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Pubertal Status Associations with Reward and Threat Sensitivities and Subcortical Brain Volumes during Adolescence

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Abstract

Adolescence is characterized by complex developmental processes that impact behavior, biology, and social functioning. Two such adolescence-specific processes are puberty and increases in reward sensitivity. Relations between these processes are poorly understood. The present study focused on examining unique effects of puberty, age, and sex on reward and threat sensitivities and volumes of subcortical brain structures relevant for reward/threat processing in a healthy sample of 9 to 18 year-olds. Unlike age, pubertal status had a significant unique positive relationship with reward sensitivity. In addition, there was a trend for adolescent females to exhibit higher threat sensitivity with more advanced pubertal development and higher reward and threat sensitivity with older age. Similarly, there were significant puberty by sex interaction effects on striatal volumes, i.e., left nucleus accumbens and right pallidum. The present pattern of results suggests that pubertal development, independent of chronological age, is uniquely associated with reward hypersensitivity and with structural differences in striatal regions implicated in reward processing.

Keywords

Puberty; adolescence; reward sensitivity; behavioral approach system (BAS); behavioral inhibition system (BIS)

1. Introduction

Adolescence is a period of transition into adulthood, involving biological, psychological, and social changes. An essential normative process during adolescence is the development

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of sexual maturity, or puberty. Increasingly, pubertal development has been empirically linked to the maturation of emotional processing functions that extend beyond sexual or reproductive contexts (e.g., Forbes et al., 2010; Quevedo, Benning, Gunnar, & Dahl, 2009; Silk et al., 2009; Stroud et al., 2009). Recently, another important normative process in adolescence related to emotional processing has gained empirical support—an increase in sensitivity to rewards (Casey, Jones, & Hare, 2008; Ernst, Pine, & Hardin, 2006; Nelson et al., 2005; Somerville, Jones, & Casey, 2010; Steinberg, 2008; Urošević et al., 2012). Theories posit that pubertal changes may drive the observed increases in reward sensitivity (Dahl, 2004; Forbes & Dahl, 2010; Steinberg, 2008), potentially through hormonal effects on the subcortical structures involved in emotional/reward processing (Blakemore, Burnett, & Dahl, 2010). However, empirical examinations of the associations between pubertal development and adolescent reward sensitivity and relevant subcortical brain structures are sparse. After a brief overview of relevant literature, the present study aims to address these empirical gaps by examining unique effects of sex, pubertal status, and chronological age on reward and threat sensitivities and subcortical brain volumes during adolescence.

1.1 Heightened Reward Sensitivity during Adolescence

Over the last decade, empirical support for the hypothesis that reward sensitivity is excessive during adolescence has grown immensely. In epidemiological studies, adolescents exhibit greater rates of incentive-driven behavior with a high potential for negative consequences, such as substance use and unsafe sex (Eaton et al., 2006). In comparison to other ages, adolescents exhibit heightened reward sensitivity on self-report measures (e.g., Urošević et al., 2012), stronger effects of monetary incentives on task performance (Hardin et al., 2007; Jazbec et al., 2006), and greater positive affect in response to the receipt of monetary rewards (Ernst et al., 2005). Similarly, in experimental paradigms assessing responses to variable rewards and risks, adolescents exhibit greater sensitivity to positive feedback compared to other ages (Cauuffman et al., 2010). Finally, adolescents who prefer high-risk, high-reward choices in an experimental task also endorse more high-risk behaviors in the real world (Rao et al., 2012).

Neuroimaging studies also provide support for greater reward sensitivity as indexed by greater ventral striatum (VS) activation in reward paradigms. Compared to adults, adolescents exhibit greater VS activation to receipt of monetary reward (e.g., Ernst et al., 2005) and in risk-taking paradigms with variable rewards (Galvan et al., 2006). Striatal activity in response to unexpected reward feedback also peaks during adolescence (Cohen et al., 2010), as well as VS activity in response to positively-valenced stimuli (Somerville, Hare, & Casey, 2010). Geier and colleagues (2010) observed decreased VS activity during reward cue evaluation, but increased VS activity during anticipation of behavioral responses to rewards. The VS, and the nucleus accumbens (Nacc) in particular, is a key node in the brain's reward system with a role in facilitating responses to reward stimuli by translating motivational tendencies to approach behavior (Depue & Collins, 1999). The VS also facilitates higher-order goal-directed behavior (Atallah et al., 2007; Voorn et al., 2004).

Overall, increased VS activity during reward paradigms in adolescence, although present, may not be ubiquitous (Bjork et al., 2004, 2010). However, bolstering the case for

adolescence as a significant developmental period for VS functioning, structural imaging studies show striatal development continuing into early 20's (e.g., Sowell et al., 1999; Sowell et al., 2002). Similarly, in a recent longitudinal study of healthy 9 to 23 year olds, Nacc volumes peaked in adolescence and then decreased into the early 20's (Uroševi, Collins, Muetzel, Kim, & Luciana, 2012).

This increased sensitivity to rewards during adolescence implicates an increased sensitivity of the behavioral approach system (BAS). The BAS is a behavioral-motivational system proposed to facilitate approach to rewards (e.g., Depue & Collins, 1999; Gray, 1991; Gray, 1994). The other behavioral-motivational system, the behavioral inhibition system (BIS), is involved in responses to threat and inhibits approach in situations of conflict between reward and risk (Gray & McNaughton, 2000). Both systems are implicated in theoretical models of adolescent behavior (Ernst, Pine, & Hardin, 2006; Luciana, Wahlstrom, Porter, & Collins, 2012). Adolescent BAS hypersensitivity is linked to substance use and other risky behaviors (e.g., Giles & Price, 2008; Knyazev et al., 2004; O'Connor et al., 2009), whereas increased BIS sensitivity during adolescence is linked to increased anxiety-related behaviors, such as internalizing symptoms (Colder & O'Connor, 2004) and negative affective reactivity (Leen-Feldner, Zvolensky, & Feldner, 2004).

1.2 Theoretical and Empirical Associations between Pubertal Development and Adolescent Reward Sensitivity

Forbes and Dahl (2010) proposed that the hormonal changes in puberty provoke behavioral increases in appetitive motivation, particularly in the social domain. Furthermore, others have theorized that pubertal hormonal changes may lead to a reorganization of reward-related brain structures and/or dopaminergic pathways (e.g., Blakemore et al., 2010; Nelson et al., 2005). The potential influence of pubertal development on adolescents' dopaminergic pathways is intriguing given recent proposals for adolescents' reward hypersensitivity to be driven by developmental changes in reward-relevant striatal dopaminergic activity (Luciana et al., 2012; Spear, 2011; Wahlstrom, Collins, White, & Luciana, 2010). Despite the appeal of these theoretical models, empirical evidence of the hypothesized associations is still sparse, particularly in humans.

Recent cross-sectional studies are largely supportive of increased emotional sensitivity during adolescence as a function of pubertal stage. Neuroimaging studies using facial expression paradigms are inconsistent, with some supporting a link between pubertal development and overall emotional reactivity (Moore et al., 2012) and other studies showing less emotional reactivity in structures such as the amygdala with advanced pubertal development (Forbes et al., 2011). However, more advanced pubertal status has predicted increased negative affective reactivity, as measured by a range of psychophysiological indices (Stroud et al., 2009), enhanced startle reflex responses (Quevedo et al., 2009), and increased basal cortisol levels (Gunnar et al., 2009). Pubertal status also predicts overall emotional reactivity to both positively and negatively valenced stimuli as indexed by pupillary dilation and better recall of emotional words (Silk et al., 2009).

The very few studies examining pubertal development and reward processing in human adolescents are supportive of a positive association between these two processes. Forbes and

colleagues (2010) linked more advanced pubertal development to greater medial PFC and less striatal activation (specifically in the caudate) in response to reward outcomes, but not reward anticipation, in a card-guessing task. In addition, the enhancement of the postauricular reflex, a psychophysiological measure proposed to tap into BAS and provoked by positively valenced stimuli, seems to emerge in mid-to-late puberty (Quevedo et al., 2009).

Studies examining the associations of sex hormones levels (e.g., testosterone and estradiol), as a proxy for pubertal development (Huang et al., 2012), and reward responsiveness are mixed. Plasma testosterone levels have been positively related to caudate activity during reward anticipation in boys, suggesting a positive association between reward sensitivity and pubertal status, but the same study supports a negative association between testosterone levels and caudate activity during reward receipt in both sexes (Forbes et al., 2010). In contrast, another study found a positive association between saliva testosterone levels and VS activity during reward versus loss receipt in both sexes (Op de Macks et al., 2011). To date, only one study has reported on the association between sex hormones and trait measures of reward (i.e., BAS) and threat (i.e., BIS) sensitivities, finding a positive association between estradiol levels and BAS sensitivity in both boys and girls (Vermeersch et al., 2009).

In sum, pubertal status appears to be positively related to overall increased emotional reactivity during adolescence (e.g., Moore et al., 2012; Silk et al., 2009). The few studies examining pubertal status in relation to reward processing are contradictory, with some reporting a negative relationship (e.g., Forbes et al., 2010) and others a positive relationship (Op de Macks et al., 2011; Vermeersch et al., 2009). Consequently, the direction and nature of puberty's association with reward sensitivity remains unclear. Inconsistencies across studies may be due to methodological issues, such as difficulties in using single measures of hormone levels to infer an individual's relative status (Shirtcliff, Dahl, & Pollack, 2009).

1.3 Pubertal Effects on Subcortical Brain Structures during Adolescence

Pubertal influences on the brain's development are most often hypothesized to occur through direct and/or indirect effects of fluctuating sex hormonal levels (e.g., Blakemore et al., 2010; Nelson et al., 2005), which are grouped into either activational or organizational effects. Activational effects of sex hormones influence existing neural structures to produce novel adult behaviors, whereas organizational effects influence the development of neural circuitry, including regional brain structure. Increased reward sensitivity may be driven by activational (and possibly organizational) effects of pubertal spikes in sex hormone levels on volumes of subcortical structures involved in emotional processing (e.g., Blakemore et al., 2010; Nelson et al., 2005). Moreover, Nelson and colleagues (2005) proposed that these pubertal effects of sex hormones on reward-relevant subcortical structures (e.g., Nacc) lead to generalized changes in behavioral responses to all social, not just sexual, stimuli.

Very few human studies have examined pubertal effects on subcortical structures relevant for reward, or overall emotional, processing. Bramen and colleagues (2011) found amygdala and hippocampal volumes to increase in boys, but decrease in girls, with pubertal development. In contrast, Neufang and colleagues (2009) found increased amygdala

volumes in both boys and girls, and decreased hippocampal volumes in girls, with pubertal development; moreover, amygdala volume increases in boys and hippocampal decreases in girls tended to be associated with greater testosterone levels. Clearly, preliminary studies support pubertal status associations with subcortical brain structures, but differ in the direction of these associations and suggest that they may vary by sex and/or type of pubertal assessment.

There is also some support for higher testosterone links to higher whole-brain gray matter volume in boys and higher estradiol links to lower total gray matter volume, as well as estradiol level effects on regional gray matter density, in girls (Peper et al., 2009). Peper and colleagues (2009) observed sex differences in subcortical regions, such as the amygdala, putamen, hippocampus, and caudate, but these differences were not explained by sex hormonal levels, a proxy for pubertal development. Additional studies with larger samples are needed to fully examine individual differences in the volumes of subcortical structures in relation to pubertal status.

1.4 Common Methodological Issues in Pubertal Development Research

The field has yet to adopt a set of clear standards with respect to self-report or hormonal assays of pubertal status (Shirtcliff, Dahl, & Pollack, 2009). Pubertal status assessment approaches range from clinician ratings, use of single self-report items, self-report scales, to sex hormonal assays, with each approach having advantages (e.g., sex hormone levels may directly reflect puberty's biological effects) and disadvantages (e.g., non-pubertal effects on sex hormone vary across time and may be impacted by individual differences). Given this current state of the field, it would be beneficial to use and report findings with multiple pubertal status assessment methods within the same sample.

In addition, chronological age and pubertal development are positively correlated in healthy, normally developing adolescents (e.g., Moore et al., 2012; Silk et al., 2009). To test theoretical models of pubertal development and associations with approach motivation (e.g., Forbes & Dahl, 2010), it is important to disentangle the unique effects of puberty versus effects of other maturational processes indexed by chronological age. In addition, temporal aspects of puberty, such as the age when an adolescent reaches a specific pubertal stage or how one's pubertal stage compares to same-aged peers (i.e., pubertal timing) and how quickly one progresses through stages of puberty (i.e., pubertal tempo) predict physical and psychological functioning (e.g., Marceau et al., 2011). In order to disentangle effects of age from effects of puberty, studies often use samples with limited age ranges (e.g., 11 to 13 years, 12 to 13 years, 14 to 15 years), and as such are ideally suited to examine effects of pubertal timing (i.e., effects of being more or less developed than same-aged peers). Still, despite the restricted age ranges, the positive relationship between pubertal status and chronological age often remains significant (e.g., Moore et al., 2012). Moreover, when age range is restricted but sampling methods seek to maximize the pubertal status range, it is unclear whether samples are representative of the larger adolescent population.

Another approach to examining unique effects of chronological age and pubertal status would be to allow both age and pubertal status to vary freely and then to statistically examine unique effects of each variable on reward sensitivity. This alternative approach has

been proposed to be a conservative analysis of unique pubertal effects due to greater specificity in measurement of chronological age (Silk et al., 2009). Still, it allows an examination of chronological age effects above and beyond pubertal status effects on reward sensitivity, and vice versa. Studies examining the specificity of pubertal status' effects on reward hypersensitivity by also studying puberty's effects on threat sensitivity are also needed.

1.5 Overview of the Present Study

The present study utilizes concurrent assessments of threat/BIS and reward/BAS sensitivities, subcortical brain volumes, and stages of pubertal development, as assessed by three indices, in a large sample of adolescents ages 9 to 18, and aims to parse puberty-versus age-specific influences on reward and threat sensitivities and volumes of subcortical brain structures. Based on prior research suggesting links between sex hormones and reward sensitivity (e.g., Vermeersch et al., 2009), we hypothesize that pubertal status will be uniquely and positively associated with greater reward sensitivity, but not threat sensitivity. Similarly, we predict that pubertal status will have a significant association with volumes of striatal brain regions involved in reward processing (e.g., Nacc). Finally, some studies support increased emotional reactivity in adolescent girls with advanced pubertal development (e.g., Gunnar et al., 2009) and older age (e.g. Urošević et al., 2012), whereas others find similar effects of sex hormones on reward sensitivities in boys and girls (e.g., Vermeersch et al., 2009). We will explore whether any unique pubertal status and chronological age effects are distinct for adolescent boys versus girls.

1. Method

2.1 Participants

The present sample is part of a larger longitudinal study of normative development of individuals ages 9 to 23 (see section 2.2 for citations). The present study focused on examining effects of puberty only within adolescence as traditionally defined. Participants who had reached young adulthood (i.e., those above the age of 18) were excluded. This exclusion is further justified by the observation that these individuals over-represent post-pubertal stages of development in the full sample. This selection strategy resulted in a final sample with an age range from 9 to 18 that represented the full range of pubertal development (i.e., Tanner stages 1 to 5). One hundred twenty-six adolescents (63 male, 63 female) yielded complete data for the present analyses. Minors (9-17 years) were recruited via two methods. First, potential participants were compiled from a database maintained by the University of Minnesota's Institute of Child Development, which consisted of families that agreed to be contacted for participation in university studies at the time of their child's birth. Families with children in the desired age ranges were contacted by phone and asked if they would be interested in participating in the current study. Second, postcards were mailed to University of Minnesota employees directing them to contact our laboratory if they had children within the desired age ranges interested in study participation. Young adult participants (age 18) were recruited through fliers posted throughout campus that directed them to contact our laboratory if they were interested in the study. All participants and/or

their parents provided informed consent and assent prior to their inclusion in the study. The study protocol was approved by the University of Minnesota's Institutional Review Board.

Study eligibility was determined with a short phone screening and in-person comprehensive clinical interview using the Kiddie - SADS - Present and Lifetime Version (K-SADS-PL), which assesses for current and past history of DSM-IV axis I disorders (Kaufman, Birmaher, Brent, Rao, & Ryan, 1996). Exclusion criteria included any history of neurological or psychiatric disorders, preterm birth or other birth complications, current or past alcohol or drug abuse, loss of consciousness, learning disabilities, current or past psychoactive prescription drug use, non-native English speaking, and vision or hearing that had not been corrected to normal. In addition, participants in this study were asked to participate in a magnetic resonance imaging (MRI) structural imaging protocol, so left-handedness (Oldfield, 1971) and all imaging contraindications (e.g., metallic implants, braces, etc.) resulted in study exclusion.

The present sample was predominantly Caucasian (89.7%), with 1.6% of the sample self-reported as African American, 2.4% as Hispanic, 4% as Asian/Pacific Islander, and 2.4% as 'other.' In addition, participants' socio-economic status was determined by their parents' education (70.2% of mothers and 65.3% of fathers completed bachelor's degrees or higher) and average family income ($M = 101,780.70$, $SD = 80,678.95$ U.S. dollars), which yielded a sample with a predominantly middle to upper-middle class background.

2.2 Procedure

Participants completed a three-hour session on one day (including the demographics assessment and a diagnostic interview) and, on another day, they completed a set of questionnaires, a neurocognitive battery, psychophysiological testing, and structural brain imaging. The present study focuses on measures of chronological age, sex, BIS/BAS sensitivities, stage of puberty as measured by two self-report measures, and subcortical brain volumes as assessed by structural MRI. This is the first examination of puberty effects on BIS/BAS sensitivities and subcortical brain volumes within this longitudinal study (for other findings please see Luciana et al., 2009; Muetzel et al., 2008; Olson et al., 2007; Olson et al., 2009; Porter et al., 2011; Urošević et al., 2012). An additional report examines major trait domains of personality in relation to pubertal development (Schissel et al., 2011).

2.3 Measures

2.3.1 The BIS/BAS scales—Individual differences in sensitivities to threat (i.e., BIS) and reward (i.e., BAS) were assessed using the BIS/BAS scales (Carver & White, 1994), which are comprised of a 7-item BIS scale (e.g., "I worry about making mistakes") and three BAS subscales: a 5-item Reward Responsiveness scale (e.g., "When I get something I want, I feel excited and energized"), a 4-item Drive scale (e.g., "I go out of my way to get things I want"), and a 4-item Fun Seeking scale (e.g., "I crave excitement and new sensations"). The three BAS subscales may also be summed to yield a BAS Total score. The possible scores range from 7 to 28 for BIS, 5 to 20 for BAS Reward Responsiveness, 4 to 16 for BAS Drive and BAS Fun Seeking, and 13 to 52 for the BAS Total scale.

The majority of existing studies on adolescence have assessed BIS and BAS sensitivities using the BIS/BAS scales, which have a large amount of empirical support for their construct validity based on associations with other behavioral and psychophysiological measures (Carver & White, 1994; Harmon-Jones & Allen, 1997; Sutton & Davidson, 1997). In a longitudinal twin study, a moderate genetic effect was found accounting for approximately one third of variance in the BIS/BAS scales (Takashi et al., 2007). Another study found the same four-factor structure of the BIS/BAS scales in large adolescent and adult samples, suggesting that scores are comparable across development (Cooper, Gomez, & Aucote, 2007). Cooper and colleagues (2007) reported acceptable internal consistencies across development—for adults (i.e., Cronbach's alphas ranging from .77 for BIS to .89 for BAS Reward Responsiveness) and adolescents (i.e., Cronbach's alphas ranging from .68 for BIS to .82 for BAS Reward Responsiveness). The BIS/BAS scales' relative brevity and ease of administration are also advantages.

2.3.2 Magnetic Resonance Imaging (MRI)—MRI images were acquired on a 3-Tesla Siemens Trio scanner (Siemens Medical Systems, Erlangen, Germany) at the University of Minnesota's Center for Magnetic Resonance Research. Three-dimensional brain images were obtained with a coronal T₁-weighted Magnetization Prepared Rapid Gradient Echo (MPRAGE) sequence (TR = 2530 msec, TE = 3.65 msec, TI = 1100 msec, 240 slices, voxel size = 1.0mm × 1.0mm × 1.0mm, flip angle = 7°, FOV = 256 mm × 256 mm). These high-resolution anatomical brain images were processed using standard procedures in the *FreeSurfer* v.4.5.0 image analysis suite, which is documented and freely available to download online (<http://surfer.nmr.mgh.harvard.edu/>). The technical details of processing procedures are described in prior publications from the *FreeSurfer* group (Dale & Sereno, 1993; Dale, Fischl, Sereno, 1999; Fischl et al., 1999; Fischl, Sereno, Dale, 1999; Fischl & Dale, 2000; Fischl, Liu, Dale, 2001; Fischl et al., 2002; Fischl et al., 2004a; Fischl et al., 2004b; Han et al., 2006; Jovicich et al., 2006; Segonne et al., 2004). Briefly, they included removal of non-brain tissue using a hybrid watershed/surface deformation procedure (Segonne et al., 2004), automated Talairach transformation, segmentation of the subcortical white matter and deep gray matter volumetric structures (Fischl et al., 2002; Fischl et al., 2004a), intensity normalization (Sled, Zijdenbos, Evans, 1998), tessellation of the gray matter/white matter boundary, automated topology correction (Fischl, Liu, Dale, 2001; Segonne et al., 2004), and surface deformation following intensity gradients to optimally place the gray/white and gray/cerebrospinal fluid borders at the location where the greatest shift in intensity defines the transition to the other tissue class (Dale & Sereno, 1993; Dale, Fischl, Sereno, 1999; Fischl & Dale, 2000).

The *FreeSurfer* subcortical segmentation procedure yielded amygdala, caudate, hippocampus, Nacc, pallidum, putamen, and thalamus volumes within each hemisphere. *FreeSurfer's* morphometric procedures show good test-retest reliability across scanner manufacturers and across field strengths (Han et al., 2006). *FreeSurfer's* automatized subcortical segmentation has been found to be as reliable as manual procedures (Fischl et al., 2002). All automatically generated surface volumes were inspected for accuracy, and manual corrections using *FreeSurfer* tools were carried out as needed. The volume of each

region was corrected for total brain volume prior to analysis and is represented as a ratio of each region's volume to total brain volume.

2.3.3 Pubertal status assessment—Pubertal development was assessed using line drawings depicting each one of five Tanner stages of puberty (Taylor et al., 2001) and a self-report questionnaire of pubertal development, the Pubertal Development Scale (PDS; Petersen et al., 1988). The self-report assessments of pubertal development were chosen for their relatively non-invasive nature (i.e., in comparison to physical examinations, which were impractical, or assays of sex hormones, which are imprecise without the use of repeated assessments) and their adequate agreement with physician ratings of pubertal development (e.g., Cohen's kappas with an upper range of .75, Taylor et al., 2001).

The Tanner drawings have sex-specific sets of pictures depicting pubertal development (Taylor et al., 2001). For females, two series of drawings depicted Tanner's stages of breast and pubic hair development, respectively. For males, two series of drawings depicted Tanner's stages of pubic hair and genitalia development, respectively. Participants indicated the line drawing in each set of pictures that most accurately described their current state of development. For each participant, two scores, ranging from 1 to 5 and representing Tanner's stages of pubertal development (from pre-puberty, early puberty, mid-puberty, late puberty, and post-puberty), were derived in this manner. Some prior studies of puberty have focused on breast/genital development to determine stage of pubertal development (e.g., Forbes et al., 2010), but self-reports of pubic hair development may have better agreement with physician's ratings (Shirtcliff, Dahl, & Pollack, 2009). In the current study, the two Tanner drawing ratings yielded excellent internal consistency, Cronbach's $\alpha = .89$ for the whole sample and within each sex: Cronbach's α of .85 for boys and of .92 for girls. Thus, an average of the self-report ratings for the breast/genital and pubic hair development was used as one index of pubertal development in the present study.

The *PDS* (Peterson et al., 1988) is a questionnaire that assesses both sex-specific and sex-independent physical characteristics of puberty. Physical characteristics of pubertal development common to both sexes that are assessed are growth, height, body hair, and acne. For females, the PDS also assesses breast development and menstrual status; for males, voice changes and facial hair are assessed. Ratings on these PDS items were used to create sex-specific *PDS total scores*. One female participant did not have complete PDS data, reducing the sample to 125 for analyses including the PDS scores.

In addition, *PCA puberty factor scores* were calculated based on a principal components analysis, with promax rotation, of the z-score transformations of PDS items and Tanner ratings. Z-score transformations of the individual items were used in order to calculate factor scores across items with different rating scales. In turn, the PCA puberty factor scores represent more advanced (for positive numbers) or less advanced (for negative numbers) pubertal development than the mean pubertal status for the sample. A two-factor solution was forced in an attempt to assess for gonadal versus adrenal pubertal processes (e.g., Palmert et al., 2001). However, the PCA yielded a first factor that explained 74% of the total variance in scores and with loadings for all but one item .72; the exception was for physical height (loading = $-.04$). Thus, we used the 1st factor score loadings to calculate the

PCA puberty factor score that combined Tanner drawing ratings and PDS scores. To our knowledge, this is the first study to adopt a factor analytic approach based on multiple assessments of puberty to quantify pubertal status.

2.4 Statistical Approach

To assess whether developmental effects on BIS/BAS sensitivities are due to pubertal changes during adolescence or to developmental processes more closely related to chronological age, a set of five hierarchical regression analyses was conducted, one for each BIS/BAS subscale (i.e., BAS total, BAS Drive, BAS Reward Responsiveness, BAS Fun Seeking, and the BIS scale) as outcome variables. Similarly, to assess whether developmental effects on subcortical brain volumes are due to pubertal changes or to developmental processes more closely related to chronological age, a series of 14 hierarchical regressions was conducted with subcortical regional volumes corrected for total brain volume as outcome variables. There were two hierarchical regressions per each subcortical volume—one for right hemisphere estimates and one for left hemisphere estimates. All hierarchical regression models had the PCA puberty factor score, sex, and age as predictors in Step 1, followed by the interaction term for sex by PCA puberty factor score in Step 2. A separate set of analogous hierarchical regression analyses with the interaction term for sex by age in Step 2 instead of the sex by puberty interaction was also conducted, in order to assess for unique sex-specific effects of chronological age.

3. Results

3.1 Descriptive Statistics

Table 1 summarizes means and standard deviations for age, all three puberty indices, BIS/BAS subscale scores, and subcortical volume estimations. Subcortical brain volume values reported in Table 1 are not corrected for total brain volume, but they are corrected in all subsequent analyses by using ratios of regional brain volume to total brain volume.

As others have reported (e.g., Stroud et al., 2009) and as summarized in Table 2, pubertal stage and chronological age are significantly correlated for all three pubertal status indices, i.e., average Tanner score, PDS total score, and PCA puberty factor score. The three pubertal indices were also significantly correlated with each other. In the present analyses, results using the PCA puberty factor score as the index of pubertal development are presented. Findings from the separate Tanner and PDS measures are highly similar, as will be described.

3.2 Pubertal Status Effects on BAS/Reward Sensitivity

In hierarchical regression analyses predicting BAS scales, the Step 1 models, which included sex, age, and PCA puberty factor scores, predicted a significant portion of the variance in BAS Total scores, $R^2 = .099$, $p = .005$, BAS Fun Seeking, $R^2 = .090$, $p = .010$, BAS Reward Responsiveness scores, $R^2 = .084$, $p = .014$, and BAS Drive scores, $R^2 = .084$, $p = .014$.

In examining unique effects of age, puberty, and sex, as depicted in Table 3, PCA puberty factor scores had a significant positive relationship with BAS Total and BAS Fun Seeking scores, suggesting increased BAS sensitivity with advanced pubertal development. There was also a significant unique sex effect with females exhibiting lower scores than males on BAS Fun Seeking, $\text{partial } r = -.18, p = .047$, but no other significant sex effects. In Step 2 models, there were no significant puberty by sex interaction effects on any of the BAS scales.

An analogous series of hierarchical regression analyses examining the interaction of sex by chronological age in Step 2 of the models yielded a significant interaction on BAS Drive, $b = .35, t = 2.44, p = .016$. Follow-up analyses revealed that adolescent girls exhibited greater BAS Drive scores with older age ($r = .41, p = .001$), whereas adolescent boys did not ($p = .968$). No other sex by age interaction effects were significant.

The same pattern of results was obtained when average Tanner scores were used as a measure of pubertal development. Analyses with the PDS total scores yielded significant overall models and a significant age by sex interaction effect on BAS Drive, but no significant unique effects of sex, puberty or age.

3.3 Pubertal Status Effects on BIS/Threat Sensitivity

In a hierarchical regression predicting BIS scale scores, the Step 1 model with age, sex, and puberty predictors, was significant, $R^2 = .073, p = .026$. There was a significant unique effect of sex (i.e., females > males) on BIS scores, $\text{partial } r = .20, p = .025$. There were no unique effects of age or puberty and no puberty by sex interaction. An analogous hierarchical regression analysis examining the interaction of sex by chronological age in Step 2 of the model yielded a significant interaction effect on BIS, $b = .40, t = 2.04, p = .043$. Follow-up analyses revealed that adolescent girls exhibited greater BIS scores with older age ($r = .38, p = .003$), whereas adolescent boys did not ($p = .796$).

The same pattern of results was obtained when average Tanner or PDS total scores were used as measures of pubertal development, except that the PDS total score analyses yielded a non-significant trend sex effect on BIS ($p = .059$).

3.4 Pubertal Status Effects on Subcortical Brain Volumes

In hierarchical regression analyses predicting subcortical brain volumes corrected for total brain volume, the Step 1 models, which included sex, age, and PCA puberty factor scores, significantly predicted volumes in parts of the basal ganglia, i.e., left Nacc, $R^2 = .089, p = .010$, right Nacc, $R^2 = .138, p < .001$, left pallidum, $R^2 = .083, p = .014$, and right pallidum, $R^2 = .130, p < .001$, as well as volumes of the right amygdala, $R^2 = .064, p = .046$, right hippocampus, $R^2 = .102, p = .005$, right thalamus, $R^2 = .237, p < .001$, and left thalamus, $R^2 = .202, p < .001$.

Next, unique effects of age, puberty, and sex in the significant Step 1 models were examined. As summarized in Table 4, there were unique effects of sex on left and right Nacc, right amygdala, and right hippocampal volumes, with females exhibiting greater volumes than males in these brain regions corrected for total brain volume. In addition, there

was a unique effect of sex on the left pallidum, with males exhibiting greater pallidum volumes than females. There were no unique effects of PCA puberty factor scores. The only significant unique effect of chronological age was on the right thalamus, *partial* $r = .26$, $p = .004$, with right thalamus volumes increasing with older age.

As depicted in Table 4, in Step 2 models examining effects of PCA puberty factor scores by sex interactions, there were significant interaction effects of puberty by sex on left Nacc, right pallidum, and right thalamus volumes. Follow-up analyses revealed that with more advanced pubertal development, left Nacc volumes were significantly smaller in adolescent girls ($r = -.31$, $p = .012$), whereas there was a trend for left Nacc volumes to be larger in adolescent boys ($r = .23$, $p = .077$), as illustrated in Figure 1. More advanced pubertal development was also significantly linked with larger right pallidum volumes in adolescent boys ($r = .46$, $p < .001$), but not in adolescent girls ($p = .191$). Finally, there was a significant positive association between right thalamus volumes and pubertal development in adolescent boys, which was larger ($r = .52$, $p < .001$) than the same association in adolescent girls ($r = .29$, $p = .019$).

After a Bonferroni-correction for multiple comparisons (i.e., adjusted $p = .0035714$), there was still a significant unique effect of sex on left and right Nacc volumes and right hippocampus volumes. The only interaction effect of puberty by sex that survived Bonferroni-correction was on left Nacc volumes.

These overall patterns of significant effects of sex, age, and puberty by sex on subcortical brain volumes were replicated with average Tanner or PDS total scores as measures of pubertal development. Two exceptions were that analyses using Tanner ratings did not yield sex differences in left pallidum volumes and neither Tanner ratings or PDS total analyses yielded a puberty by sex interaction effect on volumes of the right thalamus.

Finally, additional analyses were initiated to examine whether the observed pubertal status effects on BAS Fun Seeking and BAS Total were mediated by subcortical left Nacc, right pallidum, and right thalamus volumes. However, bivariate correlations found no significant associations between relevant ROI volumes and relevant BAS subscale scores in boys or girls or in the sample as a whole, failing to meet necessary conditions for mediation (Baron & Kenny, 1986).

4. Discussion

The present study parses out associations between pubertal development versus chronological age and reward (i.e., BAS) and threat (i.e., BIS) sensitivities during adolescence. This examination of unique effects of puberty and chronological age was possible due to our approach of examining broad ranges of ages and pubertal status during adolescence. After controlling for effects of age and sex, pubertal status, as indexed by a PCA-derived puberty factor score, significantly predicted greater reward sensitivity as measured by the BAS Total and BAS Fun Seeking scales in adolescents. There were no unique main effects of chronological age after controlling for puberty and sex effects on reward sensitivity. Interestingly, prior studies have linked BAS Fun Seeking with reward-

related impulsivity (Smillie, Jackson & Dalgleish, 2006) and substance use (O'Connor, Stewart & Watt, 2009). This pattern of results has two important implications for normative adolescent development. First, reward sensitivity (broadly construed) is uniquely associated, in a linear fashion, with pubertal changes during adolescence, supporting current theoretical models (Dahl, 2004; Forbes & Dahl, 2010; Steinberg, 2008). Second, this association is largely due to the impact of pubertal development on aspects of reward sensitivity that reflect tendencies to engage in reward-related risk-taking and impulsivity versus those associated with motivational drives or hedonic pleasure. These latter processes, indexed through the BAS-Drive and BAS-Reward Responsiveness subscales, were not uniquely associated with pubertal status, suggesting that they are mediated by a distinct set of neural mechanisms. Moreover, these facets of reward sensitivity have been associated in prior studies with quadratic age-related changes (Urošević et al., 2012).

The present finding of a positive relationship between pubertal status and aspects of appetitive motivation in adolescence is consistent with prior studies linking sex hormonal levels with greater trait reward sensitivity, measured by the BIS/BAS scales, (Vermeersch et al., 2009) and with greater VS activation in response to reward receipt (Op de Macks et al., 2011), but not with studies finding inverse relationships between sex hormonal levels and striatal activation during reward outcome (Forbes et al., 2010). There are many methodological differences between the present study and prior studies that may explain these discrepancies. For example, whereas the present study examined associations of puberty with self-reported reward sensitivity and regional brain volumes, prior studies have focused on pubertal status and functional activation of reward-relevant brain regions in the context of reward-related decision-making (e.g., Forbes et al., 2010). Moreover, some prior studies have focused on limited age-ranges, examining effects of pubertal status on reward sensitivity at only one stage of adolescence, usually early adolescence (e.g., 11 to 13 year olds), leaving open the possibility that age by puberty interactions are salient in relation to some of the observed effects. Additional studies using multi-method approaches for assessing reward sensitivity (e.g., self-report, functional neuroimaging assessments of responses to rewards, behavioral measures of reward sensitivity) and pubertal status are needed to reconcile these discrepancies.

Another study has examined pubertal effects on the related but distinct construct of sensation seeking in adolescents aged 10 to 16 (Steinberg et al, 2008). After controlling for chronological age and other covariates, advanced pubertal status predicted greater self-reported sensation seeking in males but not females (Steinberg et al., 2008). Sensation seeking refers to the pursuit of highly arousing and novel experiences with a willingness to take risks to attain those experiences (Zuckerman et al., 1978). This construct overlaps with, but is not identical to, the construct of reward sensitivity, i.e., strength of response to positively-valenced stimuli that vary in novelty and the extent to which they are arousing, regardless of risk-taking. BAS Fun Seeking scores are associated with sensation seeking scores, but also reflect other aspects of positive incentive-guided behavior (e.g., Smillie et al., 2006). Future studies that incorporate measures of both constructs are needed to further explore the specificity of pubertal associations with fun-seeking aspects of reward sensitivity versus sensation seeking, particularly in males.

Interestingly, in the present study, after controlling for the effects of puberty, chronological age predicted an increased sex difference in both reward (i.e., BAS Drive) and threat (i.e., BIS) sensitivities. In both of these age by sex interactions, increasing age was associated with higher scores for females but not males. This pattern of results suggests that multiple mechanisms, which are not limited to puberty, contribute to increased emotional reactivity in adolescent females compared to adolescent males. These mechanisms could include sex-specific environmental stressors, behavioral tendencies such as rumination or negative affect, or other characteristics that operate alone or in combination with neurodevelopmental processes. The present finding of increased threat sensitivity in adolescent females is consistent with prior research showing increased cortisol reactivity to stressors in adolescent females compared to males (e.g., Gunnar et al., 2009). It is also consistent with prior studies reporting adolescent females versus adolescent males exhibited increased self-report threat/punishment sensitivity, which was further associated with the feedback-response negativity (FRN) as measured by EEG during task performance (Santesso, Dzyundzyak, & Segalowitz, 2011). Given the importance of the anterior cingulate region for the generation of the FRN, future studies might focus on cortical-to-subcortical connectivity to better resolve the neural correlates of this sex difference. Additional studies are also needed to determine whether increases in reward and threat sensitivities in adolescent females are linked to emerging sex differences in rates of depression during adolescence (Hankin et al., 1998).

The present study also found significant sex-specific effects of advanced pubertal status on striatal volumes, i.e., Nacc and pallidum volumes, as well as volumes of the right thalamus. Moreover, after controlling for total brain volume and effects of chronological age and after controlling for multiple comparisons, advanced pubertal development was linked with smaller left Nacc volumes in adolescent girls, but with larger left Nacc volumes in adolescent boys, as depicted in Figure 1. The present findings are consistent with a recent longitudinal study showing pubertal effects on Nacc volumes (Goddings et al, in press).

These findings of pubertal effects on the Nacc, pallidum, and thalamus, are important given these structures' integral roles in facilitating appetitive motivation. The Nacc is a key brain structure for reward valuation and translation of approach motivation into goal-directed behaviors (e.g., Depue & Collins, 1999), with neuroimaging studies showing associations between Nacc activation and magnitude/probability of reward (for review see Haber & Knutson, 2010). Similarly, the pallidum is a major striatal output region with indirect connections to the cerebral cortex; specifically, the ventral pallidum serves as the major output region of the Nacc (Haber & Knutson, 2010). Lesion and stimulation studies indicate that it is critical for the affective experience of consummatory pleasure, for incentive-related Pavlovian and instrumental learning, and the coding of incentive salience (Smith et al., 2009). The thalamus, long thought to play a restricted role in sensory processing, receives inputs from the pallidum, projects to both the cerebral cortex and back to VS (Haber & Knutson, 2010) and, through these interconnections, influences the selection of goal-directed actions (Bradfield, Hart & Balleine, 2013). The pulvinar nucleus of thalamus, which represents the largest nuclear grouping within that structure, broadly implicated in visual and other attentional processes, has been highlighted in recent models of affective information processing given that it receives multiple inputs from frontal, parietal, cingulate, insular, and visual cortical areas (Pessoa & Adolphs, 2010). The pulvinar has been proposed to facilitate

detection and awareness of affectively salient stimuli in the environment through multiple thalamo-cortical loops (Pessoa & Adolphs, 2010). Although we cannot resolve specific thalamic nuclei within our MRI analyses, the potential importance of this structure for salience detection during adolescence is an important area for future investigation.

Coordinated activity of these structures in the service of positive goal-directed action is supported by functional neuroanatomic models suggesting that topographic subcomponents of the pallidum and thalamus are involved in multiple, parallel corticostriatal circuits that project to specific frontal cortical areas involved in motor behavior, cognition, and reward valuation (Alexander, DeLong, & Strick, 1986). Interconnections among the Nacc, ventral pallidum, mediodorsal thalamus, and ventromedial PFC/OFC, influence reward valuation, cost-benefit analyses, and, ultimately, reward pursuit (e.g., Haber & Knutson, 2010). The finding of a main effect of pubertal status, independent of age, on volumes of multiple structures within this integrated network suggests that hormonal tone may critically impact the functional output of this circuitry through other neurochemical interactions.

Concordantly, in rats, more advanced puberty predicted increased sensitivity to natural rewards and greater c-fos protein expression in the Nacc following odor-reward conditioning vs. sham training, indicative of greater activation of this brain region during learning of reward contingencies (Friemel, Spanagel, and Schneider, 2010). Moreover, in male rats, prefrontal cortical projections to the ventral tegmental area (VTA), the major source of afferent dopaminergic projections to the ventral striatum and orbitofrontal cortex (Haber & Knutson, 2010), were the most enriched with androgen intracellular receptors, suggesting a potential mechanism for androgen hormones to regulate dopaminergic cell firing in the VTA (Aubele & Kritzer, 2012). Research in female rats is sparse, but numerous studies suggest that estrogen regulates dopamine (i.e., D2) receptor activity in the striatum (Hsu et al., 2011) and that estradiol modulates cocaine-induced activation in brain structures for reward processing, such as Nacc and medial PFC (Segarra et al., 2010).

There is also preliminary evidence that sex hormones affect structure, not just function, in striatum and other subcortical brain regions in sex-specific ways. Animal studies with female Syrian hamsters suggest that estradiol can influence structural changes in Nacc, such as decreased density of dendritic spines on medium spiny neurons (Staffend, Loftus, & Meisel, 2011). In male Syrian hamsters, pubertal testosterone regulates neuronal numbers but that the nature of this regulation varies by brain region (De Lorme et al., 2012). Animal studies with adult males of various species suggest androgen effects on spine synapse growth in hippocampus and PFC (Hajszan et al., 2008). In rats, sex hormones appear to regulate the addition and/or survival of new cells in sexually-dimorphic brain regions (Ahmed et al., 2008). In adolescent girls, testosterone levels are inversely related to volumes of other subcortical structures, such as amygdala (Bramen et al., 2011), and estradiol levels are inversely related to overall gray matter volumes (Peper et al., 2009). In adolescent boys, increased levels of testosterone are linked to greater total gray matter brain volumes (Peper et al., 2009) and greater amygdala and diencephalic volumes (Neufang et al., 2009). Similarly, studies investigating genetic disorders leading to extremely low or high testosterone levels support positive relationship between testosterone levels and regional brain volumes in boys (Giedd et al., 2006; Mueller et al., 2011). Based on these animal and

human studies, the present study's finding of decreased Nacc volumes in adolescent girls and increased Nacc volumes in adolescent boys in relation to advanced pubertal development could be due to sex-specific sex hormonal regulations of neuronal survival (e.g., increased cell survival in boys only), of synaptic integrity (e.g., estradiol in promoting decreased dendritic spine density in girls), and/or of synaptic growth (e.g., testosterone promoting synapse growth in boys).

There are many methodological issues with hormonal assays and a general lack of studies that have examined these hormonal effects across the full range of adolescence. Thus, conclusions regarding hormonal influences on the development of reward-specific brain structures remain tentative. Nonetheless, the present findings provide compelling links between findings observed in animal models with respect to hormonal influences over synaptic structure. Additional studies are needed to determine the precise set of biological and environmental mechanisms through which changes in pubertal status impact the structure and function of subcortical structures implicated in reward processing.

In the present study, sex-specific pubertal effects on neural structures did not mediate the observed associations between pubertal development and increases in self-reported reward sensitivity. Specifically, even though pubertal development appears to differentially organize reward brain structures (e.g., Nacc) in boys versus girls, both sexes exhibited increased self-reported behavioral reward sensitivity with advanced pubertal development, which were not linked to sex-specific brain structural differences. This lack of triangulation could be due to methodological limitations of the current study, as described below. Alternatively, it could imply that a common behavioral outcome is reached through distinct patterns of synaptic structure in males versus females as a function of gonadal hormonal influences unique to each sex. The current study cannot resolve this question.

Nonetheless, our findings of puberty effects on reward sensitivity (i.e., BAS Total and BAS Fun Seeking), and on the structural integrity of the subcortical network that promotes appetitive behavior, cohere with recent theories of pubertal effects on adolescent behaviors (Forbes & Dahl, 2010) and the development of subcortical structures (e.g., Blakemore et al., 2010; Nelson et al., 2005). The present findings suggest that the link between puberty and overall reward sensitivity may go beyond rewards in social contexts, as has been suggested by some authors (e.g., Nelson et al., 2005).

4.1 Limitations

The present study is not without limitations. For example, the present sample is predominantly Caucasian and from middle to upper-middle socio-economic backgrounds. Replications in more diverse samples are needed to establish the generalizability of the present findings. While sample sizes are relatively large, this study is similar to others cited herein in that the full range of adolescent age combined with the full range of pubertal status is insufficiently represented for each sex with an adverse effect on statistical power. In addition, pubertal development and BIS and BAS sensitivities in the present study were assessed using self-report measures. BAS sensitivities are reflected through three subscales, each of which is represented by a relatively small number of items. Whether findings that emerged from the BAS scales can be replicated using more comprehensive measures of

appetitive motivation is an important question for further construct validation. However, both the pubertal self-report measures (e.g., Dorn et al., 1990; Taylor et al., 2001) and the BIS/BAS scales (e.g., Carver & White, 1994; Harmon-Jones & Allen, 1997) are reported to be psychometrically reliable and valid. Moreover, the main set of findings was consistent across three self-report indices of pubertal development. The consistency of main findings across the three pubertal indices also encourages confidence in the results despite the relatively large number of analyses performed. The subcortical brain volume analyses were not corrected at the outset for multiple comparisons given the exploratory nature of the present study and as such require future replication. It should be noted that even after applying a Bonferroni correction for multiple comparisons, the pubertal development status by sex interaction effect on the left Nacc volumes, depicted in Figure 1, remains significant. Finally, the present study did not support mediation of associations between pubertal development and self-reported reward sensitivity by sex-specific patterns of variation in regional brain volumes.

4.2 Conclusions

The present study suggests a unique relationship between puberty and reward sensitivity and sex-specific unique relationships between puberty and Nacc volumes. There were no pubertal effects on threat sensitivity and volumes of structures typically linked to threat sensitivity, such as the amygdala. Future research would need to replicate the present associations using alternative self-report measures of appetitive motivation as well as non-self-report measures of reward sensitivity (e.g., relative left frontal asymmetry using electroencephalography, neuroimaging indices of brain activation during anticipation of rewards). Additional studies are needed to fully unpack the biological mechanisms of these pubertal effects. Future longitudinal studies may selectively enroll pre-pubertal children at younger ages to more precisely determine how the transition from pre-puberty to active puberty impacts behavior and brain structures. Furthermore, such longitudinal studies would set the stage for the examination of neurobiological and behavioral effects of pubertal timing and tempo.

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Abbreviations

BAS	behavioral activation/approach system
BIS	behavioral inhibition system
Nacc	nucleus accumbens

OFC	orbitofrontal cortex
PCA	principal component analysis
PFC	prefrontal cortex
VS	ventral striatum

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Highlights

- Associations between puberty and reward sensitivity in adolescence are examined.
- Controlling for age, pubertal status has unique relationship to reward sensitivity.
- Pubertal status has sex-specific unique effects on nucleus accumbens volumes.

Figure 1. Interaction effect of Pubertal Stage X Sex on left Nacc volumes corrected for total brain volume

The pattern of results suggests a decrease in the left Nacc volumes (corrected for total brain volume) for adolescent girls, and an increase for adolescent boys, with more advanced stages of pubertal development. Note that PCA puberty scores are derived from z-score transformations of the PDS and Tanner items, and as such, a value of 0 reflects the mean pubertal development for the sample, negative scores reflect less advanced pubertal development, and positive scores reflect relatively more advanced pubertal development. TBV = total brain volume.

Table 1

Means and Standard Deviations for Age, Puberty, BIS/BAS scales, and Subcortical Region Volumes

Measures	Female (<i>n</i> = 63)	Male (<i>n</i> = 63)
Age	14.28 (3.15)	14.95 (2.67)
Average Tanner Score	3.21 (1.38)	3.60 (1.18)
PDS Total	14.26 (5.01)	13.30 (4.13)
PCA Puberty Factor	0.02 (1.09)	−0.02 (0.91)
BAS Total	38.90 (5.11)	39.84 (5.17)
BAS Drive	9.73 (2.48)	10.60 (2.34)
BAS Fun Seeking	11.63 (2.13)	12.22 (2.00)
BAS Reward Respons.	17.54 (1.79)	17.02 (2.16)
BIS Scale	19.81 (3.28)	18.56 (3.09)
R Amygdala	1667.03 (181.01)	1766.14 (178.11)
L Amygdala	1537.21 (166.84)	1697.75 (155.01)
R Caudate	4148.24 (504.62)	4528.37 (545.40)
L Caudate	4192.46 (503.10)	4560.56 (537.09)
R Hippocampus	4308.56 (348.18)	4570.65 (438.44)
L Hippocampus	4155.21 (340.53)	4497.65 (369.54)
R Nucleus Accumbens	702.22 (97.54)	716.73 (97.16)
L Nucleus Accumbens	658.71 (90.69)	681.68 (97.06)
R Pallidum	1794.86 (227.87)	2086.05 (251.18)
L Pallidum	1998.44 (227.52)	2313.46 (264.81)
R Putamen	5951.97 (548.17)	6462.87 (552.07)
L Putamen	6208.73 (554.50)	6796.10 (597.72)
R Thalamus	7734.17 (751.64)	8866.14 (896.20)
L Thalamus	7851.37 (769.16)	8972.68 (881.46)

Note: R= right hemisphere, L= left hemisphere. All subcortical brain volumes are presented in mm³ and not corrected for total brain volumes in this table even though they are in all analyses.

Table 2

Associations between Chronological Age and Pubertal Indices

Adolescent Girls				
	1.	2.	3.	4.
1. Age	--	.87 ^a	.90 ^a	.90 ^a
2. Average Tanner		--	.92 ^a	.96 ^a
3. PDS Total			--	.97 ^a
4. PCA Puberty Factor				--
Adolescent Boys				
1. Age	--	.88 ^a	.90 ^a	.89 ^a
2. Average Tanner		--	.90 ^a	.95 ^a
3. PDS Total			--	.98 ^a
4. PCA Puberty Factor				--

^aNote: $p < .001$. Age = chronological age. Average Tanner = average score across two drawing sets' ratings. PDS Total = Puberty Developmental Scale's total score. PCA puberty factor = factor score based on the 1st factor loadings of principal component analysis of z-score transformed PDS and Tanner items.

Table 3

Unique Effects of Puberty on BAS/Reward Sensitivity

BAS Total Scale			
	<i>b</i>	<i>t</i>	<i>p</i>
Puberty	2.06	2.11	.037
Age	−0.20	−0.60	ns
Sex	−1.01	−1.11	ns
BAS Fun Seeking			
Puberty	1.06	2.64	.009
Age	−0.23	−1.65	ns
Sex	−0.75	−2.01	.047

Note: Sex was dummy-coded with 0 = male, 1 = female; ns = non-significant.

Table 4

Unique Effects of PCA Puberty Factor Scores and Sex on Subcortical Brain Volumes

Volume	Change R ²	F/t	p	Partial r
<i>Unique Sex Effects in Step 1 Model</i>				
R Amygdala	--	2.50	.014	.22
R Hippocampus	--	3.38	.001	.29
L Nacc	--	3.37	.001	.29
R Nacc	--	4.00	<.001	.34
L Pallidum	--	-2.01	.047	-.18
<i>PCA Puberty Factor Score X Sex Effects in Step 2 Model</i>				
L Nacc	.064	9.03	.003	-.27
R Pallidum	.033	4.67	.033	-.19
R Thalamus	.027	4.46	.037	-.19

Note: Sex was dummy-coded with 0 = male, 1 = female. Nacc = nucleus accumbens; L = left hemisphere, R = right hemisphere.