

Longitudinal Change in the Neural Bases of Adolescent Social Self-Evaluations: Effects of Age and Pubertal Development

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Self-evaluations undergo significant transformation during early adolescence, developing in parallel with the heightened complexity of teenagers' social worlds. Intuitive theories of adolescent development, based in part on animal work, suggest that puberty is associated with neural-level changes that facilitate a "social reorientation" (Nelson et al., 2005). However, direct tests of this hypothesis using neuroimaging are limited in humans. This longitudinal fMRI study examined neurodevelopmental trajectories associated with puberty, self-evaluations, and the presumed social reorientation during the transition from childhood to adolescence. Participants ($N = 27$, mean age = 10.1 and 13.1 years at time points one and two, respectively) engaged in trait evaluations of two targets (the self and a familiar fictional other), across two domains of competence (social and academic). Responses in ventromedial PFC increased with both age and pubertal development during self-evaluations in the social domain, but not in the academic domain. These results suggest that changes in social self-evaluations are intimately connected with biology, not just peer contexts, and provide important empirical support for the relationship between neurodevelopment, puberty, and social functioning.

Introduction

Adolescence is widely regarded as a special time for self-discovery and identity exploration. Research confirms that this is a period of significant self-development, including a growing sense of uniqueness but also connection with others, which is affected by multiple factors, including biology and context (Harter, 1999). For example, pubertal development is thought to fuel a "social reorientation" (Nelson et al., 2005) that heightens the salience of peer relations. As a result, social self-concepts (evaluative self-knowledge pertaining to the peer domain) might be in a state of

considerable flux and sensitivity. Transitioning from elementary to middle school, meanwhile, is known to significantly impact academic self-concepts (Eccles et al., 1993); they become more negative overall, and academic engagement decreases. Yet we know very little about how changes in brain function relate to adolescent self-development, and in particular we lack information about longitudinal changes in the neural correlates of self-evaluations across social and academic domains.

The current investigation advances the study of self-development through the use of developmental social neuroscience methods, in contrast to the self-report and theory-based approaches that have dominated past work in this area. Reviews of the neural systems supporting adult self-evaluations have converged on a set of critical regions, predominantly focusing on cortical midline structures: medial prefrontal cortex (mPFC, including rostral anterior cingulate cortex [ACC]) and medial posterior parietal cortex (mPPC) (Van Overwalle, 2009; Northoff et al., 2011). To our knowledge, only three studies have examined the neural systems supporting self-evaluations in typically developing samples. Together, they confirm that mPFC (including rostral ACC) is central to self-referential processing in children and adolescents (Pfeifer et al., 2007, 2009; Ray et al., 2009). However, the current study is the first to apply a longitudinal fMRI approach to the study of self-development. This allows us to investigate within-subject neural changes related to age and puberty at the transition point from childhood to adolescence, rather than broad cross-sectional differences among children,

Received Aug. 24, 2012; revised Feb. 12, 2013; accepted March 11, 2013.

Author contributions: J.H.P., M.D.L., J.C.M., and M.D. designed research; J.H.P. and C.L.M. performed research; J.H.P., L.E.K., J.S.M., S.J.P., and K.V. analyzed data; J.H.P., L.E.K., J.S.M., S.J.P., K.V., C.L.M., M.D.L., and M.D. wrote the paper.

This work was supported by the National Institutes of Health Grants F31MH075299, L40HD059442, and L40MH087356 to J.H.P.; the Sante Fe Institute Consortium, Brain Mapping Medical Research Organization, Brain Mapping Support Foundation, Pierson-Lovelace Foundation, Ahmanson Foundation, Tamkin Foundation, Jennifer Jones-Simon Foundation, Capital Group Companies Charitable Foundation, Robson Family, William M. and Linda R. Dietel Philanthropic Fund at the Northern Piedmont Community Foundation, and Northstar Fund; and National Center for Research Resources Grants RR12169, RR13642 and RR00865, a component of the National Institutes of Health. Its contents are solely the responsibility of the authors and do not necessarily represent the official views of National Center for Research or National Institutes of Health. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

The authors declare no competing financial interests.

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DOI:10.1523/JNEUROSCI.4074-12.2013

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adolescents, and adults. Furthermore, although there are strong links between puberty and changes in social behaviors (Forbes and Dahl, 2010), much of the evidence connecting pubertal development with neural changes comes from animal models (Romeo, 2003; Sisk and Zehr, 2005; Schulz et al., 2009; Spear, 2011). We hypothesized that the heightened salience of self-development and peer relations in adolescence would be reflected in longitudinal increases in mPFC response during self-evaluations, particularly in the social domain as a function of puberty (Nelson et al., 2005).

Materials and Methods

Twenty-seven neurotypical individuals (18 female) with no history of psychiatric, neurological, or learning disorders were scanned while making evaluations of self and other in the social and academic domains, once at age 10 (mean \pm SD, 10.1 ± 0.35 years) and again at age 13 (13.1 ± 0.33 years). The other target was a fictional character, Harry Potter, about whom participants all had substantial knowledge (as indicated via questionnaire). An equal number of items were positive and negative valence. Sample phrases included: "I am popular," "I wish I had more friends," "I like to read just for fun," and "Writing is so boring" (see Pfeifer et al., 2007, for a complete description of paradigm development and full list of stimuli). Three participants were included both in this sample and that of Pfeifer et al. (2007).

As described previously by Pfeifer et al. (2007), one phrase was presented every 3 s, leaving ~ 2 s to respond as phrases averaged 1 s in duration. The 40 phrases were organized into four blocks of 20 stimuli each, and the four task blocks alternated between reporting whether the phrase described oneself or a fictional, highly familiar other: Harry Potter. Before the scan, it was ensured that all participants had sufficient familiarity with Harry Potter based on self-reports of knowledge about him on a 5-point scale (mean, 3.76 and 3.59 for T1 and T2, respectively). Variability in knowledge across time points was not significantly correlated with brain activity extracted from the region of ventral mPFC that demonstrated longitudinal increases during self > other evaluations. Objectively, each participant reported reading at least one book, or watching at least three movies, from the series. Block order was counter-balanced between participants. The initial block was always followed by a block containing the same phrases but applied to the remaining target (self or other), and then the last two blocks contained the remaining phrases (applied to the self and other targets in the same order as the first two blocks). Each of the four blocks was 75 s long, and included the 20 stimulus trials (ordered pseudorandomly) and five null events during which no phrase was presented. Blocks were separated by 21 s of rest. Participants were verbally instructed on this task outside the scanner and before the initiation of the run, and then reminded of these instructions at the start of each block during the run.

At both time points, participants also self-reported about observed changes in visible secondary sex characteristics (e.g., pubic hair, skin problems, genital development) using the Pubertal Development Scale (PDS) (Petersen et al., 1988).

The PDS was always administered with a researcher nearby to answer any questions participants had about the meaning of items. Parents were notified several days in advance of the session that a form assessing pubertal development would be part of the assessment, which gave parents the opportunity to talk with their children about this topic in advance if they so desired. We used the scoring guidelines provided by Petersen et al. (1988), and we omitted the social comparison question (about development relative to the pace of peers). There was a highly significant increase from T1 to T2 on the PDS (mean \pm SD: T1, 1.64 ± 2.58 ; T2, 0.46 ± 0.68 ; $t_{(1,26)} = 7.95$, $p \sim 0$). Because there were no significant gender differences in PDS scores at either time point (female, 1.66 and 2.66, male 1.60 and 2.40, not significant), analyses collapsed across gender to increase statistical power (consistent with the methods of Pfeifer et al., 2011) and further appropriate because there were no significant differences in task performance by gender. At T1, there was no relationship between chronological age and pubertal development ($r_{(25)} = 0.04$, not significant). At T2, chronological age and pubertal development were moderately corre-

lated in the expected direction, although this was only a trend ($r_{(25)} = 0.29$, one-tailed $p = 0.07$). It should be noted that two participants (one girl and one boy) each "regressed" by less than one point on average in their self-reports of pubertal development, but the presence and proportion of "regressions" in this sample are highly consistent with that reported in other longitudinal research using the PDS (e.g., Petersen et al., 1988). Furthermore, excluding these two participants from correlational analyses relating to pubertal development did not change the results. To assess the influence of puberty independently from that of chronological age, linear regression was conducted to obtain unstandardized residual values of pubertal development, indexing variability in PDS scores that could not be explained by age (in other words, age was used to predict PDS at each time point and the unstandardized residuals were saved, then used in further analyses).

fMRI images were acquired on a Siemens Allegra 3T scanner. The functional scan lasted 4 min 54 s (gradient echo, TR = 3000 ms, TE = 25 ms, flip angle = 90° , matrix size 64×64 , FOV = 20 cm, 36 slices, 3.125 mm in-plane resolution, 3 mm thick). For each participant, a high-resolution structural T2-weighted echo-planar imaging volume (spin-echo, TR = 5000 ms, TE = 33 ms, matrix size 128×128 , FOV = 20 cm, 36 slices, 1.56 mm in-plane resolution, 3 mm thick) was also acquired coplanar with the functional scan. Stimuli were presented to participants through high-resolution magnet-compatible goggles.

fMRI data were converted from dicoms using MRIconvert (<http://lcnl.uoregon.edu/~jolinda/MRIConvert/>), and then skull-stripped using FSL's Brain Extraction Tool (<http://www.fmrib.ox.ac.uk/analysis/research/bet/bet.pdf>). ARTrepair (<http://cibr.stanford.edu/tools/human-brain-project/artrepair-software.html>) was used to detect and fix bad slices in the unprocessed functional data. Structural images were then manually reoriented to the AC-PC, after which preprocessing was performed in NeuroElf (<http://neuroelf.net/>) using SPM8 functions as follows: (1) structural images for each participant were first coregistered to the SPM T1 template; (2) functional images were then realigned to correct for head motion using a two-pass least-squares approach and a six parameter (rigid body) spatial transformation (to the first image, then to the mean image); (3) realigned images were coregistered to their respective high-resolution structural image using a rigid-body transformation in three dimensions; (4) the structural image was segmented based on the SPM template tissue probability maps; (5) the determined parameters from the segmentation were used to spatially normalize functional images into a Talairach-compatible atlas using 12 parameter affine transformation; and (6) finally, all functional images were smoothed using an 6 mm full-width, half-maximum isotropic Gaussian kernel. In each run, participants demonstrated <5% of images with bad slices detected and fixed by ARTrepair, and <0.5 mm mean image-to-image motion or <5 mm max (single) image-to-image motion.

After preprocessing, statistical analyses were implemented in SPM8 (Wellcome Department of Cognitive Neurology, London; <http://www.fil.ion.ucl.ac.uk/spm/>). For each subject, condition effects were estimated according to the general linear model, following the methods by Pfeifer et al. (2007). Blocks (Self Social, Other Social, Self Academic, and Other Academic) were convolved with a canonical hemodynamic response function. Low-frequency drifts were removed by global scaling, and motion parameters were included as regressors of no interest. T1 and T2 were modeled as two separate runs. The resulting contrast images were entered into group-level analyses using random effects models. Paired t tests and a $2 \times 2 \times 2$ ANOVA was conducted with three factors: target (self and other), domain (social and academic), and age (T1 and T2). Unless otherwise noted, results were thresholded at $p < 0.001$, $k = 10$ voxels ($3 \times 3 \times 3$ mm), to balance between types I and II errors; in particular, results surviving FWE correction are indicated as such in the text and table.

Results

Our first analyses investigated responses during self and other evaluations that were stable over time. The main effect of target (self vs other) revealed robust activations not only in cortical midline structures, but also in ventral striatum (VS) (Fig. 1; Table 1). Responses in mPFC (rostral and dorsal ACC) as well as VS

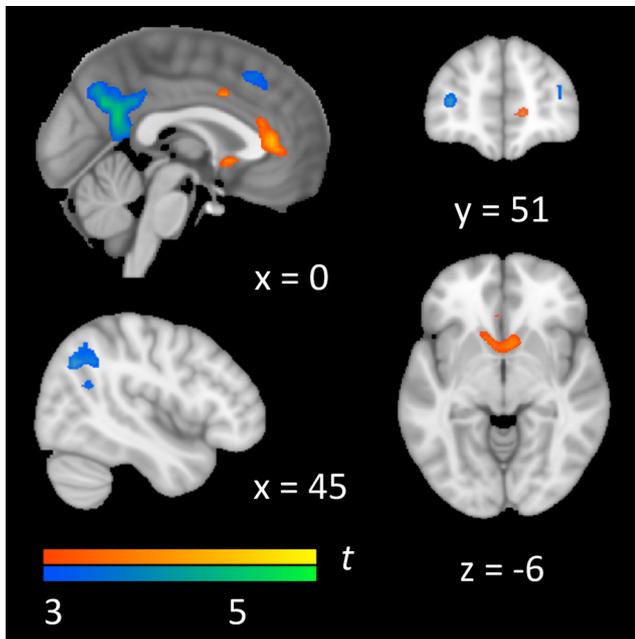


Figure 1. Hot colors represent the self > other contrast, and cool colors represent the other > self contrast. *x*, *y*, and *z* refer to the left–right, anterior–posterior, and superior–inferior coordinates in MNI space.

Table 1. Neural responses to self and other evaluations (main effect of target) across time points^a

Region	BA	<i>x</i>	<i>y</i>	<i>z</i>	<i>t</i>	<i>k</i>
Self > Other						
mPFC (rACC)	24/32	^b -3	36	6	5.48	259
Ventral striatum		^b 6	15	-3	4.32	259
dACC	24	3	9	36	4.68	18
Other > Self						
mPPC	23/26/29/31	^b 9	-51	15	5.61	368
dmPFC	8	3	24	48	4.26	49
dIPFC	6/8	-39	12	45	4.07	51
rIPFC	10/46	33	51	9	3.73	16
TPJ	39	45	-63	36	3.66	42

^aResults were thresholded at $p < 0.001$, uncorrected for magnitude; and $k = 10$ voxels ($3 \times 3 \times 3$ mm).

^bClusters that survived FWE correction.

BA, Brodmann's area; *x*, left–right; *y*, anterior–posterior; *z*, inferior–superior; *t*, *t* score at those coordinates (local maxima or submaxima); *k*, the number of voxels in the cluster; PFC, prefrontal cortex; ACC, anterior cingulate cortex; PPC, posterior cingulate cortex; TPJ, temporoparietal junction; m, medial; r, rostral; d, dorsal; l, lateral.

were greater during self-evaluations, whereas responses in mPPC, lateral PFC, and temporoparietal junction were greater during other-evaluations.

We conducted an additional pair of conjunction analyses to explore the main effect of target. As implemented in SPM8 and following the recommendations of Nichols et al. (2005), we used the “logical and” strategy, which requires that the results of all contrasts entered into the conjunction analysis survive the minimum test statistic. Two conjunction analyses were run. One looked for conjunctions of self > other effects at both time points, whereas the other looked for conjunctions of other > self effects at both time points. Initially, only one cluster survived: for other > self, common activation across time points was observed in the mPPC (9, -51, 15, $t = 3.95$, $k = 138$). When the minimum test statistic was relaxed to $p < 0.005$ (from $p < 0.001$, which may be advisable as the “logical and” conjunction analysis is conservative; Nichols et al., 2005), whereas the extent threshold was maintained (at $k = 10$), two additional clusters survived: for

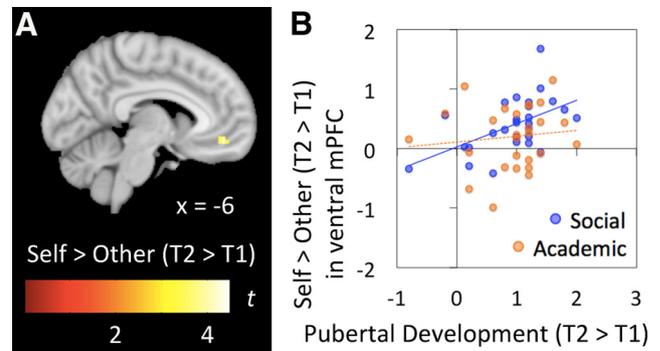


Figure 2. T1 and T2 refer to age 10 and 13, respectively. *x* indicates the left–right coordinate in MNI space. **A**, Responses that increase from T1 to T2 during evaluations of self > other. **B**, Mean parameter estimates of activity are extracted from the ventral mPFC cluster shown in **A**.

self > other, common activations across time points were observed in the mPFC (-6, 36, 6, $t = 3.04$, $k = 10$) and VS (3, 12, -3, $t = 3.01$, $k = 12$). This confirmed that the three clusters reported in Table 1 to survive FWE correction (mPFC and VS for self > other, mPPC for other > self) were indeed responsive at both time points.

Our primary inquiries, however, focused on change over time. As hypothesized, responses in a ventral aspect of mPFC (-9, 45, -12, $t = 4.5$, $k = 14$) increased from age 10 to age 13, more for evaluations of self than other (Fig. 2A). Indeed, this was the only region across the whole brain to demonstrate longitudinal increases. No regions exhibited significant decreases from age 10 to age 13 when collapsing across domains (although in the social domain only, there was a significant longitudinal decrease in hippocampal activity [-27 -18 -9, $t = 4.5$, $k = 16$] during the self > other contrast).

Post hoc ROI analyses were performed by extracting parameter estimates of blood-oxygenation level-dependent signal change in this ventral mPFC cluster exhibiting longitudinal change (averaging across all voxels), from each condition relative to baseline, at each time point (following the methods of Pfeifer et al., 2011). These analyses demonstrated that the increase in ventral mPFC response was significant in the social domain ($p = 0.0001$) but marginal in the academic domain ($p = 0.0556$).

Furthermore, as predicted, pubertal development (PDS scores at age 13, controlling for PDS scores at age 10, each of which was residualized for age within time point) was significantly positively correlated with increased responses in this ventral mPFC ROI during evaluations of self versus other in the social domain ($r_{(25)} = 0.53$, $p < 0.005$), but not in the academic domain ($r_{(25)} = 0.11$, not significant; Fig. 2B), and these two correlations were significantly different ($z = 2.25$, $p = 0.025$). Additionally, correlations between pubertal development and responses in this ventral mPFC ROI during evaluations of self versus other in the social domain were consistent across gender ($r_{(16)} = 0.45$ for girls, $r_{(7)} = 0.74$ for boys; $p = 0.06$ and 0.02 , respectively). Results were also the same whether correlations between ventromedial PFC activity were conducted using raw or residualized PDS scores, perhaps because of the borderline moderate correlation between PDS and age at T2 only. Such a pattern is to be expected within a tight age range, although with a much larger age range, the PDS would be more strongly correlated with age. Finally, supplementary whole-brain analyses indicated that pubertal development was not significantly positively or negatively correlated with longitudinal changes in any other brain regions when collapsing across domains.

Discussion

This longitudinal fMRI study allowed a robust characterization of neural responses during evaluations of self versus other in late childhood and early adolescence. Evaluations of another social target engaged mPFC, lateral PFC, and temporoparietal junction, a region implicated in mentalizing and attention (Scholz et al., 2009). This suggests that executive functions, memory, and perspective taking are implicated in other evaluations. Meanwhile, self-evaluations commonly engaged mPFC and VS, a region implicated in reward processing (Cooper and Knutson, 2008), including rewards tied to self-specific processing and self-disclosure (Lieberman et al., 2004; Northoff and Hayes, 2011; Tamir and Mitchell, 2012). Together with the robust body of work demonstrating anatomical and functional linkages between VS and ventral mPFC, this suggests that self-evaluative processing may inherently involve the “generation of affective meaning” (Roy et al., 2012, p. 147).

The degree to which ventral mPFC responded more during self-evaluations than other-evaluations increased from age 10 to 13, particularly in the social domain. Ventral mPFC is not only associated with self-referential processing (Van Overwalle, 2009; Northoff et al., 2011), but also with reward and valuation processes (Rangel et al., 2008; Chib et al., 2009; Hare et al., 2009). As such, this neurodevelopmental pattern is consistent with the heightened importance adolescents place on peer relationships and sociometric status (for review, see Pfeifer and Peake, 2011). It also extends prior neuroimaging work conducted with a largely nonoverlapping sample comparing 10-year-olds with young adults, which found that a more dorsal region of mPFC was more responsive in children during self-evaluations than adults. Thus, whereas dorsal mPFC may be more engaged in late childhood during self-evaluations, ventral mPFC may be increasingly recruited in early adolescence. Future studies should endeavor to track responses in both these regions during self-evaluations (relative to evaluations of others) to determine when recruitment of each region peaks.

Furthermore, this same region of ventral mPFC differentiates between self and others in neurotypical adults but fails to do so in adults and adolescents with autism spectrum disorders (Lombardo et al., 2010; Pfeifer et al., 2013). In typically developing children and adolescents, the degree to which ventral mPFC responds more to self than other is significantly positively correlated with social responsiveness (Pfeifer et al., 2013). Together, these findings suggest that this differential response in ventral mPFC during self-evaluative processing makes important contributions to successful social cognition.

Finally, the discovery that level of pubertal development (independent of age) was significantly associated with increased self-other differentiation in ventral mPFC for the social but not academic domain is an important contribution to the existing literature. Existing animal work demonstrates that puberty affects neurodevelopment of structures and transmitters strongly implicated in social behavior (Romeo, 2003; Sisk and Zehr, 2005; Ahmed et al., 2008; Schulz et al., 2009), but studies directly testing the theorized associations between neural, pubertal, and social changes in adolescent humans are still few in number. Prior studies also linked pubertal development either with structural metrics (Bramen et al., 2011; Peper et al., 2011), or with responses elicited by socioemotional or rewarding stimuli (Forbes et al., 2010, 2011; Op de Macks et al., 2011; Moore et al., 2012). To our knowledge, however, only one study has contrasted patterns of brain function between conditions that were relatively more and

less socially relevant (Goddings et al., 2012). In this study, levels of sex steroid hormones positively correlated with responses in left temporal pole during social emotion processing (embarrassment and guilt, compared with basic emotion processing of fear and disgust). Meanwhile, age (controlling for pubertal development) negatively correlated with activity in dorsal (but not ventral) mPFC, making the findings complementary. In the present study, assessing evaluative processing in an academic domain (Hymel et al., 1999; Denissen et al., 2007), which is comparatively much less social and more objective by definition, likewise allowed us to conduct an empirical test that provided strong support at the neural level for the “social reorientation” teenagers are proposed to experience (Nelson et al., 2005). More generally, our findings illustrate the tight coupling between biological and social changes during puberty that may facilitate refinement of a unique, multifaceted, and relational self during adolescence. In other words, while academic self-evaluations may change because of contextual factors, such as school transitions (Eccles et al., 1993), social self-evaluative change is intimately connected with biology and not just interpersonal contexts.

Notes

Supplemental material for this article is available at http://dsn.uoregon.edu/Publications_files/SuppFig1.pdf. The figure depicts paired scores on the Pubertal Development Scale across time points. This material has not been peer reviewed.

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