4579 (−0.2726 ns)	Left cerebellar tonsil	
	−35 −66 −20	27	−0.4833 (−0.3877)	Left declive	
0 −43 30		383	−0.4974 (−0.1964 ns)	Left cingulate gyrus	31
	0 −43 30	310	−0.4893 (−0.1662 ns)	Left cingulate gyrus	31
	0 −29 32	56	−0.5244 (−0.3158)	Left cingulate gyrus	31
	3 −14 33	17	−0.5573 (−0.3062)	Right cingulate gyrus	23
−51 5 −24		399	−0.4782 (−0.2684 ns)	Left middle temporal gyrus	21
	−51 5 −24	215	−0.4753 (−0.2786)	Left middle temporal gyrus	21
	−53 −54 −16	35	−0.4884 (−0.3100)	Left fusiform gyrus	37
	−60 −37 −9	59	−0.4852 (−0.2642 ns)	Left middle temporal gyrus	21
	−47 16 −23	12	−0.4894 (−0.2559 ns)	Left superior temporal gyrus	38
	−58 −25 −9	34	−0.4868 (−0.2009 ns)	Left middle temporal gyrus	21
	−43 −15 −27	20	−0.4567 (−0.3234)	Left inferior temporal gyrus	20
	−63 −40 5	16	−0.4410 (−0.1736 ns)	Left middle temporal gyrus	22
62 −18 −20		99	−0.4702 (−0.2851)	Right inferior temporal gyrus	20
	62 −18 −20	47	−0.4804 (−0.2591 ns)	Right inferior temporal gyrus	20
	69 −37 −5	38	−0.4602 (−0.3115)	Right middle temporal gyrus	21
	61 −36 −12	14	−0.4631 (−0.3067)	Right middle temporal gyrus	21
50 −60 39		231	−0.4844 (−0.2516)	Right inferior parietal lobule	39
−23 16 −15		66	−0.4541 (−0.3460)	Left inferior frontal gyrus	47
	−23 16 −15	35	−0.4565 (−0.3923)	Left inferior frontal gyrus	47
	−27 24 −21	12	−0.4574 (−0.3326)	Left inferior frontal gyrus	47
	−37 32 −16	19	−0.4477 (−0.2676 ns)	Left middle frontal gyrus	11
−3 −7 12		76	−0.4545 (−0.3713)	Left thalamus	
46 19 45		59	−0.4428 (−0.2178 ns)	Right middle frontal gyrus	8

Lower r values indicate greater contrast values in adolescents than older children and young adults. Peak statistics in parens reflect the analysis including all trials, with ns = not significant at P < .05. Peaks are identified with Talairach coordinates.

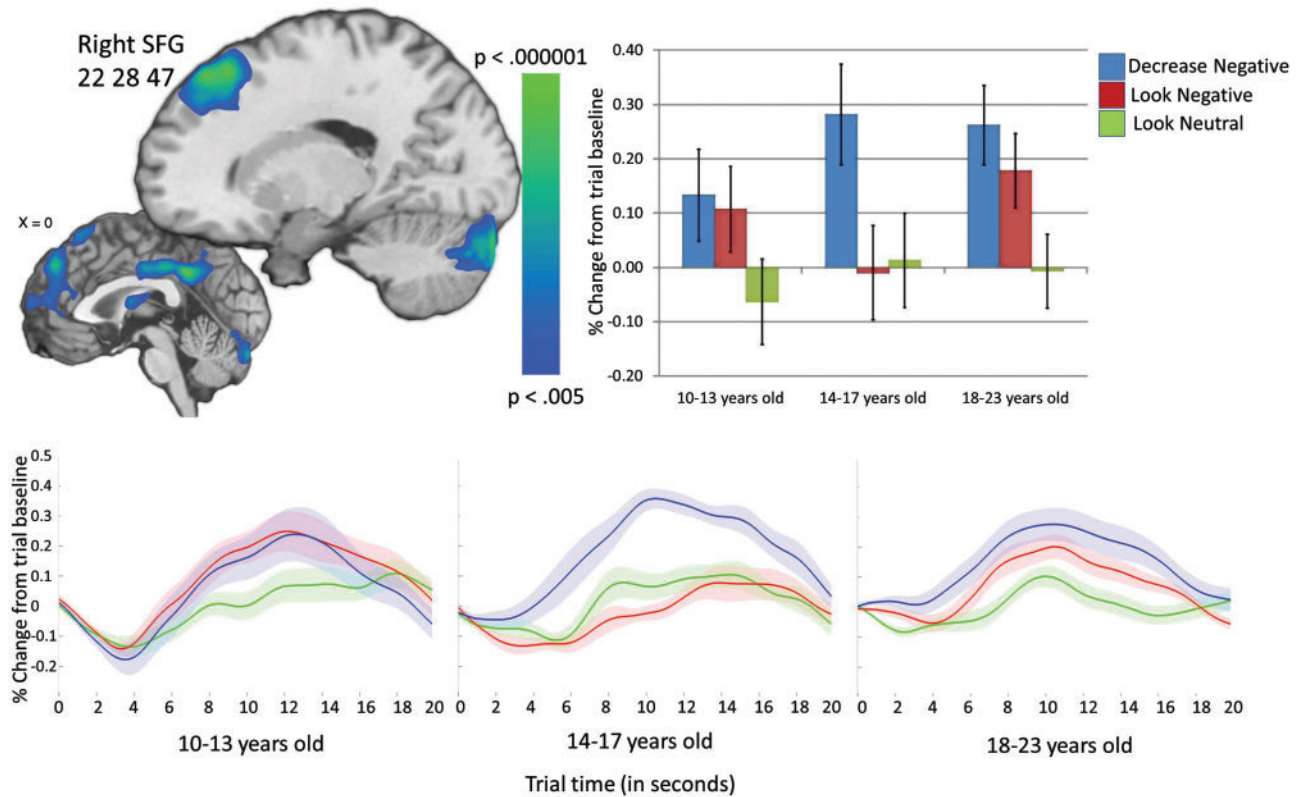**Fig. 4** Right mPFC activation identified in the quadratic relationship between age and the look negative > look neutral contrast (top left), mean parameter estimates for the identified cluster shown by age group for descriptive purposes (top right) and time courses by age group from the identified cluster (bottom). Inset at $X = 0$ demonstrates the central extent of the right SFG activation. Time courses were interpolated using a windowed-sinc interpolation to a 100-ms resolution and are shown for descriptive purposes only. Values shown here were computed by using the value at the onset each trial ($\pm 2\,s$) as baseline for that trial and averaging across conditions and participants. Standard error is represented in error bars (top left) and in the light 'halo' around each dark-colored mean time course (bottom) but should not be used for assessing significance. The peak is identified with Talairach coordinates.

While we found no age-related differences in emotional reactivity, measured either by self-reported affect or amygdala activation, we did observe both linear increases and a quadratic relationship between reappraisal ability and age. This provides support for the notion that some of the variation observed in emotionality over development may be due to the maturation of various cognitive abilities that can be applied to emotion regulation (Dahl, 2003; Steinberg, 2005; Luna, 2009). To date, however, cognitive and emotional skills have largely been studied separately, which has not allowed for the testing of this theory using cognitive processes that deliberately influence emotions. Assessing emotional well-being at any age may require measuring not just individual differences in how we react to situations and cognitive abilities, but whether and how well we can harness our regulatory skills for the purpose of modifying our emotional responses. Below, we review the component processes in reappraisal that may be reflected in the linear and quadratic relationships with age.

Linear changes in cognitive development
Although we observed no linear relationships between age and activation in regions typically thought to index negative

emotional reactivity, we did observe linear increases in activation with age in the fusiform gyrus. Several of the emotional stimuli in the present data set did contain human faces (65% of the negative photos), and previous work has demonstrated increases in fusiform gyrus activation with age (Golarai *et al.*, 2010). In addition, we observed age-related decreases in activation in the ventromedial prefrontal cortex (vmPFC). The vmPFC has been previously implicated in the re-construction or re-evaluation of affective meaning in a new context. For example, it is engaged during extinction learning (Delgado *et al.*, 2008), and the evaluation of material in a self-relevant context (Kelley *et al.*, 2002) and has been previously implicated in successfully transformed affect due to reappraisal in older adults (Urry *et al.*, 2006). Because we observed this relationship with age during emotional reactivity, it is possible that for the youngest children, each negative stimulus is evaluated in relation to the present context, including how it fits in with the other stimuli in the experiment, and how it relates to them. As individuals age, their unregulated negative responding may not involve such extensive elaboration of context-sensitive meaning, and perhaps is better characterized as rapid categorization of stimuli based on

stimulus-driven perceptual properties (the processing in the fusiform) as opposed to evaluation of context or self-relevance (the processing in the vmPFC).

In adults, reappraisal ability is considered one type of a more general set of cognitive control skills (Ochsner and Gross, 2008; Schmeichel *et al.*, 2008). Consistent with this view, the linear increases in reappraisal ability that we observed were accompanied by linear increases in activation in a region thought to support some types of cognitive control in adults, the left ventrolateral prefrontal cortex (Wager and Smith, 2003; Narayanan *et al.*, 2005). Age-related increases in this region have been observed previously during tasks that involve working memory, especially verbal tasks (Wager and Smith, 2003; Thomason *et al.*, 2009). During reappraisal, age-related activation in this region may reflect verbal working memory to generate and maintain the alternate interpretation of the negative stimulus. It is unknown whether the engagement of this region (and the verbal working memory processes that it may reflect) is necessary or sufficient for successful reappraisal. However, it is clear that of several processes and regions engaged during reappraisal, this one shows strong linear increases in activation over the course of development.

Non-linear changes in social-cognitive development

Previous studies have observed heightened emotional reactivity during adolescence, as indexed by heightened amygdala activation (Williams *et al.*, 2006; Guyer *et al.*, 2008; Hare *et al.*, 2008; Pfeifer *et al.*, 2011) and greater frontal N2 amplitudes (Lewis *et al.*, 2006). We did not observe heightened amygdala activation in adolescents. In fact, we did not observe any age differences in amygdala activation, or any differences in regions thought to index emotional reactivity to indicate that the adolescents stood out from the other two age groups. Whether this is due to the content of the emotional pictures selected to be in the task, the instructions we used that separated out reactivity from regulation, or the sample of adolescents in our study is unknown. However, we did observe non-linear relationships between age and activation in other regions previously implicated in social cognition, particularly perspective taking. These regions were under-activated during emotional reactivity in adolescents compared to the other two age groups, but showed an even greater response during reappraisal compared to the other groups.

The present results indicate that reappraisal success shows both linear and quadratic relationships with age, and those in adolescence (14–17 year olds) show greater increases in activation in medial prefrontal, posterior cingulate and temporal regions during reappraisal compared with children and adults. This finding is consistent with several reports that adolescents engage mPFC to a greater extent than adults during tasks that explicitly require mental state attribution (Blakemore, 2008). In this context, the present finding of increased mPFC activation might reflect the fact that

adolescents engage perspective-taking processes during reappraisal to a greater extent than older children or younger adults. However, because of the masking procedure we used, we were able to determine that activation in these regions during reappraisal reflects lower activation in these regions during unregulated responding, that is then significantly increased to levels comparable to the other two age groups during reappraisal. This suggests that if activation in these regions reflects social cognitive processing, adolescents do not engage these processes during unregulated responding, but then engage these processes strongly during reappraisal. Therefore, the shift between reacting naturally and reappraising may involve a stronger recruitment of social cognitive processes such as mental state attribution in adolescents than those in the other age groups.

While this study was not designed to isolate the specific social cognitive processes, such as mental state attribution, involved in reappraisal, one possibility is that adolescents do not spontaneously take the perspective of the person in the picture, but are then able to do so when asked to reappraise. Another possibility is that the activation swing does not represent a greater engagement of social cognitive processes specifically. Instead, relatively increased mPFC and posterior cingulate cortex activation during reappraisal might reflect greater disengagement from the default mode network (Gusnard *et al.*, 2001). In other words, adolescents may have more fully directed their attention to the reappraisal task, disengaging from their self-focused thoughts while completing the task. This seems unlikely, however, given the fact that they did not in fact perform better on the task than the young adults who showed lesser mPFC activation during reappraisal. Therefore, we find more plausible the interpretation that adolescents may use a social cognitive process, such as perspective taking, to engage in qualitatively different emotion regulation strategies compared to unregulated responding.

Limitations and future directions

The present study is the first investigation to identify the continuous linear and non-linear effects of age on the neural processes engaged during cognitive reappraisal. As such, there are some limitations of the results we present here and the conclusions that can be drawn. First, the data we present are cross-sectional, and future investigations should ideally utilize longitudinal designs to examine changes in emotion regulation ability over the course of development within participants. Second, we were underpowered to detect gender differences with our sample, but gender differences have been previously reported in the brain structure of adolescents (Blankstein *et al.*, 2009) as well as in the neural correlates of emotion regulation in adults (McRae *et al.*, 2008). With a lager sample, significant gender differences may emerge.

In addition, we selected pictures *post hoc* to as closely equate behavioral performance across age as possible, and

observed age-related differences in regulation, but not re-activity. It is possible that there were age-related differences in responses to the images—e.g. qualitative differences in the emotions evoked—that were not captured by our negative affect ratings. Future work should utilize a variety of emotional stimuli, including those developed for use with children and adults.

We feel that it is important to note that the stimuli in the present study were not exclusively social, nor did we obtain any behavioral measures that specifically captured social, empathetic or perspective-taking processes. Our interpretation of the regions that display a quadratic pattern of activation with age is based on a large number of previous studies that show co-activation of these regions during social cognitive tasks. Future studies are needed to confirm these hypotheses inspired by our data. These studies should directly manipulate the social nature of the stimuli to be reappraised and examine the effects of age.

Finally, it will of course be essential that future work seek to further clarify the specific processes engaged by reappraisal that increase linearly or non-linearly with age. This is important not only for a model of the basic neural architecture of emotion regulation, but also for understanding the behavioral consequences of the differences we report between children, adolescents and adults.

SUPPLEMENTARY DATA

Supplementary data are available at *SCAN* online.

Conflict of Interest
None declared.

REFERENCES

Adolphs, R. (2009). The social brain: neural basis of social knowledge. *Annual Review of Psychology*, 60, 693–716.

Amodio, D.M., Frith, C.D. (2006). Meeting of minds: the medial frontal cortex and social cognition. *Nature Reviews Neuroscience*, 7, 268–77.

Barnea-Goraly, N., Menon, V., Eckert, M., et al. (2005). White matter development during childhood and adolescence: a cross-sectional diffusion tensor imaging study. *Cerebral Cortex*, 15, 1848–54.

Blakemore, S.J. (2008). The social brain in adolescence. *Nature Reviews Neuroscience*, 9, 267–77.

Blankstein, U., Chen, J.Y., Mincic, A.M., McGrath, P.A., Davis, K.D. (2009). The complex minds of teenagers: neuroanatomy of personality differs between sexes. *Neuropsychologia*, 47, 599–603.

Bunge, S.A., Wright, S.B. (2007). Neurodevelopmental changes in working memory and cognitive control. *Current Opinion in Neurobiology*, 17, 243–50.

Burnett, S., Bird, G., Moll, J., Frith, C., Blakemore, S.J. (2009). Development during adolescence of the neural processing of social emotion. *Journal of Cognitive Neuroscience*, 21, 1736–50.

Carrington, S.J., Bailey, A.J. (2009). Are there theory of mind regions in the brain? A review of the neuroimaging literature. *Human Brain Mapping*, 30, 2313–35.

Carthy, T., Horesh, N., Apter, A., Edge, M.D., Gross, J.J. (2010). Emotional reactivity and cognitive regulation in anxious children. *Behavioral Research and Therapy*, 48, 384–93.

Casey, B.J., Jones, R.M., Levita, L., et al. (2010). The storm and stress of adolescence: insights from human imaging and mouse genetics. *Developmental Psychobiology*, 52, 225–35.

Cohen, J.D., MacWhinney, B., Flatt, M., Provost, J. (1993). PsyScope: a new graphic interactive environment for designing psychology experiments. *Behavioral Research Methods, Instruments, and Computers*, 25, 257–71.

Dahl, R.E. (2003). The development of affect regulation: bringing together basic and clinical perspectives. *Annals of the New York Academy of Sciences*, 1008, 183–8.

Delgado, M.R., Nearing, K.I., LeDoux, J.E., Phelps, E.A. (2008). Neural circuitry underlying the regulation of conditioned fear and its relation to extinction. *Neuron*, 59, 829–38.

Frith, C.D., Frith, U. (1999). Interacting minds—a biological basis. *Science*, 286, 1692–5.

Frith, C.D., Frith, U. (2006). The neural basis of mentalizing. *Neuron*, 50, 531–4.

Forman, S.C.J.D., Fitzgerald, M., Eddy, W., Mintun, M., Noll, D. (1995). Improved assessment of significant activation in functional magnetic resonance imaging (fMRI): use of a cluster-size threshold. *Magnetic Resonance in Medicine*, 33, 636–47.

Garnefski, N., Koopman, H., Kraaij, V., ten Cate, R. (2009). Brief report: cognitive emotion regulation strategies and psychological adjustment in adolescents with a chronic disease. *Journal of Adolescence*, 32, 449–54.

Garnefski, N., Legerstee, J., Kraaij, V., Van Den Kommer, T., Teerds, J.A.N. (2002). Cognitive coping strategies and symptoms of depression and anxiety: a comparison between adolescents and adults. *Journal of Adolescence*, 25, 603–11.

Giuliani, N.R., Gross, J.J. (2009). Reappraisal. In: Sander, D., Scherer, K.R., editors. *Oxford Companion to the Affective Sciences*. New York: Oxford University Press, pp. 329–30.

Giuliani, N.R., McRae, K., Gross, J.J. (2008). The up- and down-regulation of amusement: experiential, behavioral, and autonomic consequences. *Emotion*, 8, 714–9.

Golarai, G., Liberman, A., Yoon, J.M., Grill-Spector, K. (2010). Differential development of the ventral visual cortex extends through adolescence. *Frontiers in Human Neuroscience*, 3, 80.

Gross, J.J. (1998). Antecedent- and response-focused emotion regulation: divergent consequences for experience, expression, and physiology. *Journal of Personality and Social Psychology*, 74, 224–37.

Gross, J.J., John, O.P. (2003). Individual differences in two emotion regulation processes: implications for affect, relationships, and well-being. *Journal of Personality and Social Psychology*, 85, 348–62.

Gross, J.J., Thompson, R.A. (2007). Emotion regulation: Conceptual foundations. In: Gross, J.J., editor. *Handbook of Emotion Regulation*. New York: Guilford Press, pp. 3–24.

Gusnard, D.A., Akbudak, E., Shulman, G.L., Raichle, M.E. (2001). Medial prefrontal cortex and self-referential mental activity: relation to a default mode of brain function. *Proceedings of the National Academy of Sciences*, 98, 4259–64.

Guyer, A.E., Monk, C.S., McClure-Tone, E.B., et al. (2008). A developmental examination of amygdala response to facial expressions. *Journal of Cognitive Neuroscience*, 20, 1565–82.

Hajcak, G., Nieuwenhuis, S. (2006). Reappraisal modulates the electrocortical response to unpleasant pictures. *Cognitive, Affective, Behavioral Neuroscience*, 6, 291–7.

Hall, G.S. (1904). *Adolescence: In Psychology and Its Relation to Physiology, Anthropology, Sociology, Sex, Crime, Religion, and Education*. Englewood Cliffs, NJ: Prentice-Hall.

Hare, T.A., Tottenham, N., Galvan, A., Voss, H.U., Glover, G.H., Casey, B.J. (2008). Biological substrates of emotional reactivity and regulation in adolescence during an emotional go-nogo task. *Biological Psychiatry*, 63, 927–34.

Kalisch, R. (2009). The functional neuroanatomy of reappraisal: time matters. *Neuroscience Biobehavioral Reviews*, 33, 1215–26.

Kelley, W.M., Macrae, C.N., Wyland, C.L., Caglar, S., Inati, S., Heatherton, T.F. (2002). Finding the self? an event-related fMRI study. *Journal of Cognitive Neuroscience*, 14, 785–94.

Kim, S.H., Hamann, S. (2007). Neural correlates of positive and negative emotion regulation. *Journal of Cognitive Neuroscience*, 19, 776–98.

Kober, H., Kross, E.F., Mischel, W., Hart, C.L., Ochsner, K.N. (2010). Regulation of craving by cognitive strategies in cigarette smokers. *Drug Alcohol Dependence*, 106, 52–5.

Lang, P.J., Bradley, M.M., Cuthbert, B.N. (2001). International Affective Picture System (IAPS). Instruction Manual and Affective Ratings. Technical ReportThe University of Florida, Gainesville, FL: The Center for Research in Psychophysiology.

Levesque, J., Eugene, F., Joanette, Y., et al. (2003). Neural circuitry underlying voluntary suppression of sadness. *Biological Psychiatry*, 53, 502–10.

Levesque, J., Joanette, Y., Mensour, B., et al. (2004). Neural basis of emotional self-regulation in childhood. *Neuroscience*, 129, 361–9.

Lewis, M.D., Lamm, C., Segalowitz, S.J., Stieben, J., Zelazo, P.D. (2006). Neurophysiological correlates of emotion regulation in children and adolescents. *Journal of Cognitive Neuroscience*, 18, 430–43.

Lewis, M.D., Stieben, J. (2004). Emotion regulation in the brain: conceptual issues and directions for developmental research. *Child Development*, 75, 371–6.

Lieberman, M.D. (2007). Social cognitive neuroscience: a review of core processes. *Annual Review of Psychology*, 58, 259–89.

Luna, B. (2009). Developmental changes in cognitive control through adolescence. *Advances in Child Development and Behavior*, 37, 233–78.

McRae, K., Hughes, B., Chopra, S., Gabrieli, J.D.E., Gross, J.J., Ochsner, K.N. (2010). The neural bases of distraction and reappraisal. *Journal of Cognitive Neuroscience*, 22, 248–62.

McRae, K., Misra, S., Prasad, A.K., Periera, S.C., Gross, J.J. (in press). Bottom-up and top-down emotion generation: implications for emotion regulation. *Social, Cognitive and Affective Neuroscience*, doi:10.1093/scan/nsq103.

McRae, K., Ochsner, K.N., Mauss, I.B., Gabrieli, J.D.E., Gross, J.J. (2008). Gender differences in emotion regulation: An fMRI study of cognitive reappraisal. *Group Processes and Intergroup Relations*, 11, 143–62.

Mitchell, J.P., Banaji, M.R., Macrae, C.N. (2005). The link between social cognition and self-referential thought in the medial prefrontal cortex. *Journal of Cognitive Neuroscience*, 17, 1306–15.

Narayanan, N.S., Prabhakaran, V., Bunge, S.A., Christoff, K., Fine, E.M., Gabrieli, J.D. (2005). The role of the prefrontal cortex in the maintenance of verbal working memory: an event-related FMRI analysis. *Neuropsychology*, 19, 223–32.

Ochsner, K.N., Bunge, S.A., Gross, J.J., Gabrieli, J.D.E. (2002). Rethinking feelings: An FMRI study of the cognitive regulation of emotion. *Journal of Cognitive Neuroscience*, 14, 1215–29.

Ochsner, K.N., Gross, J.J. (2005). The cognitive control of emotion. *Trends in Cognitive Sciences*, 9, 242–9.

Ochsner, K.N., Gross, J.J. (2008). Cognitive emotion regulation: Insights from social cognitive and affective neuroscience. *Current Directions in Psychological Science.*, 17, 153–8.

Ochsner, K.N., Knierim, K., Ludlow, D., Hanelin, J., Ramachandran, T., Mackey, S. (2004). Reflecting upon feelings: An fMRI study of neural systems supporting the attribution of emotion to self and other. *Journal of Cognitive Neuroscience*, 16, 1746–72.

Ochsner, K.N., Ray, R.D., Cooper, J.C., Robertson, E.R., et al. (2004). For better or for worse: neural systems supporting the cognitive down- and up-regulation of negative emotion. *Neuroimage*, 23, 483–99.

Ochsner, K.N., Ray, R.R., Hughes, B., et al. (2009). Bottom-up and top-down processes in emotion generation: common and distinct neural mechanisms. *Psychological Science*, 20, 1322–31.

Olson, I.R., Plotzker, A., Ezzyat, Y. (2007). The enigmatic temporal pole: a review of findings on social and emotional processing. *Brain*, 130, 1718–31.

Olsson, A., Ochsner, K.N. (2008). The role of social cognition in emotion. *Trends in Cognitive Sciences*, 12, 65–71.

Perlman, S.B., Pelphrey, K.A. (2011). Developing connections for affective regulation: age-related changes in emotional brain connectivity. *Journal of Experimental Child Psychology*, 108, 607–20.

Pfeifer, J.H., Masten, C.L., Borofsky, L.A., Dapretto, M., Fuligni, A.J., Lieberman, M.D. (2009). Neural correlates of direct and reflected self-appraisals in adolescents and adults: when social perspective-taking informs self-perception. *Child Development*, 80, 1016–38.

Pfeifer, J.H., Masten, C.L., Moore, I., et al. (2011). Entering adolescence: resistance to peer influence, risky behavior, and neural changes in emotion reactivity. *Neuron*, 69, 1029–36.

Pitskel, N.B., Bolling, D.Z., Kaiser, M.D., Crowley, M.J., Pelphrey, K.A. (2011). How grossed out are you? The neural bases of emotion regulation from childhood to adolescence. *Developmental Cognitive Neuroscience*, 1, 324–37.

Preston, A.R., Thomason, M.E., Ochsner, K.N., Cooper, J.C., Glover, G.H. (2004). Comparison of spiral-in/out and spiral-out BOLD fMRI at 1.5 and 3 T. *Neuroimage*, 21, 291–301.

Ray, R.D., McRae, K., Ochsner, K.N., Gross, J.J. (2010). Cognitive reappraisal of negative affect: converging evidence from EMG and self-report. *Emotion*, 10, 587–92.

Schaefer, S.M., Jackson, D.C., Davidson, R.J., Aguirre, G.K., Kimberg, D.Y., Thompson-Schill, S.L. (2002). Modulation of amygdalar activity by the conscious regulation of negative emotion. *Journal of Cognitive Neuroscience*, 14, 913–21.

Schmeichel, B.J., Volokhov, R.N., Demaree, H.A. (2008). Working memory capacity and the self-regulation of emotional expression and experience. *Journal of Personality and Social Psychology*, 95, 1526–40.

Silk, J.S., Vanderbilt-Adriance, E., Shaw, D.S., et al. (2007). Resilience among children and adolescents at risk for depression: Mediation and moderation across social and neurobiological contexts. *Development and Psychopathology*, 19, 841–65.

Singer, T. (2006). The neuronal basis and ontogeny of empathy and mind reading: Review of literature and implications for future research. *Neuroscience Biobehavioral Reviews*, 30, 855–63.

Sokol-Hessner, P., Hsu, M., Curley, N.G., Delgado, M.R., Camerer, C.F., Phelps, E.A. (2009). Thinking like a trader selectively reduces individuals' loss aversion. *Proceedings of the National Academy of Sciences*, 106, 5035–40.

Steinberg, L. (2005). Cognitive and affective development in adolescence. *Trends in Cognitive Sciences*, 9, 69–74.

Thomason, M.E., Race, E., Burrows, B., Whitfield-Gabrieli, S., Glover, G.H., Gabrieli, J.D. (2009). Development of spatial and verbal working memory capacity in the human brain. *Journal of Cognitive Neuroscience*, 21, 316–32.

Urry, H.L., van Reekum, C.M., Johnstone, T., et al. (2006). Amygdala and ventromedial prefrontal cortex are inversely coupled during regulation of negative affect and predict the diurnal pattern of cortisol secretion among older adults. *Jounal of Neuroscience*, 26, 4415–25.

van't Wout, M., Chang, L.J., Sanfey, A.G. (2010). The influence of emotion regulation on social interactive decision-making. *Emotion*, 10, 815–21.

Wager, T.D., Davidson, M.L., Hughes, B.L., Lindquist, M.A., Ochsner, K.N. (2008). Prefrontal-subcortical pathways mediating successful emotion regulation. *Neuron*, 59, 1037–50.

Wager, T.D., Smith, E.E. (2003). Neuroimaging studies of working memory: A meta-analysis. *Cognitive, Affective Behavioral Neuroscience*, 3, 255–74.

Williams, L.M., Brown, K.J., Palmer, D., et al. (2006). The mellow years?: neural basis of improving emotional stability over age. *The Journal of Neuroscience*, 26, 6422–30.