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Individual Differences in Boys' and Girls' Timing and Tempo of Puberty: Modeling Development With Nonlinear Growth Models

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Abstract

Pubertal development is a nonlinear process progressing from prepubescent beginnings through biological, physical, and psychological changes to full sexual maturity. To tether theoretical concepts of puberty with sophisticated longitudinal, analytical models capable of articulating pubertal development more accurately, we used nonlinear mixed-effects models to describe both the timing and tempo of pubertal development in the sample of 364 White boys and 373 White girls measured across 6 years as part of the National Institute of Child Health and Human Development Study of Early Child Care and Youth Development. Individual differences in timing and tempo were extracted with models of logistic growth. Differential relations emerged for how boys' and girls' timing and tempo of development were related to physical characteristics (body mass index, height, and weight) and psychological outcomes (internalizing problems, externalizing problems, and risky sexual behavior). Timing and tempo are associated in boys but not girls. Pubertal timing and tempo are particularly important for predicting psychological outcomes in girls but only sparsely related to boys' psychological outcomes. Results highlight the importance of considering the nonlinear nature of puberty and expand the repertoire of possibilities for examining important aspects of how and when pubertal processes contribute to development.

Keywords

puberty; tempo and timing; longitudinal analysis; nonlinear; growth modeling

Puberty is a period of the life span marked by major psychological, endocrine, and physical changes that contribute to the metamorphosis of children into reproductively mature

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adolescents. At its core, puberty is a within-person developmental process driven by reactivation of gonadotropin-releasing hormone in the hypothalamus and the release of gonadotropins, gonadal steroids, and physical growth (Grumbach & Styne, 1998). This biological cascade provides the basis for pubertal changes in secondary sexual characteristics (breast, genitals, pubic hair), reproductive capability, height, weight, and accompanying psychological and behavioral changes.

Given the inherent challenges in measuring changes in the underlying neuroendocrine biology, scientists interested in pubertal development have effectively used observable changes in secondary sexual characteristics as proxies for the degree of pubertal maturation. Most prominently, these changes were systematically described by Tanner and colleagues (Marshall & Tanner, 1969, 1970; Tanner, 1962) and more recently elaborated by Biro et al. (2001). Briefly, Tanner (1971) conceptualized and characterized pubertal development as progression through a series of five maturational stages (from prepubescence to full sexual maturity), each of which described the degree of physical maturation of breasts (girls), genitals (boys), and pubic hair (boys and girls). These five stages of pubertal development serve as the primary basis for the measurement and tracking of pubertal maturation by both scientists and clinicians. It should be noted that although we (inclusive of Tanner, the current literature, and the medical community) use the term *stage* to orient researchers to different points in the progression of breast, genital, and pubic hair development, the physiological changes underlying pubertal development are considered to be a continuous process (Grumbach & Styne, 1998).

Interindividual differences in pubertal development can be described in terms of timing and tempo. *Timing*, as a measure of interindividual differences in pubertal development, describes how mature children are relative to their same-sex and -age peers. Adolescents are considered early, on time, or late depending on their relative physical maturity (Ge, Brody, Conger, Simons, & Murry, 2002). Often, in cross-sectional studies, timing is thought of as the Tanner stage a child is in compared with same-sex peers—at a given age or measurement occasion. In longitudinal designs, however, timing may also be conceptualized as the relative age of a child, compared with same-sex peers, at a given stage in the pubertal process. The use of age at menarche as a measure of timing is an example of this latter conceptualization. *Tempo*, in contrast, describes how quickly or slowly individuals progress along the path to full sexual maturity. Adolescents are considered slow, average, or fast maturers depending on how long it takes them to progress from Stage 1 (prepubertal) to Stage 5 (full sexual maturity).

Understanding the process of puberty is especially salient for psychological research because pubertal changes are related to many physical and psychosocial outcomes in adolescence and adulthood (Costello, Mustillo, Erkanli, Keeler, & Angold, 2003; Negriff & Susman, 2011). Nonetheless, despite progress in knowledge regarding the influences of the timing of puberty on physical, mental, and behavioral development, gaps in our understanding remain. First, multiple inconsistencies exist regarding the positive and/or negative effects of earlier or later timing of puberty in boys and girls (described below). Second, few studies examine the potential contribution of tempo to physical maturity and behavioral outcomes. Third, puberty, although generally conceptualized as a progressive, within-person process characterized by a nonlinear trajectory, has not been modeled as such (with the exception of Eaves et al., 2004, who used a nonlinear function to create one latent “puberty” construct). The purpose of this report is to address these gaps in the literature with the aim of advancing understanding of how differences in the timing and tempo of pubertal development relate and contribute to physical and psychological outcomes. Specifically, using longitudinal data collected from boys and girls 9.5–15.5 years of age, we modeled individual differences in timing and tempo within a framework that considers the nonlinear nature of pubertal development, and examined how those differences relate to one another and to physical growth and behavioral outcomes previously shown to be related to pubertal maturation.

Timing

To date, the vast majority of literature relating puberty to psychological and physical development examines the relative timing of puberty compared with same-age and -sex adolescents. Timing of puberty has been related to physical characteristics, including height (e.g., Belsky et al., 2007; Huang, Biro, & Dorn, 2009; Li et al., 2009; Llop-Viñolas et al., 2004), weight (e.g., Tanner-Smith, 2010), and body mass index (BMI; e.g., Davison, Susman, & Birch, 2003; He & Karlberg, 2001; Huang et al., 2009). In line with biological influences, earlier timing is generally associated with greater physical size and/or earlier physical growth.

There is strong and consistent evidence that deviations from normative timing (earlier or later timing) are related to psychological outcomes, including internalizing and externalizing problems (e.g., Ge, Brody, Conger, & Simons, 2006; Ge et al., 2002; Graber, Lewinsohn, Seeley, & Brooks-Gunn, 1997; Mendle, Turkheimer, & Emery, 2007). Two hypotheses that explain how timing relates to negative psychological sequelae have gained traction. The maturational deviance hypothesis posits that adolescents who develop either earlier or later relative to peers experience psychological distress and manifest behavior problems (Petersen & Taylor, 1980). The developmental readiness hypothesis posits that early maturing adolescents are at highest risk for psychological and behavioral problems because they are not emotionally or cognitively ready for the major physiological, social, and emotional changes comprising puberty (e.g., Ge et al., 2002).

Findings regarding whether earlier or later puberty affects psychological development have been mixed. A number of studies report that early maturation is associated with negative outcomes (mainly internalizing and externalizing problems) for both boys and girls (e.g., Beaver & Wright, 2005; Ge et al., 2006, 2002; Graber et al., 1997; Graber, Seeley, Brooks-Gunn, & Lewinsohn, 2004; Negriff & Susman, 2011; Negriff & Trickett, 2010; Siegel, Yancey, Aneshensel, & Schuler, 1999; Susman et al., 2007). Pubertal maturation is also associated with sexual behavior in boys and girls (Udry, Billy, Morris, Groff, & Raj, 1985; Udry, Talbert, & Morris, 1986). Early pubertal timing predicts earlier sexual initiation in boys and sometimes in girls (Crockett, Bingham, Chopak, & Vicary, 1996; Miller, Norton, Fan, & Christopherson, 1998).

Additionally, for girls, early puberty has been linked to depressive symptoms (e.g., Angold, 2003; Graber et al., 2004), other internalizing symptoms (e.g., Hayward et al., 1997), eating disorders (e.g., Blyth, Simmons, & Zakin, 1985; Graber et al., 1997), and delinquency (e.g., Caspi, Lynam, Moffitt, & Silva, 1993; Magnusson, Stattin, & Allen, 1985; see also Mendle et al., 2007, for review of detrimental outcomes associated with girls' early puberty). Deviations from average timing, earlier or later, have been associated with greater risk for emotional problems as well (Silbereisen & Kracke, 1997). In some studies, later maturation has been associated with depression in boys (Kaltiala-Heino, Kosunen, & Rimpela, 2003). However, other studies have reported that earlier maturation is unrelated to risky behaviors (i.e., delinquency) or may even serve as a protective factor against risky behavior in boys (e.g., Hayward et al., 1997; Kaplowitz, 2004; Rierdan & Koff, 1991; Stattin & Magnusson, 1990). In sum, early timing of puberty has consistently been shown to be a risk factor for girls' behavior problems, whereas findings for boys are less clear.

Tempo

Although very little research has focused on the psychological significance of tempo in pubertal development, the hypothesized mechanisms explaining the association between pubertal timing and psychological outcomes extend to pubertal tempo. For example, the key point of the maturational deviance hypothesis is that youth who experience maturational changes in a manner inconsistent from their peers (i.e., earlier or later) will develop psychological problems. Youth progressing through puberty unusually quickly or slowly, and thus arriving at developmental milestones earlier or later than their peers, are expected to be at greater risk for behavior problems. Youth progressing unusually quickly or slowly may also feel different or isolated from peers because of observable differences in their rate of development.

Similarly, the key principle of the developmental readiness hypothesis is that individuals are at greatest risk for developing psychological problems when they are not emotionally or cognitively ready for the major changes of puberty. Youth progressing through puberty too quickly may not have time to acclimate to the myriad biological and social changes they are experiencing and thus develop psychological problems. In contrast, youth who start earlier or on time but mature slowly may not have as many psychological problems because the hormone and growth changes are less compressed, allowing the individual, his or her peers, and individuals in his or her social environment more time to adapt to the myriad changes.

A few studies have examined the relation between pubertal tempo and physical characteristics. For example, Llop-Viñolas et al. (2004) examined tempo, operationalized as the number of years it took girls to progress from Tanner breast development Stage 2 to menarche. The main focus of the study was to determine whether earlier timing impacted the height trajectory of girls. Older age of onset of puberty was associated with shorter duration (tempo) of puberty and less growth in height during puberty. Similarly, other studies (Biro et al., 2001; Vizmanos, Martí-Henneberg, Clivillé, Moreno, & Fernández-Ballart, 2001) found that boys and girls who matured later tended to be taller at a given age than those who matured earlier, although, on average, final heights at full maturity did not differ. This pattern of results could indicate differences in maturational tempo. However, thus far, pubertal tempo has not been systematically examined in relation to physical growth.

Similarly, only a few studies have examined tempo in relation to psychological problems. For example, Ge et al. (2003) reported that African American boys who progressed through puberty faster during early adolescence showed an increase in depressive symptoms later in adolescence (Ge et al., 2003). Others have found that faster tempo of puberty measured through linear growth models predicted less rapid decreases in depressive symptoms for boys but that tempo was unrelated to depressive symptoms in girls (Mendle, Harden, Brooks-Gunn, & Graber, 2010). In contrast, Laitinen-Krispijn, van der Ende, and Verhulst (1999) found the opposite: Faster pubertal development was protective against depressive symptoms in boys. Overall, the findings indicate inconsistencies across studies for tempo of puberty and psychological development, perhaps due in part to the limited methodologies for distinguishing and measuring timing and tempo with few (only three) longitudinal observations.

A major methodological deficit in the literature on tempo of puberty is that the rate of pubertal development is frequently measured as the amount of time it takes for individuals to progress from Tanner Stage 2 to menarche. This measurement strategy necessarily excludes boys, as they do not have a comparable developmental landmark event. Further, menarche typically occurs around Tanner Stage 4 (Marshall & Tanner, 1969), meaning that secondary sex characteristic changes occurring at the end phases of puberty may be excluded. Here we develop a new approach for measuring the timing and tempo of pubertal development that does not rely on age of menarche (allowing application to both boys and girls) and that makes use of the full range of pubertal stages in secondary sex characteristics.

Associations Between Timing and Tempo

Timing and tempo may both contribute to individuals' adjustment. If adolescents enter puberty at an early age, and have a faster tempo, they will complete developmental milestones earlier relative to their peers throughout puberty. A faster tempo could also exacerbate the effects of early timing. Likewise, adolescents who enter puberty at a later age and who progress through puberty slowly will develop later relative to their peers, thereby exacerbating the effects of later timing. Alternatively, youth with earlier timing may be protected by a slower tempo, and youth with later timing may be protected by a faster tempo. In terms of a maturation deviance perspective, both the combination of earlier timing and faster tempo, and later timing and slower tempo, would predict psychological problems. However, in terms of developmental readiness, only faster tempo in the presence of earlier timing would be predictive of psychological problems. Tempo would be less salient for adolescents in the presence of later timing because individuals have likely already developed the cognitive and social abilities needed to adapt to the major hormonal and growth changes associated with puberty.

Apter and Vihko (1985) reported that girls who started puberty earlier also tended to reach menarche faster, suggesting a negative relation between timing and tempo (e.g., early onset with faster growth). Similarly, Pantsiotou et al. (2008) found that girls who entered Tanner Stage 2 at an earlier age (earlier timing) tended to reach menarche more quickly (fewer years between onset and menarche, a faster tempo). Investigations of pubertal development in relation to height also indirectly suggest a negative relation between timing and tempo. For example, Llop-Viñolas et al. (2004) reported that girls who entered puberty earlier (and thus were shorter upon entry) grew more quickly, making up the difference in height by the end of puberty (see also Apter & Vihko, 1985; Martí-Henneberg & Vizmanos, 1997). In contrast, Li et al. (2009) found no evidence for an association between timing and tempo in Chinese girls. In sum, the limited evidence suggests a negative relation between timing and tempo, but requires further investigation and methods that can be applied across boys and girls.

Modeling the Timing and Tempo of Pubertal Development

Thus far, pubertal development has been modeled as a linear process, despite theory and evidence that puberty follows a nonlinear trajectory with lower and upper asymptotes (e.g., Eaves et al., 2004; Susman, Houts, et al., 2010; Tanner, 1971). What is needed is a methodological framework that adequately characterizes observed changes in pubertal development and allows for examination of interindividual differences in both when children mature (timing of pubertal development) and how quickly those maturational changes proceed (tempo of pubertal development). Mixed-effects and growth curve models have become the main methods used for describing individual differences in intraindividual change (Duncan, Duncan, Stryker, Li, & Alpert, 1999; McArdle, 2009; McArdle & Nesselroade, 2003; Preacher, Wichman, MacCallum, & Briggs, 2008; Singer & Willett, 2003). In brief, mathematical functions are fit to multiperson longitudinal data to describe patterns of individual change and the interindividual differences therein. The framework is extremely flexible, allowing for representation of many different types of change processes and configurations of interindividual differences (Blozis, 2004; Browne, 1993; Browne & Du Toit, 1991; Choi, Harring, & Hancock, 2009; Grimm & Ram, 2009a, 2009b; Grimm, Ram, & Hamagami, in press; Laird & Ware, 1982; Ram & Grimm, 2007, 2009).

Here, following work by Susman, Houts, et al. (2010), we use nonlinear mixed-effects models to describe individuals' pubertal development and to extract and examine interindividual differences in both the timing and the tempo of that development. Initial work by Susman et al. using the same study sample estimated the timing of transition into specific Tanner stages (i.e., at what age individuals were likely to transition) via an ensemble of multilevel logistic regressions. Using the estimated timing scores, Susman et al. examined between-person differences in breast, genital, and pubic hair development in boys and girls, as well as racial (Black vs. White) differences in the timing of stage transitions. Tempo was indirectly estimated as the difference between estimated ages of transition (e.g., number of years from transition into Stage 2 to transition into Stage 3). In the present study, we highlight how within-person information may be used to obtain estimates of the timing and tempo of individuals' development.

As noted at the outset, pubertal development is most often characterized as a continuous, incremental change process wherein individuals progress through the five maturational stages defined by Tanner (1971). This process has some distinctive characteristics that can be described with a sigmoid curve (elongated *S* curve; see Grimm & Ram, 2009a). First, there are clear lower and upper bounds on pubertal development. By definition (e.g., Tanner, 1971), adolescents progress from a prepubescent state (Tanner Stage 1) to a full sexual maturity state (Tanner Stage 5). Second, pubertal development is a strictly progressive process. Individuals generally do not regress (errors of measurement notwithstanding). Once initiated, change proceeds monotonically until sexual maturity is reached. Such trajectories can be described by a logistic function, as shown in Figure 1. Following the plotted curve as age increases along the *x*-axis, pubertal development through the Tanner stages is seen to have its slow beginnings at Tanner Stage 1; increase through Stages 2, 3, and 4; and then is bounded to end at Stage 5. Further, the four mathematical parameters (detailed further in the Method section) used to describe the logistic curve map straightforwardly onto the prepubescent beginnings (β_0) and full sexual maturity endings (β_1) that frame pubertal development, and the timing (λ) and tempo (α) of progression between those frames. When these are placed into a nonlinear mixed-effects model, we can capture the heterogeneity of individual development and specifically examine differences in timing and differences in tempo.

Present Study

In this report we used nonlinear mixed-effects models to describe individuals' pubertal development across 6 years. Our objectives were to (a) describe individual differences in timing and tempo of puberty, (b) examine the relation between timing and tempo among boys and girls, and (c) examine whether and how timing and tempo are related to select physical characteristics and behavioral outcomes. We examined boys and girls separately, in part, because of known sex differences in the endocrine-hormone processes involved in development of the secondary sex characteristics. In boys, pubic hair development is a result of increases in androgens including testosterone and adrenal androgens, whereas in girls, pubic hair is the result of increases in only adrenal androgens. In boys, genital development results primarily from increases in testosterone, whereas in girls breast development is the result of primarily increases in estrogen (e.g., Grumbach & Styne, 1998; Susman, Dockray, et al., 2010; Susman et al., 1987).

Method

We used nonlinear mixed-effects models to examine interindividual differences in pubertal timing and tempo via longitudinal data obtained from the National Institute of Child Health and Human Development Study of Early Child Care and Youth Development (SECCYD), a study originally designed to determine how variations in child care are related to children's development. Comprehensive information about the study can be obtained from the Early Child Care Research Network (http://www.nichd.nih.gov/research/supported/seccyd/overview.cfm). A brief overview of details relevant to the present analysis is given below.

Participants

Participants for the study were recruited from designated hospitals at 10 data collection sites. The SECCYD sample of children was followed from birth in 1991 to age 15.5 years in 2006 at 10 university-based recruitment sites across the country. Initially, 1,364 families with full-term healthy newborns were enrolled. At the age 9.5 assessment, 80% of boys and 81% of girls were White, 13% of boys and girls were African American, and the remaining 7% were of other ethnicities. Following, but not condoning, the current general practice in the puberty literature for use of samples drawn from a single population (as opposed to many populations), we modeled pubertal change of only the White youth who participated in the pubertal staging portion of the study. Specifically, we used data provided by 364 White boys and 373 White girls at annual assessments when they were 9.5–15.5 years old. The remainder of the White sample was not available for assessment because they dropped out prior to puberty or declined to participate in the pubertal staging.

The sample had, on average, an income-to-needs ratio of 4.04 (SD = 3.22; at the age 6 months assessment), with 77% of families living above the poverty line (i.e., an income–needs ratio above 2.0). On average, mothers and partners had completed more than high school education (M = 14.7 years, SD = 2.4, for mothers; M = 14.8 years, SD = 2.7, for partners, as assessed when the children were 1 month old). White adolescents who provided pubertal data did not differ significantly from White adolescents who did not provide pubertal data in terms of their families' income-to-needs at age 6 months or paternal education; nonetheless, mothers of those included had significantly higher education than those not included (M = 14.7 vs. 14.3, p = .02). Additional information about the pubertal staging sample can be found in Susman, Houts, et al. (2010). Descriptive statistics on the specific variables (described below) for the White sample used here are given in Tables 1 and 2.

As with many longitudinal studies of pubertal development, there was some attrition over the course of the study. Participants ranged in number of missing assessments. Although many youth provided data at all the pubertal staging assessments (n = 155 for boys' genital development, 162 for boys' pubic hair development, 191 for girls' breast development, and 186 for girls' pubic hair development), there were a number of youth who missed or declined to participate in one or more assessments. Varying slightly from outcome to outcome, 68%–73% of the sample provided data on five or more (of seven) occasions, and less than 10% provided data on only one occasion.

We tested whether attrition was related to demographic indicators using a series of analyses of variance. For the most part, extent of missingness was not related to demographic indicators (i.e., mother or partner education, income-to-needs ratio; Fs < 3.19, ps > .05). However, the number of missing assessments for girls' pubic hair development was related to families' income-to-needs ratio, $F(1, 368) = 3.94$, p = .05, such that girls in families with a higher income-to-needs ratio at age 6 months provided fewer assessments. We ran Little's (1988) test for missing completely at random for the puberty physical and psychological outcome variables separately for boys and girls (given that analyses would be conducted separately), and the assumption of missing completely at random was not rejected for either boys, $\chi^2(1544) = 1585.65$, p = .23, or girls, $\chi^2(1774) = 1755.75$, p = .62.

Measures

We assessed youth on pubertal status using clinician-reported Tanner stages and on a number of physical and psychological outcomes, including height, weight, BMI, internalizing problems, externalizing problems, and risky sexual behaviors.

Pubertal development—Annually, starting at age 9.5, boys' and girls' pubertal development was assessed by nurse practitioners or physicians using Tanner criteria for stage of maturation (Marshall & Tanner, 1969, 1970). Following the Pediatric Research in Office Settings Network study of pubertal development and the American Academy of Pediatrics manual, *Assessment of Sexual Maturity Stages in Girls* (see Herman-Giddens & Bourdony, 1995), the assessment included use of photos showing the five Tanner stages (prepubescence to full sexual maturity) and breast bud palpation (for the age 10.5–15.5 assessments).[1] Each year clinicians were recertified for accurate assessment (requiring 87.5% reliability) of both girls (via photos from the Pediatric Research in Office Settings Network study of pubertal development; Herman-Giddens & Bourdony, 1995) and boys (via Tanner photos adapted from Tanner, 1962). In the case that adolescents were between stages, they were assigned the lower stage rating.

Individuals "staged out" and were no longer assessed when they were considered to have reached full sexual maturity. Specifically, girls staged out after having achieved menarche and Tanner Stage 5 for both breast and pubic hair development, and boys staged out after having achieved Stage 5 for both genital and pubic hair development. We note that researchers making use of the SECCYD data source should be aware that individuals who staged out are coded as missing in the data and require algorithmic extraction and replacement with "true" values. The frequency distribution of observed pubertal stage by age, as well as average stage at each age, is given in Table 1.

Physical growth—Anthropometric measurements were taken on or close to the participants' half birthday during laboratory visits each year. In the current analysis, we make use of height and weight measurements obtained at the age 12.5 assessment, as this is the assessment nearest in time to the typical growth spurt associated with puberty (e.g., Warren & Brooks-Gunn, 1989). Height was recorded twice, in inches to the nearest ⅛ in. If the two height measurements differed by more than ½ in., two additional measurements were taken. Weight was recorded twice, in pounds and ounces. If the weight measurements differed by more than 4 ounces, two additional measurements were taken to verify the weight. The average of the two measurements that fell within tolerance range was used in the analysis. Raw scores for height and weight were converted to for-age-percentile scores (Lohman, Roche, & Martorell, 1988). BMI was calculated with a program provided by the Centers for Disease Control and Prevention (http://www.cdc.gov/nccdphp/dnpa/growthcharts/guide.htm) and converted to *z* scores.

Internalizing and externalizing problems—Two measures were used to assess internalizing and externalizing problems at the age 15.5 assessment. One set of measures was obtained with reports from multiple raters on broadband subscales from the Child Behavior Checklist (CBCL; completed by mothers and fathers) and corresponding Youth Self Report (YSR, completed by adolescents; detailed information given in Achenbach, 1991). A CBCL–YSR internalizing behavior composite ($\alpha = .80$) was calculated as the average of mother, father, and youth reports (for each reporter, $\alpha > .86$) on the Withdrawn (e.g., refuses to talk, stares blankly), Somatic Complaints (e.g., feels dizzy), and Anxious/Depressed (e.g., feels worthless or inferior) subscales. Similarly, the externalizing behavior

[1]Breast palpation was not used at age 9.5, as it was not a methodological consideration when the study began.

composite (α = .82) was calculated as the average of mother, father, and youth reports (for each reporter, αs > .86) on the Delinquent Behavior (e.g., lying or cheating) and Aggressive Behavior (e.g., destroys things belonging to the family) subscales.

For additional robustness, we also used an average of mothers' and fathers' or secondary caregivers' reports of internalizing and externalizing from the Social Skills Rating Scale (SSRS: Gresham & Elliott, 1990) collected when their child was 15.5 years old. The SSRS Internalizing (e.g., appears lonely, shows anxiety being with a group of friends; α = .67) and Externalizing (e.g., has temper tantrums, fights with others; α = .68) subscales each comprised six items rated on a scale from 0 (*never*) to 2 (*very often*).

Of note, the internalizing and externalizing subscales of the SSRS are embedded among items assessing positive and negative social skills. In contrast, the items composing the internalizing and externalizing subscales of the CBCL–YSR are embedded among items assessing exclusively problem behaviors. As well, the CBCL–YSR subscales span a wider variety of problem behaviors, including more serious problem behaviors (e.g., internalizing: talks about killing self; externalizing: truancy, vandalism, and substance use). Finally, the CBCL–YSR includes youth-reported behavior, whereas the SSRS includes only parent-reported behavior. Thus, the SSRS and CBCL–YSR are measures of internalizing and externalizing behavior within slightly different contexts and tap into different aspects of the underlying constructs. Because of these important methodological distinctions between the measures (internalizing scales, $r \approx .61$; externalizing scales, $r \approx .65$), we chose to examine the relation between pubertal development and internalizing and externalizing behavior from the CBCL–YSR and SSRS separately.

Risky sexual behavior—Risky sexual behavior was measured at age 15.5 with the Risky Behavior Questionnaire (adapted from Conger & Elder, 1994). The scale consisted of four items assessing how often participants had engaged in oral sex, how often they engaged in sexual intercourse, whether they had ever been pregnant or had gotten a girl pregnant, and whether they had ever been told by a nurse or doctor that they had contracted a sexually transmitted disease. These items were averaged into a composite (α = .73) and square-root transformed to alleviate skew. Scores ranged from 0 to 1.41 (the full possible range).

Analytic Strategy

Interindividual differences in timing and tempo—Our first analytic task was to derive measures of individuals' timing and tempo of pubertal development. Making use of a logistic growth function (see Grimm & Ram, 2009a; Ram & Grimm, 2007), we estimated when adolescents entered Tanner Stage 3 and how quickly individuals were changing at Tanner Stage 3 for each measure of secondary sex characteristics (i.e., breast development for girls, genital development for boys, and pubic hair development for both). Specifically, change over age was modeled with a logistic function embedded within a nonlinear mixed-effects model, with seven longitudinal assessments nested within persons. The model was specified as

$$\text{TStage}_{ti}=\beta_0+(\beta_1-\beta_0)\left\{\frac{1}{1+\exp[-\alpha_i(\text{age}_{ti}-\lambda_i)]}\right\}+r_{ti}, \quad (1)$$

where TStage_{ti}, the observed level of breast, genital, or pubic hair development at assessment occasion *t* for individual *i*, is modeled as a function of a universal lower asymptote (e.g., Tanner Stage 1), β_0; a universal upper asymptote (e.g., Tanner Stage 5), β_1; an individual-specific rate of growth, α_i, that captures the tempo or speed, with respect to age, at which an individual progresses from the lower to upper asymptotes; an individual-specific centering term, λ_i, that indicates the timing or age at which individual i is exactly halfway between the lower and upper asymptotes (i.e., Tanner Stage 3); and a time-specific residual, r_{ti}. The time-specific residual was assumed to follow a normal distribution with zero mean and constant variance, σ_r^2. Individual-specific parameters (from the Level 1 model given in Equation 1) were modeled at Level 2 as $\alpha_i = \gamma_{00} + u_{0i}$ and $\lambda_i = \gamma_{10} + u_{1i}$, where γ_{00} and γ_{10} are sample-level means and u_{0i} and u_{1i} are individual deviations in tempo and timing, respectively. Individual deviations were assumed to follow multivariate normal distributions with zero means, variances (σ_{u0}^2 and σ_{u1}^2), and a covariance ($\sigma_{u0,u1}$). The lower and upper asymptotes (β_0 and β_1) were fixed to 1 and 5, respectively, because all individuals' pubertal development progressed from a prepubescent state (TStage = 1) to full sexual maturity (TStage = 5) over time, even if the entire scope of the developmental process was not observed in some adolescents (see Table 1). Thus, even if individuals were already past Stage 1 (left censored) or never reached Stage 5 (right censored) when assessed, the model projects backward or forward to the individual's prepubescent beginnings and full sexual maturity endings.

Using SAS PROC NLMIXED (see Appendix for script; with further details and mixed-model and structural equation model [SEM] syntax examples[2] provided in Grimm & Ram, 2009a; Ram & Grimm, 2007), we fitted the model separately to girls' and boys' data to obtain the sample-level prototypical trajectory (fixed effects) and, through calculation of Bayes empirical estimates (see Littell, Milliken, Stroup, & Wolfinger, 2006), individual-level parameters. Specifically, we obtained model-derived scores for timing, λ_i, and tempo, α_i, for each individual for each pubertal measure (i.e., breasts for girls, genitals for boys, pubic hair for both).[3] Timing scores provide a measure of the predicted age at which an individual has achieved Tanner Stage 3. Tempo scores indicate the speed at which an individual progresses from Tanner Stage 1 to Tanner Stage 5. We fit the nonlinear mixed-effects model described in Equation 1 directly to the observed longitudinal data using participants' exact age at assessment, with standard missing-at-random assumptions (Little & Rubin, 1987).

Association between timing and tempo—In addition to the prototypical and individual timing and tempo of pubertal development, we examined the relation between these two aspects of change. In particular, we were interested in whether and how timing was associated with tempo (quantified at Tanner Stage 3), as indicated by the significance and sign (positive or negative) of the covariance between interindividual differences in timing, u_{0i}, and tempo, u_{1i} (i.e., $\sigma_{u0,u1}$).

Relation of timing and tempo to physical and psychological outcomes—In the final set of analyses, we examined how the pubertal timing and tempo scores were related to a set of external criterion or outcome variables. At the general level, we examined whether and how the interindividual differences in timing and tempo were associated with interindividual differences in BMI, height, and weight at age 12.5 and internalizing, externalizing, and risky sexual behavior at age 15.5. Specifically, the empirically derived Bayes estimates for timing and tempo for each individual were extracted from the nonlinear mixed-effects models and used as predictors (main effects and interaction) in linear regression analyses (with the identical pattern of results being obtained within an SEM

[2]Note that an inherently nonlinear mixed-effects model cannot be directly estimated in the SEM. However, the model used here (Equation 1) can be approximated in the SEM framework through a first-order linearization (see Browne, 1993; Browne & Du Toit, 1991).

[3]In implementation three boys and two girls were found to have estimated parameters that were extreme outliers. These cases were examined in detail, found to have a missing data pattern that led to extreme bias, and subsequently removed, and the analysis was rerun. The general pattern of findings did not differ with or without inclusion.

framework where the growth curve and regression parameters were estimated simultaneously). Given collinearity across secondary sex characteristics (e.g., parallel developmental course of secondary sex characteristics), we regressed each outcome on each set of timing and tempo estimates (for genitals, breasts, pubic hair) separately. Significant and marginal interaction effects were probed following Aiken and West (1991) and the directionality of the pattern of effects noted. Incomplete data were deleted listwise under the previously tested missing completely at random assumption (Little, 1988).

Results

Interindividual Differences in Timing and Tempo of Puberty

For both boys and girls, and across all secondary sex characteristics, the models of logistic growth provided a better fit to the data than models of linear growth (as indicated by lower relative model fits: boys' genital development, Akaike's information criterion [AIC] = 3121.1 for logistic vs. 3589.0 for linear; boys' pubic hair development, AIC = 3120.1 vs. 3983.6; girls' breast development, AIC = 3755.8 vs. 4135.1; girls' pubic hair development, AIC = 3502.4 vs. 4046.8). Results from the logistic growth mixed-effects models are given in Table 3, with correspondent prototypical and individual trajectories plotted in Figure 2. How the obtained individual trajectories mapped on to the raw data of nine select individuals representing various combinations of slow, average, and fast tempo and early, average, and late timing is shown in Figure 3. The heterogeneity of timing and tempo was clearly evident.

Boys' genital development—As seen in Table 3, White boys, on average, were estimated to be in Tanner Stage 3 for genital development at 12.89 years of age (average timing = γ_{10}) and progressing through the stages at a rate of 0.85 Tanner stages per year (evaluated at the inflection point; average tempo = γ_{00}), as shown by the bold line in Figure 2. It should be noted that the tempo of pubertal maturation necessarily changes across development in accordance with the sigmoid shape of the logistic function on which the growth model was based—slow at the extremes and fastest at the middle. Tempo scores can be calculated at any point of interest on the curve (Biesanz, Deeb-Sossa, Papadakis, Bollen, & Curran, 2004; Rovine & Molenaar, 1998) but should be compared across persons (assessment of interindividual differences) at the same location. The common location (i.e., intercept) in our model is the inflection point, Tanner Stage 3, and represents the point of most rapid growth for all persons.

Of primary interest here was the extent of individual differences in timing and tempo as indicated by the significance of the variance components (random effects). For boys' genital development, there were significant interindividual differences in both timing ($\sigma_{u1}^2=0.799$, $p < .01$) and tempo ($\sigma_{u0}^2=0.068$, $p < .01$). As per the Bayes empirical estimates, boys' timing of genital development covered roughly a 4.2-year period between the time the earliest maturers were estimated to be in Stage 3 at 11.05 years of age and the time the latest maturers were estimated to be in Stage 3 at 15.28 years of age. Tempo scores ranged from 0.29 to 1.25 Tanner stages per year (at the inflection point, i.e., entry to Stage 3). Said differently, the slowest maturer was predicted to take approximately 13.7 years[4] to reach Tanner Stage 4 once entering Tanner Stage 2 (across the entire period of observation, this individual's Tanner stage scores for genital development progressed from 1 at the initial

[4]The same individual's Tanner stage scored for genital development progressed from 1 at the initial observation (age 9.5) to 2 at the last observation (age 15.5). Given ambiguity as to whether this difference and the resulting predictions reflect errors of measurement or a particularly slow development, we have kept the report in the data.

observation to 2 at the last observation), whereas the fastest maturer was estimated to take only about 1.7 years. Individual trajectories are depicted by gray lines in Figure 2.

Boys' pubic hair development—Consistent with expectations, boys' development of pubic hair began, on average, later and proceeded more quickly than their genital development. Average estimated age at entry to Stage 3 for pubic hair was 13.27 years of age, and average tempo was 1.04 Tanner stages per year (at the inflection point). As with genital development, there were significant interindividual differences in the timing and tempo of pubic hair development. Timing covered approximately 4.4 years, ranging from 11.40 to 15.76 years of age ($\sigma^2_{u1}=0.859$, $p < .01$), and tempo (instantaneous rate of change at the inflection point) ranged from 0.03 to 1.67 Tanner stages per year ($\sigma^2_{u0}=0.132$, $p < .01$).

Girls' breast development—There were significant interindividual differences in both timing ($\sigma^2_{u1}=1.117$, $p < .01$) and tempo ($\sigma^2_{u0}=0.054$, $p < .01$) for girls' breast development. Average timing for girls' breast Stage 3 was 12.08 years of age, and average tempo was 0.78 Tanner stages per year. As per the Bayes empirical estimates, girls' timing of breast development covered roughly a 5-year period from 9.71 to 14.64 years of age, with instantaneous rates of change ranging from 0 to 1.19 Tanner stages per year (at the inflection point).

Girls' pubic hair development—Girls' development of pubic hair on average began later than girls' breast development, though pubic hair development also progressed more slowly than breast development. On average, girls' timing of pubic hair Stage 3 occurred at 12.21 years of age, and average tempo was 0.87 Tanner stages per year. Timing of estimated entry to Stage 3 for girls' pubic hair covered the 4.7 years from 9.90 to 14.59 years of age ($\sigma^2_{u1}=1.109$, $p < .01$), and tempo (at the inflection point) ranged from 0.44 to 1.31 Tanner stages per year ($\sigma^2_{u0}=0.047$, $p < .01$).

Association Between Timing and Tempo

Boys—Among boys, timing and tempo (as quantified at the inflection point) were negatively correlated for both genital development and pubic hair development. In both cases, boys who tended to have faster tempo were, to some extent, younger when they reached Tanner Stage 3 ($\sigma_{u0,u1} = -0.101$ vs. -0.081, *p*s < .01; $r = -.44$ vs. $-.24$, for genital and pubic hair, respectively).

Girls—In contrast, among girls, timing and tempo of breast and pubic hair development were not associated at a level significantly different from zero ($\sigma_{u0,u1} = 0.004$ vs. 0.008, *p*s > .05; $r = .02$ vs. .04, respectively).

Relation of Timing and Tempo to Physical Characteristics

Using linear regressions, we examined whether the timing and tempo of development of each secondary sex characteristic and the Timing × Tempo interaction were predictive of physical characteristics at 12.5 years of age. Specific results appear in Tables 4 and 5 for boys and girls, respectively.

For boys, interindividual differences in timing and tempo of genital and pubic hair development were generally predictive of differences in physical characteristics, Fs(2, 287–292) = 2.69–56.17, *p*s < .05. Given that only one marginally significant ($p = .09$) interaction effect was found, we focus primarily on the main-effects-only models for each outcome (Model 1 in Table 4). Specific results indicate that for genital development, faster tempo was significantly associated with higher BMI *z* scores (β = .15, $p < .05$) at age 12.5, and earlier timing was associated with greater weight for age (β = −.17, $p < .05$) and height for age (β = −.46, $p < .01$). Interindividual differences in tempo of boys' pubic hair development were not significantly related to interindividual differences in BMI *z* score, weight for age, or height for age (βs < .08, *p*s > .05) at age 12.5. But timing of boys' pubic hair development was related to all three outcomes. As with genital development, earlier timing of pubic hair was associated with marginally higher BMI *z* scores (β = −.11. $p < .10$) and significantly higher weight for age (β = −.30, $p < .05$) and height for age (β = −.53, $p < .05$). It should be noted that given the positive collinearity, genital and pubic hair development is likely explaining some of the same variance across physical outcomes.

For girls, interindividual differences in timing and tempo of breast and pubic hair development were also generally predictive of differences in BMI *z* score, height for age, and weight for age, *F*s(2, 299–302) = 42.14–107.10, *p*s < .01. Specific results indicate that for breast development, tempo was not significantly associated with age 12.5 BMI *z* score, weight percentile, or height percentile, whereas timing did relate significantly to these physical characteristics. Specifically, earlier timing of breast development was associated with higher BMI *z* scores (β = −.54, $p < .01$), weight for age (β = −.65, $p < .01$), and height for age (β = −.52, $p < .01$). In contrast to that of boys, tempo and timing of girls' pubic hair development were both significantly related to interindividual differences in BMI *z* score, weight for age, and height for age. As elsewhere, faster tempo (BMI: β = .11, $p < .05$; weight for age: β = .17, $p < .01$; height for age: β = .22, $p < .01$) and earlier timing (BMI: β = −.46, $p < .01$; weight for age: β = −.59, $p < .01$; height for age: β = −.53, $p < .01$) were each independently associated with greater size at 12.5 years of age.

Relation of Timing and Tempo to Behavioral Outcomes

Linear regressions were also used to examine whether and how timing and tempo of development of each secondary sex characteristic were predictive of internalizing and externalizing behavior problems and risky sexual behaviors at 15.5 years of age. Specific results are presented in Tables 6 and 7 for boys and girls, respectively.

CBCL–YSR internalizing behavior—No significant associations were found between boys' timing and tempo of genital or pubic hair development and the CBCL–YSR internalizing behavior composite, $F(2, 333) < 0.40$, *p*s > .05.

Girls showed significant main effects of timing and tempo (for both breast and pubic hair development) on levels of CBCL–YSR internalizing behavior at age 15.5, *F*s(2, 325–349) > 7.38, *p*s < .01. Specifically, earlier timing and faster tempo were associated with more internalizing behavior problems (β = −.18, $p < .01$, and β = .10, $p < .06$, for breast timing and tempo; β = −.21, $p < .01$, and β = .11, $p < .05$, for pubic hair development).

SSRS internalizing behavior—A similar pattern of no association was found for boys' internalizing problems measured with the SSRS.

For girls, patterns observed for the SSRS internalizing measure were consistent with those captured by the CBCL–YSR. Girls experienced significantly more internalizing behavior at age 15.5 when their timing of breast development was earlier (β = −.12, $p < .05$) and marginally more internalizing when their tempo of breast development was faster (β = .10, $p < .07$). For girls' pubic hair development, earlier timing was marginally associated with more internalizing (β = −.10, $p < .06$), and faster tempo was significantly associated with more internalizing (β = −.13, $p < .05$).

CBCL–YSR externalizing behavior—For boys, faster genital development was significantly associated with more externalizing behavior (β = −.13, $p < .05$) as measured by the CBCL–YSR. Nonetheless, the overall model failed to reach statistical significance, $F(2, 333) = 1.95$, $p = .14$. Pubic hair development was not significantly related to CBCL–YSR externalizing for boys.

For girls, in contrast, the timing and tempo of breast and pubic hair development were both significantly related to externalizing behavior. Specifically, girls exhibited marginally more externalizing behavior at age 15.5 when their timing of breast development was earlier (β = −.10, $p = .052$) and significantly more externalizing when their tempo of breast development was faster (β = .15, $p < .05$). For girls' pubic hair development, earlier timing and faster tempo were both significantly associated with more externalizing (timing: β = −.12, $p < .05$; tempo: β = .15, $p < .05$).

SSRS externalizing behavior—Contrary to findings from the CBCL–YSR measure, there was a relation between boys' pubic hair development and externalizing behavior as measured with the SSRS. This association was driven not by timing or tempo independently but by the interaction between the two. The model that included the interaction (Model 2) explained significantly more variance than the main-effects-only counterparts (Model 1), $\Delta F(1, 329) = 4.00$, $p < .05$. The pattern of results suggested that for boys with earlier pubic hair development, a faster tempo was associated with relatively more externalizing behavior, whereas for later developers, a faster tempo was associated with relatively fewer externalizing behaviors (β for the interaction = −.13). The resulting interaction effect is shown in Figure 4.

For girls, a simpler pattern was found compared with that of boys. Overall significance of associations between tempo and timing and level of SRSS externalizing behavior at age 15.5 was present for girls' breast development, $F(2, 347) = 4.31$, $p < .05$. Specifically, faster tempo of breast development was associated with more externalizing behavior problems (β = .15, $p < .01$). For girls' pubic hair development, the same significant effect was housed within a marginally significant model, $F(2, 344) = 2.71$, $p = .07$; β = .12, $p < .05$.

Risky sexual behavior—Among boys, overall significance of associations between tempo and timing and level of risky sexual behavior at age 15.5 was present only for boys' genital development, $F(2, 326) = 3.24$, $p < .05$. Specifically, earlier timing of genital development predicted more risky sexual behavior (β = −.13, $p < .05$). Neither the tempo of development nor the interaction of timing and tempo of genital development predicted risky sexual behavior. Timing and tempo of pubic hair maturation did not predict risky sexual behavior for boys, $F(2, 326) = 1.36$, $p = .26$.

For girls, overall significance of associations between timing and tempo and level of risky sexual behavior at age 15.5 was present for girls' breast and pubic hair development, Fs(2, 340–343) > 4.37, ps < .05. Specifically, earlier timing of breast and pubic hair development was associated with more risky sexual behavior (β = −.14, $p < .05$, and β = −.21, $p < .01$, respectively). Neither the tempo of breast or pubic hair development nor the interaction of timing and tempo of breast or pubic hair development predicted risky sexual behavior.

Discussion

This report described interindividual differences in the timing and tempo of pubertal development and examined the associations between timing and tempo and indices of adolescents' physical growth and behavioral outcomes. The analysis capitalized on the availability of data from an existing, large sample of White boys and girls from 10 sites throughout the United States. Making use of nonlinear mixed-effects models, these findings are among the first to describe individual differences in timing and tempo of pubertal development based on a theoretical model that considers the nonlinear nature of changes during the child-to-adolescent transition.

Interindividual Differences in Timing and Tempo of Puberty

The first aim was to derive and examine individual differences in the timing and tempo of pubertal development among both boys and girls. Previous examinations of pubertal trajectories have assumed and modeled pubertal progression as a linear process. Following the initial work of Susman, Houts, et al. (2010), we used nonlinear growth models (Grimm & Ram, 2009a; Ram & Grimm, 2007) to model the progression of pubertal development in a manner consistent with existing theory. Specifically, we modeled individuals' progression through the Tanner stages as following a form characterized by an elongated S shape, a logistic growth function. For both boys and girls, and across all secondary sex characteristics, this model provided a better representation of the pubertal data than linear growth models, and provided both individual-level and sample-level description of the timing and tempo of development.

With respect to timing, boys, on average, achieved Tanner Stage 3 at ages 12.89 and 13.27 for genital and pubic hair development, respectively. In contrast, girls, on average, achieved Tanner Stage 3 at ages 12.08 and 12.21 for breast and pubic hair development, respectively. This finding of earlier pubertal timing for girls replicates previous work (Lee, 1980; Susman, Houts, et al., 2010; Wheeler, 1991). With respect to tempo, on average, boys were changing at a rate of 0.85 (genital) and 1.04 (pubic hair) Tanner stages per year (evaluated at the inflection point), whereas girls were changing at a rate of 0.78 (breast) and 0.87 (pubic hair) Tanner stages per year. These values are generally consistent with work by Marshall and Tanner (1969, 1970) for genital (on average, 0.96 Tanner stages per year from Stage 2 to Stage 4) and breast development (0.87) but showed slower pubic hair development (on average, 0.43 Tanner stages per year from Stage 2 to Stage 4 for boys, 0.56 for girls). There was significant interindividual differences in tempo of development, consistent with previous reports (Marshall & Tanner, 1969, 1970; Mendle et al., 2010).

From an endocrinology perspective, these results confirm evidence of differential timing of the reactivation of the hypothalamic–pituitary–gonadal axis and subsequent stimulus of sex steroids that are primarily responsible for the development of breasts, gonads, and pubic hair. As did Susman, Houts, et al. (2010) in their analysis of the same data, we found that for some adolescents, pubertal development begins relatively early, and for others it begins relatively late. As a follow-up, we examined correlations between our average timing and tempo parameters with Susman et al.'s previous estimates of age at Tanner Stage 3 and age at menarche for girls. The interindividual differences in timing of puberty obtained here aligned well with the previous estimates of age of achieving Tanner Stage 3 (*r*s $\approx$ .87 for breast and boys' and girls' pubic hair development, and r = .83 for boys' genital development) and, among girls, aligns with differences in age of menarche (r = .64 for breast development, r = .67 for pubic hair development). However, as expected, the within-person methods highlighted here provide a slightly different picture than obtained with the between-person and menarche methods. Our estimates of average timing were generally a few months later than those reported in Susman et al. Nevertheless, findings were markedly consistent for using different modeling techniques.

In addition to confirming previous knowledge about timing, we provide important additional information about the extent of individual differences in tempo of pubertal development. As they get developed, the tempo measures may become particularly useful for pediatricians and other health care professionals as a way to evaluate the pace of pubertal development.

After replication in more heterogeneous, population-based samples, such measures could provide the basis for benchmarks and ranges of normally paced pubertal maturation.

Association Between Timing and Tempo

The models used here provided empirical evidence that some individuals progress through puberty relatively slowly, whereas others progress relatively quickly. Our models also provided an indication of the relation between timing and tempo. Among girls, timing and tempo of both breast and pubic hair development were uncorrelated, suggesting independence of the underlying endocrine factors involved in timing and tempo. These findings are inconsistent with Pantsiotou et al. (2008), who reported an inverse relation between onset of puberty and time to peak height velocity; Biro et al. (2001), who showed an inverse relation between timing and menarche in girls; and Mendle et al. (2010), who showed an inverse relation between latent timing and tempo parameters extracted from linear growth models. However, these findings are consistent with Huang et al. (2009), who showed no relation between timing of puberty and peak height velocity in girls. The methods used to measure pubertal timing and tempo, and the age ranges used to quantify tempo in each of these reviewed studies, vary. Because pubertal tempo varies across development as indicated in the present study and others (e.g., Eaves et al., 2004; Marshall & Tanner, 1969, 1970; Susman, Houts, et al., 2010; Tanner, 1971), we may find the association between the timing and tempo of puberty changes across development. In sum, further investigation of the interrelation of timing and tempo of girls' pubertal development is needed.

In contrast, among boys, and for both genital and pubic hair development, we found that timing and tempo were inversely related, suggesting a common endocrine mechanism whereby boys tend to move through puberty more quickly if they start earlier. Overall, our findings on timing and tempo of puberty indicate that puberty does not progress in the same way for boys and girls, and that examining both timing and tempo may be especially salient to describe the pubertal process in boys. We note, though, that it is difficult to compare the current findings directly with the previous findings given that the method for estimating timing and tempo simultaneously is unique to this report.

Relation of Timing and Tempo to Physical Characteristics and Behavioral Outcomes

Finally, we examined how variations in timing and tempo related to physical characteristics (BMI, height, and weight) and behavioral outcomes (internalizing, externalizing, and risky sexual behavior). As expected, and in line with previous studies (e.g., Davison et al., 2003), our pattern of results indicated that timing of pubertal development was related to degree of physical maturation in both boys and girls. Earlier timing was predictive of greater size at 12.5 years of age. Tempo was also related to degree of physical maturation in both boys and girls, but in different ways. Among boys, tempo of genital development was related to physical size at age 12.5 (BMI), whereas tempo of pubic hair development was not. In contrast, among girls, the tempo of pubic hair development was related to physical size at age 12.5 (BMI, weight, and height), whereas tempo of breast development was not.

The findings regarding timing confirm previous findings regarding the association between physical maturation and pubertal maturation and provide some external validity for our measures of timing and tempo of puberty. Timing of puberty is controlled to a large degree by genes that activate gonadotropin-releasing hormone and the cascade of hormones that influence height and weight. Tempo may be influenced by different factors, such as prenatal growth (van Weissenbruch & Delemarre-van de Waal, 2006). The new findings regarding tempo of pubertal development and physical characteristics indicate the need to examine the endocrine and genetic mechanisms involved in the tempo of pubertal development—which to date have not been examined.

Our findings also show that puberty is associated with internalizing and externalizing problems in girls but only externalizing problems in boys. Differences in the patterns of results for boys versus girls suggest that different mechanisms are responsible for the associations in boys compared with girls. For girls, both earlier timing and faster tempo are associated with more internalizing problems. These findings are fairly consistent across measures of internalizing behavior. However, there was some evidence that tempo of pubic hair development was more predictive of internalizing behavior than tempo of breast development, whereas timing of breast development was more predictive of internalizing behavior than the timing of pubic hair development. This further underscores differences between the endocrine processes underlying timing and tempo and suggests that the timing and tempo of each hormonal axis may differentially affect behavior problems during adolescence.

Findings regarding externalizing problems were somewhat mixed for girls. With the CBCL–YSR, both earlier timing and faster tempo were associated with more externalizing problems; with the SSRS, in contrast, only a faster tempo—not earlier timing—was associated with more externalizing problems. This could reflect differences in the measures assessing externalizing behavior. A possible source of these differences is that the CBCL–YSR included youth self-reported externalizing behavior, whereas the SSRS did not. Girls may be particularly sensitive to the timing of puberty, surfacing in the reports of their own externalizing behavior.

The findings for timing of puberty were consistent with past research on earlier timing and behavior problems in girls (Angold, 2003; Caspi et al., 2003; Ge et al., 2003; Graber et al., 2004; Hayward et al., 1997). For girls, the developmental readiness hypothesis was supported for both internalizing and externalizing problems. Though the developmental readiness hypothesis applies mainly to early adolescent development, a faster and more compressed development also appears to lead to behavior problems, specifically externalizing problems.

For boys, timing and tempo only sparsely predicted internalizing or externalizing problems. No consistent significant relationship was found between pubertal development and internalizing problems. Faster genital tempo predicted more CBCL–YSR externalizing behaviors, and the interaction between pubic hair timing and tempo was associated with SSRS externalizing behaviors, such that boys with earlier timing and faster tempos experienced the most problems and boys with later timing and faster tempos experienced the least problems.

The findings for CBCL–YSR externalizing behavior in boys support the developmental readiness hypothesis. However, the interaction of timing and tempo of pubic hair development supported the maturational deviance hypothesis by demonstrating that boys with early and late timing experience more externalizing behavior on the SSRS, depending on the tempo of their development. Of course, this finding does not preclude the developmental readiness hypothesis, as the two hypotheses overlap in prediction to some extent. These differences could also reflect differences in the measures assessing externalizing behavior. For example, the CBCL–YSR assessed many externalizing behaviors in a questionnaire asking specifically about a wide variety of problem behaviors. However, the SSRS assessed fewer externalizing behaviors embedded within questions asking about general social skills as opposed to purely problematic behaviors in a general context. Thus, participants may have rated externalizing behavior pertaining to social situations on the SSRS but externalizing behavior across multiple contexts or more generally on the CBCL–YSR. If this is the case, then the context of externalizing behavior may be particularly important for the associations between pubertal maturation and externalizing problems in boys.

Our findings help to explain why the literature is reliably inconsistent when examining the association between earlier puberty and behavior problems in boys. For boys, the tempo of development, and the interaction between timing and tempo, showed that going through puberty faster or earlier and faster than peers was a risk factor for externalizing problems at age 15.5. Had only timing been examined, the conclusion would be that timing does not predict behavior problems for boys; it is the combination of the timing and tempo trajectory that is a risk for externalizing problems in boys. Studies only examining timing in boys may contribute inconsistent findings depending on the strength of the association between timing and tempo, either inflating or deflating the association between timing and psychological development for boys.

For risky sexual behavior, only early timing of pubertal maturation was associated with risky sexual behavior for boys (genital development) and girls (breast and pubic hair development). This suggests that the mechanisms linking pubertal maturation and risky sexual behavior are similar for boys and girls. Both boys and girls engage in risky sexual behavior in middle adolescence when they begin their pubertal maturation relatively earlier. The common interpretation is that the social stimulus value of a relatively young, physically mature adolescent attracts the opposite sex. But in both animal and human model studies, increases in testosterone and estrogen are known to increase interest in sexual activities (Finkelstein et al., 1998). Collectively, the findings indicate that early timing is a risk factor and potential marker for early intervention to prevent sexual activities with untoward effects.

Modeling and Assessment

Importantly, our analytical approach provides a novel and elegant framework for quantifying and examining the substantial heterogeneity in both when and how quickly pubertal development proceeds for both boys and girls. Additionally, the logistic growth mixed-effects model allowed for examination of the association between interindividual differences in timing and tempo of puberty. Benefits of this model were the correspondence of the model to the bounded, monotonic nature of pubertal development and the straightforward manner in which the parameters mapped onto conceptual notions of timing and tempo. The analytic framework provided a statistically sophisticated way to extract and examine individual differences in the timing and tempo of puberty, while maintaining the theoretically derived (sigmoid) shape of pubertal development.

Of course, the model and framework still carry with them some perhaps overly restrictive assumptions. Our study sample was composed entirely of White youth. Whereas the homogeneity was helpful for model development, future studies should strive for greater representativeness of race and ethnicity and allow for and examine possible differences among subpopulations. For example, Susman, Houts, et al. (2010) suggested that there are racial differences in girls' timing but not tempo of puberty and in boys' timing and tempo of puberty. Further, in the absence of nonage-based criteria evaluating the relative spacing of Tanner stages, we relied on the usual assumption that Tanner stages are measured on an interval-level measurement scale. That is, the developmental distance between Tanner stages is equivalent (e.g., distance, or amount of change, between Stages 2 and 3 is the same as the distance between Stages 4 and 5). Additional work is needed to develop more objective criteria for measuring level of pubertal development in a manner that actually taps into the endocrine events driving the process.

On a related note, the mathematical structure of the model led to an evaluation of interindividual differences at an inflection point located at Tanner Stage 3—an intercept at the middle of the 5-point (continuous) scale. Substantively, it is not clear whether Tanner Stage 3 should actually be considered the midpoint of all the biological processes involved in pubertal development. After all, secondary sex characteristics are only one of many potential indicators of neuroendocrine biology. Methodologically, the model can be reparameterized to relocate the intercept at any desired location along the curve (see Ram & Grimm, 2007; Rovine & Molenaar, 1998), and the interindividual differences in tempo reexamined from a somewhat different perspective, without any change in model fits.

The logistic growth mixed-effects model makes a key assumption about the shape of growth. A defining feature of the logistic function is that there is symmetry to the growth pattern such that progression through the first two stages, from Stage 1 to Stage 3, takes the same amount of time as progression through the last two stages, Stage 3 to Stage 5. This may or may not map to reality. For example, the estimated length of time between stages was, on average, 2 years from Stages 2 to 3 but only about 1.1 years from Stages 3 to 4 (Susman, Houts, et al., 2010). We chose this model as a first step in tethering the theorized nonlinearity of pubertal development to an appropriate analytical framework and conducted the analysis in a top–down manner (theory to method). Further study is needed to determine whether the pattern of changes occurring during the early phases of puberty matches the pattern of changes occurring during the later phases of puberty and to determine the most useful metrics for quantifying tempo and timing (see, e.g., surge area reparameterization in Choi, Harring, & Hancock, 2009; modeling Tanner stages as ordinal outcomes in Huang, Biro, & Dorn, 2009).

Bottom–up (method to theory) approaches in which many functional forms are fitted to the data and relative fits are compared will be extremely useful in identifying a common set of shapes that can be used to accurately describe the pattern of observed changes and the interindividual differences therein (see, e.g., Grimm & Ram, 2009a; Muthén & Shedden, 1999; Nagin & Odgers, 2010; Ram & Grimm, 2009; Ram, Grimm, Gatzke-Kopp, & Molenaar, in press). For example, asymmetrical nonlinear growth functions (e.g., Gompertz and Richards functions; see Grimm & Ram, 2009a) and nonlinear growth mixtures (see Grimm, Ram, & Estabrook, 2010) may provide even more accurate representations of pubertal development and the (quantitative and qualitative) interindividual differences therein.

Of particular benefit in the model expansions is the traction gained from the framing of puberty by prepubescent beginnings and full sexual maturity endings. Although this, in some respects, disqualifies the use of linear, quadratic, and many other polynomial models, it provides access to the myriad sigmoid and asymptotic models used to model a wide variety of biological growth processes (see Grimm & Ram, 2009a, for more discussion). In the future, this modeling technique may be applied to other developmental questions, such as the growth trajectories of height and weight, and interrelations of trajectories of different types of physical growth. Beyond physical growth, we hope that the analytic techniques will be a model for the advanced modeling of other growth trajectories. For example, nonlinear models could be used for emotional development, especially in the early years, when development occurs possibly more rapidly than later in life. Nonlinear models have also been used to model change in cognitive development, including the rate of decline of errors in speech across early childhood (e.g., Burchinal & Appelbaum, 1991), learning tasks (e.g., Browne & Du Toit, 1991), and letter–word identification in early elementary school (e.g., Grimm & Ram, 2009a).

As researchers make progress on modeling the nonlinear nature of the developmental process of puberty, they shall soon run into the limitations of the data. In the SECCYD, pubertal development was assessed through observation of secondary sex characteristics over 6 years, at 1-year intervals. Such an assessment schedule is likely to miss many of the nuances and spurts that characterize many growth processes. To obtain a more complete picture, especially during the periods of most rapid development, more regular assessments may be necessary. For example, to extract asymmetries in the shape of the sigmoid curve, researchers may need assessments every 6 months, and ideally some biologically based markers obtained from saliva and blood. Of course, more frequent and invasive assessments are likely necessary to get the intensive data streams needed. However, the current sample already suffered from attrition, even assessing on a yearly basis. Researchers do not yet have the answers on how to balance the data needs with the attrition consequences.

In conclusion, the findings described here are useful in understanding variation in the timing and tempo of development in secondary sexual characteristics among White youth. The simultaneous modeling of timing and tempo of pubertal development indicates that puberty is not strictly linear but may progress in a sigmoidal manner. In addition, the findings indicate that tempo is important to consider in relation to the development of internalizing and externalizing problems, particularly for girls. The findings will be useful to developmentalists interested in preventing the upsurge in behavioral problems during early adolescence as they add the almost entirely underresearched dimension of tempo. Future research will profit from simultaneously including both timing and tempo in the modeling of pubertal change and how those changes are related to changes in behavior. Replication of the findings in a representative sample and exploration of possible asymmetries in pubertal development are now warranted.

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Appendix A. Sample Programming Script for Fitting Nonlinear Mixed-Effects Logistic Growth Model in SAS

Note: Data must be in long (i.e., person-period) format (see Grimm & Ram, 2009a). Uppercase text indicates SAS commands. Lowercase text indicates data-specific variables and model parameters. Comments are indicated with an asterisk. The outcome variable, *tstage*, is the variable containing the repeated measures of individuals' pubertal development (in this example, Tanner stage of boys' genital development).

```
*Model for Boys' Genital Development;
PROC NLMIXED DATA = datalong;
TITLE1 "Logistic Model random effects lambda, alpha";
*Model constraints;
b0 = 1; *lower asymptote = 1 for all persons;
b1 = 5; *upper asymptote = 5 for all persons;
*Nonlinear mixed effects model equation;
traject = b0 + (b1-b0)*(1/(1 + exp(-alpha*(age-lambda))));
*Model;
MODEL tstage ~ NORMAL(traject, v_e);
*Random effects (and output of individual-level estimates);
RANDOM alpha lambda ~ NORMAL([m_alpha, m_lambda], [v_alpha, cov_alam,
v_lambda])
SUBJECT=id OUT=out_individestimates;
*Starting values;
PARMS m_alpha = .9
m_lambda = 13.5
v_e = 1.0
v_alpha = 1.0
cov_alam = –.3
v_lambda = 1.5;
*Output of model fit and parameter estimates;
PREDICT traject OUT=out_individpredscore;
ODS OUTPUT FITSTATISTICS=out_fit
PARAMETERESTIMATES=out_sampleparms;
RUN;
```

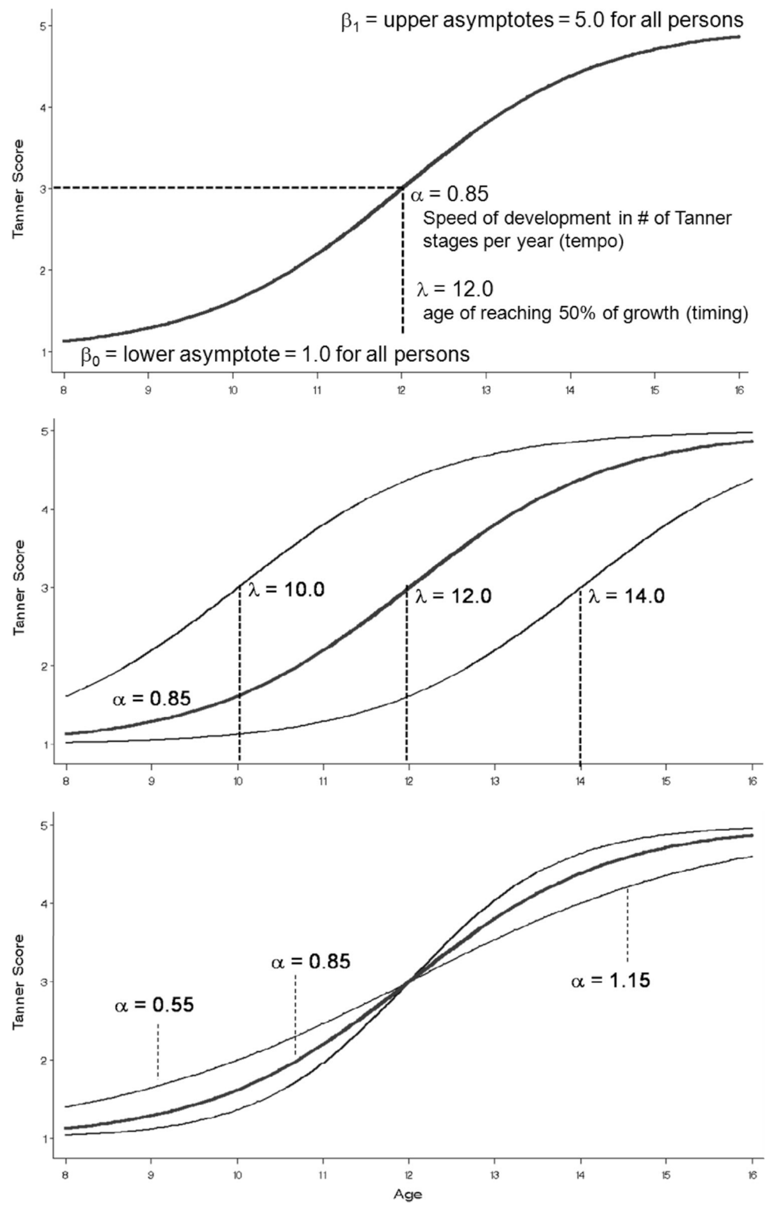

Figure 1.

Logistic growth model. β_0 describes the level of the lower asymptote of the curve, with all persons beginning in Tanner Stage 1 (prepubescence). β_1 describes the level of the upper asymptote, with all persons ending in Tanner Stage 5 (sexual maturity). α describes the slope of the curve at the inflection point (onset of Tanner Stage 3) and is used to represent tempo. λ describes the left-to-right shift of the curve as indexed by the location of the inflection point with respect to time (age) and is used to represent timing.

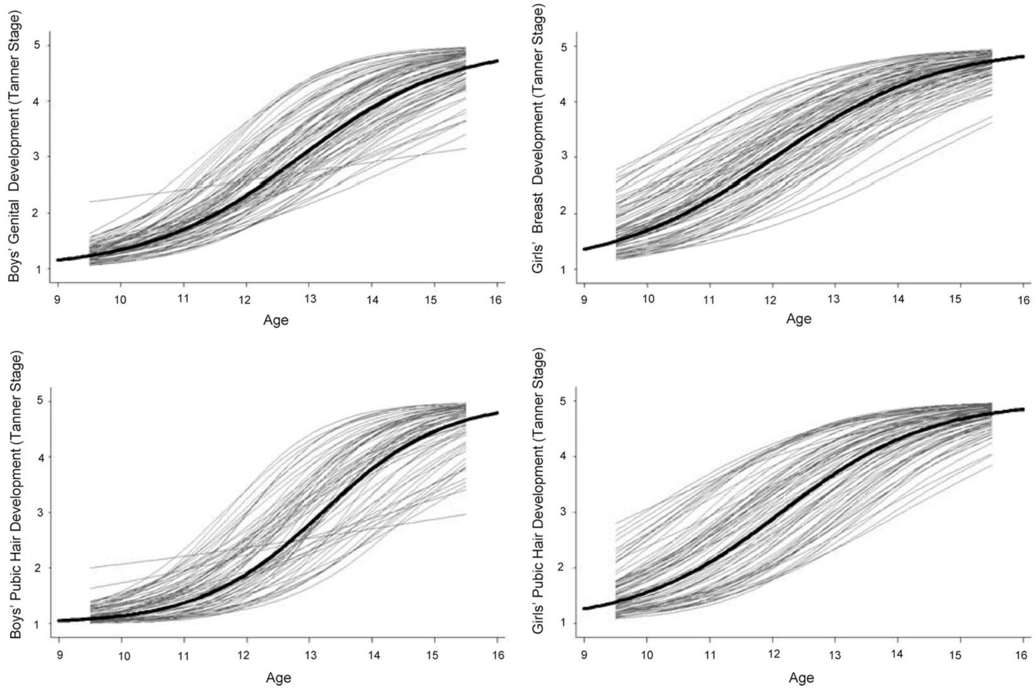

Figure 2.

Predicted pubertal development. These plots illustrate the range of individual differences in pubertal development. Prototypical logistic trajectory of development is shown in black. Predicted individual trajectories (n = 50) are shown in gray. Note: Some individuals show a linear rather than a nonlinear pattern and progress very slowly through puberty (i.e., boys' pubic hair).

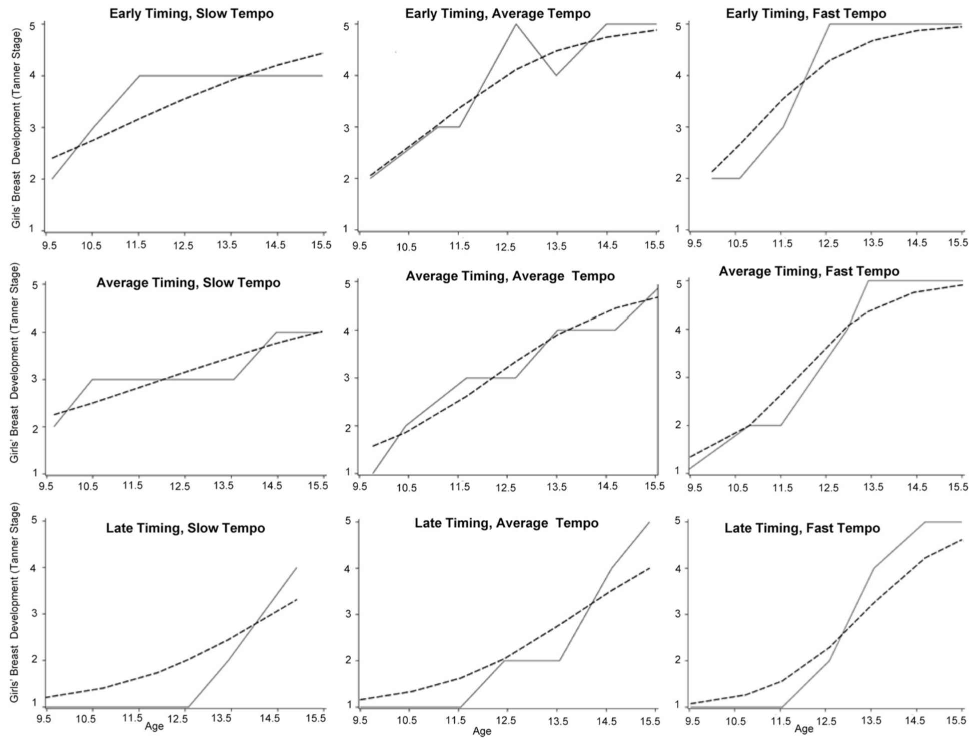

Figure 3.

Observed and predicted pubertal development. These plots illustrate how well the fitted curve fits the observed data for nine combinations of early, average, and late timing and slow, average, and fast tempo. Girls' breast development was used for this plot. Each figure represents one individual, with the observed Tanner stage in gray and the fitted curve in black.

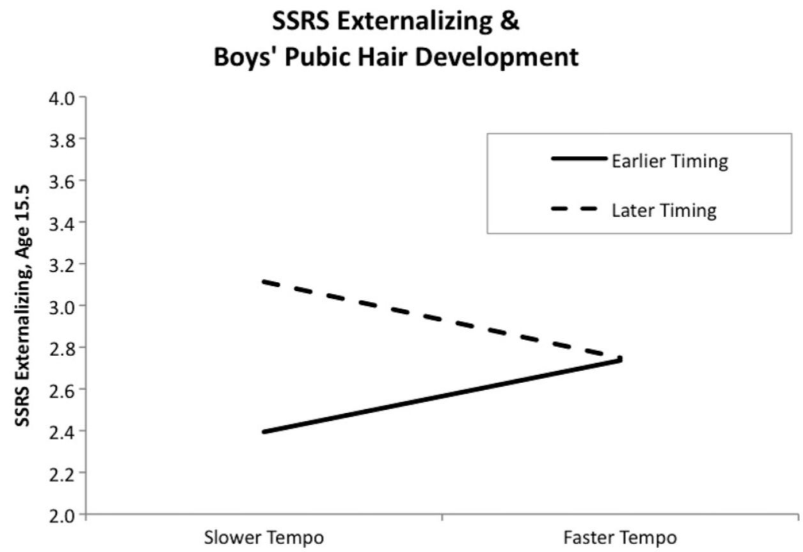

Figure 4.
Interactions of timing and tempo of pubic hair development predicting Social Skills Rating Scale (SSRS) externalizing.

Table 1

Distributions of Pubertal Stage for Boys and Girls at 9.5–15.5 Years of Age

	Boys' genital development								**Boys' pubic hair development**							
				No. youth in Tanner stage								**No. youth in Tanner stage**				
Age	***N***	***M***	***SD***	**1**	**2**	**3**	**4**	**5**	***N***	***M***	***SD***	**1**	**2**	**3**	**4**	**5**
9.5	326	1.26	0.44	241	85	0	0	0	327	1.07	0.26	303	24	0	0	0
10.5	275	1.60	0.55	117	150	8	0	0	277	1.21	0.45	225	47	5	0	0
11.5	271	2.00	0.64	53	169	46	3	0	271	1.56	0.69	148	97	24	2	0
12.5	268	2.67	0.85	15	108	98	45	2	270	2.38	0.96	55	93	88	32	2
13.5	258	3.57	0.94	2	32	84	96	44	260	3.39	1.05	9	50	66	101	34
14.5	241	4.26	0.79	0	7	31	95	108	247	4.19	0.88	2	12	29	97	107
15.5	234	4.69	0.56	0	0	11	50	173	242	4.59	0.65	0	5	6	72	159
	Girls' breast development[a]								Girls' pubic hair development							
9.5	340	1.52	0.63	194	122	23	1	0	333	1.31	0.54	240	83	9	1	0
10.5	324	2.02	0.85	98	141	72	11	2	312	1.80	0.84	137	112	52	11	0
11.5	292	2.64	0.92	33	95	118	40	6	287	2.53	0.98	46	96	97	44	4
12.5	284	3.29	0.96	8	47	115	85	29	280	3.26	0.97	4	62	99	86	29
13.5	281	4.00	0.86	0	13	64	114	90	279	3.97	0.87	0	13	71	107	88
14.5	268	4.56	0.59	0	1	11	95	161	266	4.55	0.59	0	0	13	94	159
15.5	253	4.84	0.37	0	0	1	38	214	256	4.85	0.36	0	0	0	39	217

[a] Girls with average breast development between stages are counted in the lower stage.

Table 2

Means and Standard Deviations of Outcome Variables

	Boys			Girls		
Variable	***N***	***M***	***SD***	***N***	***M***	***SD***
Physical outcomes, age 12.5 years						
BMI *z* score	287	0.50	1.12	301	0.42	1.01
Weight-for-age percentile	292	63.12	29.29	302	64.25	28.48
Height-for-age percentile	288	60.61	27.20	302	58.89	28.81
Behavioral outcomes, age 15.5 years						
CBCL–YSR internalizing	333	53.31	3.52	352	53.25	3.70
CBCL–YSR externalizing	333	52.68	3.55	352	53.58	4.66
SSRS internalizing	329	3.19	1.80	347	3.48	1.86
SSRS externalizing	329	2.80	2.09	347	2.98	2.10
Risky sexual behavior	326	0.08	0.23	343	0.10	0.26

Note. BMI = body mass index; CBCL = Child Behavior Checklist; YSR = Youth Self Report; SSRS = Social Skills Rating Scale.

Table 3

Logistic Growth Models for Boys' and Girls' Genital or Breast and Pubic Hair Development

	Boys				Girls			
	Genital (*N* = 364)		Pubic hair (*N* = 364)		Breast (*N* = 373)		Pubic hair (*N* = 370)	
Parameter	**Estimate**	***SE***	**Estimate**	***SE***	**Estimate**	***SE***	**Estimate**	***SE***
Fixed effects								
Timing, γ_{10}	12.893**	0.051	13.273**	0.046	12.083**	0.057	12.208**	0.055
Tempo, γ_{00}	0.847**	0.017	1.041**	0.020	0.777**	0.015	0.865**	0.015
Lower asymptote, β_0	1		1		1		1	
Upper asymptote, β_1	5		5		5		5	
Random effects								
Timing variance, σ^2_{u1}	0.799**	0.078	0.859**	0.081	1.117**	0.099	1.109**	0.097
Tempo variance, σ^2_{u0}	0.068**	0.011	0.132**	0.020	0.054**	0.009	0.047**	0.008
Timing–tempo covariance, $\sigma_{u0,u1}$	−0.101**	0.021	−0.081**	0.030	0.004	0.023	0.008	0.024
Residual variance, σ^2_r	0.190**	0.008	0.172**	0.007	0.219**	0.008	0.197**	0.008
Fit statistics								
−2 log-likelihood	3109.1		3108.1		3743.8		3490.4	
AIC	3121.1		3120.1		3755.8		3502.4	

** $p < .01$.

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Table 4

Relationship Between Pubertal Timing and Tempo and Boys' Physical Outcomes

	Genital development						Pubic hair development					
	Model 1			Model 2			Model 1			Model 2		
Variable	***B***	***SE B***	β	***B***	***SE B***	β	***B***	***SE B***	β	***B***	***SE B***	β
BMI *z* score, age 12.5 years (*N* = 287)												
Timing	0.05	0.10	.04	0.06	0.10	.04	−0.15	0.08	−.11†	−0.13	0.09	−.10
Tempo	0.87	0.40	.15*	0.83	0.41	.15*	0.30	0.24	.08	0.28	0.25	.07
Timing × Tempo				0.17	0.37	.03				0.10	0.23	.03
R^2		0.02			0.02			0.02			0.02	
F for change in R^2		2.69†			0.20			3.27*			0.20	
Weight-for-age percentile, age 12.5 years (*N* = 292)												
Timing	−6.16	2.43	−.17*	−5.98	2.48	−.17*	−10.17	1.96	−.30**	−9.98	2.21	−.29**
Tempo	15.56	10.11	.10	14.73	10.35	.10	2.44	5.99	.02	2.21	6.13	.02
Timing × Tempo				3.64	9.43	.02				1.05	5.75	.01
R^2		0.06			0.06			0.09			0.09	
F for change in R^2		9.33**			0.15			15.01**			0.03	
Height-for-age percentile, age 12.5 years (*N* = 288)												
Timing	−15.18	2.06	−.46**	−14.48	2.09	−.44**	−16.56	1.63	−.53**	−16.02	1.84	−.51**
Tempo	3.56	8.58	.03	0.43	8.74	.00	2.03	5.00	.02	1.39	5.11	.01
Timing × Tempo				13.71	7.95	.10†				3.00	4.78	.04
R^2		0.22			0.23			0.28			0.28	
F for change in R^2		41.21**			2.96†			56.17**			0.40	

Note. BMI = body mass index.

† $p < .10$.

* $p < .05$.

** $p < .01$.

Table 5

Relationship Between Pubertal Timing and Tempo and Girls' Physical Outcomes

	Breast development						Pubic hair development					
	Model 1			Model 2			Model 1			Model 2		
Variable	*B*	*SE B*	β	*B*	*SE B*	β	*B*	*SE B*	β	*B*	*SE B*	β
BMI *z* score, age 12.5 years (breast, N = 301; hair, N= 299)												
Timing	−0.55	0.05	−.54**	−0.52	0.05	−.52**	−0.47	0.05	−.46**	−0.43	0.06	−.42**
Tempo	−0.28	0.28	−.05	−0.26	0.28	−.05	0.74	0.35	.11*	0.75	0.35	.11*
Timing × Tempo				0.34	0.30	.06				0.69	0.36	.11†
R^2		0.29			0.30			0.22			0.23	
F for change in R^2		61.93**			1.21			42.14**			3.65†	
Weight-for-age percentile, age 12.5 years (breast, N = 302; hair, N = 300)												
Timing	−18.58	1.27	−.65**	−18.34	1.38	−.64**	−17.41	1.34	−.59**	−16.55	1.45	−.56**
Tempo	0.10	7.22	.00	0.31	7.24	.00	31.98	8.84	.17**	32.20	8.82	.17**
Timing × Tempo				3.54	7.83	.02				13.66	9.15	.07
R^2		0.42			0.42			0.38			0.38	
F for change in R^2		107.10**			0.20			90.90**			2.22	
Height-for-age percentile, age 12.5 years (breast, N = 302; hair, N = 300)												
Timing	−15.00	1.44	−.52**	−15.36	1.56	−.53**	−15.62	1.41	−.53**	−16.20	1.53	−.55**
Tempo	12.65	8.13	.08	12.31	8.16	.07	41.83	9.26	.22**	41.69	9.26	.21**
Timing × Tempo				−5.16	8.85	−.03				−9.16	9.65	−.05
R^2		0.27			0.27			0.33			0.33	
F for change in R^2		55.33**			0.34			71.52**			0.90	

Note. BMI = body mass index.

† $p < .10$.

* $p < .05$.

** $p < .01$.

Table 6

Relationship Between Pubertal Timing and Tempo and Boys' Behavioral Outcomes

	Genital development						Pubic hair development					
	Model 1			Model 2			Model 1			Model 2		
Variable	***B***	***SE B***	β	***B***	***SE B***	β	***B***	***SE B***	β	***B***	***SE B***	β
CBCL–YSR internalizing, age 15.5 years (N = 333)												
Timing	−0.01	0.29	.00	0.01	0.29	.00	−0.05	0.24	−.01	−0.11	0.27	−.03
Tempo	0.90	1.20	.05	0.83	1.23	.04	−0.02	0.74	.00	0.05	0.77	.00
Timing × Tempo				0.33	1.13	.02				−0.29	0.70	−.03
R^2		0.00			0.00			0.00			0.00	
F for change in R^2		0.40			0.08			0.02			0.18	
SSRS internalizing, age 15.5 years (N = 329)												
Timing	−0.04	0.15	−.02	−0.08	0.15	−.03	−0.13	0.12	−.06	−0.24	0.14	−.11†
Tempo	0.88	0.61	.09	1.00	0.63	.11	−0.09	0.38	−.01	0.08	0.40	.01
Timing × Tempo				−0.57	0.58	−.06				−0.60	0.36	−.11†
R^2		0.01			0.01			0.00			0.01	
F for change in R^2		1.79			0.96			0.52			2.86†	
CBCL–YSR externalizing, age 15.5 years (N = 333)												
Timing	0.26	0.29	.06	0.26	0.26	.06	0.20	0.24	.05	0.13	0.28	.03
Tempo	2.38	1.21	.13*	2.36	1.23	.13†	0.62	0.75	.05	0.72	0.77	.06
Timing × Tempo				0.06	1.14	.00				−0.39	0.70	−.04
R^2		0.01			0.01			0.00			0.00	
F for change in R^2		1.95			0.00			0.54			0.30	
SSRS externalizing, age 15.5 years (N = 329)												
Timing	0.33	0.17	.12†	0.27	0.17	.10	0.37	0.14	.15**	0.22	0.16	.09
Tempo	0.43	0.71	.04	0.65	0.73	.06	−0.25	0.44	−.03	−0.02	0.45	.00
Timing × Tempo				−0.99	0.67	−.09				−0.82	0.41	−.13*
R^2		0.01			0.02			0.03			0.04	

Variable	Genital development						Pubic hair development					
	Model 1			Model 2			Model 1			Model 2		
	B	***SE B***	**β**	***B***	***SE B***	**β**	***B***	***SE B***	**β**	***B***	***SE B***	**β**
F for change in R^2		1.98			2.16			4.35*			4.00*	
Risky sexual behavior, age 15.5 years (*N* = 326)												
Timing	−0.04	0.02	−.15*	−0.04	0.02	−.15*	−0.03	0.02	−.09	−0.02	0.02	−.09
Tempo	−0.02	0.08	−.01	−0.02	0.08	−.01	0.00	0.05	.00	0.00	0.05	.00
Timing × Tempo				0.00	0.08	.00				0.01	0.05	.01
R^2		0.02			0.02			0.01			0.01	
F for change in R^2		3.24*			0.00			1.36			0.02	

Note. CBCL = Child Behavior Checklist; YSR = Youth Self Report; SSRS = Social Skills Rating Scale.

† $p < .10$.

* $p < .05$.

** $p < .01$.

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Table 7

Relationship Between Pubertal Timing and Tempo and Girls' Behavioral Outcomes

	Breast development						Pubic hair development					
	Model 1			Model 2			Model 1			Model 2		
Variable	***B***	***SE B***	β	***B***	***SE B***	β	***B***	***SE B***	β	***B***	***SE B***	β
CBC–YSR internalizing, age 15.5 years (breast, *N* = 352; hair, *N* = 349)												
Timing	−0.69	0.20	−.18**	−0.81	0.22	−.21**	−0.77	0.20	−.21**	−0.89	0.22	−.24**
Tempo	2.21	1.18	.10†	2.11	1.18	.09†	2.80	1.35	.11*	2.73	1.35	.11*
Timing × Tempo				−1.76	1.28	−.08				−1.79	1.40	−.07
R^2		0.04			0.05			0.05			0.05	
F for change in R^2		7.38**			1.88			9.07**			1.64	
SSRS internalizing, age 15.5 years (breast, *N* = 347; hair, *N* = 344)												
Timing	−0.23	0.10	−.12*	−0.28	0.11	−.15*	−0.19	0.10	−.10†	−0.21	0.11	−.11†
Tempo	1.10	0.60	.10†	1.06	0.60	.09†	1.68	0.69	.13*	1.67	0.69	.13*
Timing × Tempo				−0.70	0.65	−.06				−0.31	0.71	−.03
R^2		0.02			0.03			0.03			0.03	
F for change in R^2		4.00*			1.17			4.43*			0.18	
CBCL–YSR externalizing, age 15.5 years (breast, *N* = 352; hair, *N* = 349)												
Timing	−0.49	0.25	−.10†	−0.53	0.28	−.11†	−0.57	0.25	−.12*	−0.58	0.28	−.12*
Tempo	4.14	1.50	.15**	4.11	1.50	.15**	4.98	1.72	.15**	4.97	1.72	.15**
Timing × Tempo				−0.57	1.63	−.02				−0.15	1.78	.00
R^2		0.03			0.03			0.03			0.03	
F for change in R^2		5.42**			0.12			6.22**			0.01	
SSRS externalizing, age 15.5 years (breast, *N* = 347; hair, *N* = 344)												
Timing	−0.12	0.11	−.06	−0.19	0.12	−.09	−0.13	0.12	−.06	−0.10	0.13	−.05
Tempo	1.89	0.68	.15**	1.84	0.68	.14**	1.69	0.79	.12*	1.70	0.79	.12*
Timing × Tempo				−0.96	0.74	−.08				0.36	0.82	.03
R^2		0.02			0.03			0.02			0.02	

Variable	Breast development						Pubic hair development					
	Model 1			Model 2			Model 1			Model 2		
	B	***SE B***	**β**	***B***	***SE B***	**β**	***B***	***SE B***	**β**	***B***	***SE B***	**β**
F for change in R^2		4.31*			1.72			2.71†			0.19	
Risky sexual behavior, age 15.5 years (breast, N = 343; hair, N = 340)												
Timing	−0.04	0.01	−.14*	−0.04	0.02	−.15*	−0.05	0.01	−.21**	−0.06	0.02	−.22**
Tempo	0.13	0.08	.09	0.13	0.08	.08	−0.01	0.09	−.01	−0.02	0.09	−.01
Timing × Tempo				−0.04	0.09	−.03				−0.04	0.10	−.02
R^2		0.03			0.03			0.04			0.04	
F for change in R^2		4.37*			0.19			7.57**			0.14	

Note. CBCL = Child Behavior Checklist; YSR = Youth Self Report; SSRS = Social Skills Rating Scale.

† $p < .10$.

* $p < .05$.

** $p < .01$.