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Longitudinal Associations Between Pubertal Development and Youth Behavioral Adjustment in the Context of Parent and Peer Relationships

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ABSTRACT

Puberty is a key developmental process influencing youths' psychosocial adjustment, yet research has rarely examined its links to adaptive outcomes such as prosocial behavior. Using data from the Avon Longitudinal Study of Parents and Children, we applied linear mixed-effects models to test associations between pubertal timing and tempo—derived from SITAR growth curve modeling of up to nine assessments (ages 8–17 years)—and mother-reported behavioral adjustment at age 16 years. Pubertal data were available for 5013 girls and 4822 boys. Pre-registered analyses showed no associations between puberty and either prosocial behavior or externalizing problems at age 16. Exploratory analyses revealed that earlier pubertal timing and faster tempo were linked to more internalizing problems at age 16. At age 13, earlier timing predicted more externalizing problems, whereas later timing predicted more prosocial behavior. Most of these associations were attenuated in moderation analyses examining interactions between pubertal maturation and either parent–child disclosure or friendship satisfaction. Findings highlight developmental specificity in puberty–behavior links and suggest that supportive social relationships may buffer risks of early or rapid pubertal maturation.

1 | Introduction

1.1 | Pubertal Timing and Tempo

Puberty, a period of substantial biological and psychosocial change, marks the end of childhood and the transition into adulthood (Abreu and Kaiser 2016). Importantly, significant individual differences exist in terms of when puberty begins—pubertal timing—and the speed of progression through puberty—pubertal tempo (Biro et al. 2018; Cheng et al. 2020; Tanner and Whitehouse

1976). Moreover, girls typically begin puberty 12–18 months ahead of boys (Elhakeem et al. 2024; Marshall and Tanner 1969, 1970), and this, along with other sex-related variations, may evoke different responses from the environment in terms of social role expectations (Benjet and Hernández-Guzmán 2002). Given that adolescence is a period during which many mental health problems emerge or intensify (Dalsgaard et al. 2020; Solmi et al. 2022), these considerations have inspired investigation into the links between pubertal development and psychosocial adjustment in adolescence.

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1.2 | Pubertal Maturation Relates to Behavioral Adjustment

The majority of existing studies have examined individual differences in pubertal development in relation to maladjustment, and a large body of literature suggests that earlier pubertal timing is a risk factor for externalizing problems, internalizing problems and risky health behaviors (e.g., Askelund et al. 2024; Kowalski et al. 2021; Pham et al. 2025; Senia et al. 2018; Ullsperger and Nikolas 2017). Although pubertal timing has been more extensively researched than pubertal tempo due to a preponderance of cross-sectional data, patterns of accelerated pubertal development have also been linked to both internalizing (Cheng et al. 2020) and externalizing problems (Beltz et al. 2014; Castellanos-Ryan et al. 2013; Dimler and Natsuaki 2015; Marceau et al. 2011). Because puberty may be a challenging developmental phase for many youths, early pubertal timing may confer additional risk because early maturing adolescents often enter this transition before they are developmentally prepared to cope with its biological and socio-emotional demands (Graber 2013). As a result, pubertal timing has been mostly studied as a risk factor in associations with maladaptive outcomes.

Only a handful of studies have explored associations with adaptive adjustment, where earlier pubertal timing was found to be linked to better executive functioning and higher social competence (Benjet and Hernández-Guzmán 2002; Carlo et al. 2012; Chaku and Hoyt 2019; Klopach et al. 2020; Koerselman and Pekkarinen 2017).

Despite the well-established importance of pubertal development on adolescent outcomes, our understanding of how individual variation in pubertal timing and tempo affects behavioral adjustment remains limited.

1.3 | The Importance of Parents and Peers

Parallel to the growing literature linking pubertal timing and tempo to behavioral adjustment, recent work suggests that individual differences in pubertal maturation need to be examined in the context of the individual's social environment (DiLalla et al. 2021).

The social context is particularly important in adolescence, a life stage when relationships with parents and peers change substantially (Crone and Achterberg 2022). As part of this shift, adolescents are more in control of how much information they voluntarily share with their parents. Adolescent disclosure refers to the extent to which the adolescent is sharing details from their lives with their caregivers (Laird and Zeringue 2019). Higher adolescent disclosure may indicate higher levels of openness, warmth and communication in the parent–adolescent relationship (Kearney and Bussey 2015) and has previously been linked to higher quality of parent–child relationships (Laird and Zeringue 2019) and lower depressive symptoms and delinquency (Hamza and Willoughby 2011; Kapetanovic et al. 2019). Disclosure to parents may be especially important during adolescence and may buffer against risks associated with early puberty by facilitating parental guidance and support, whereas low disclosure may limit opportunities for monitoring and intervention. Even

though child-to-parent disclosure is considered a proxy of the parent–child relationship, it is also acknowledged that adolescent disclosure is a larger construct than just a proxy of parent–child relationship (Crouter and Head 2002).

During adolescence, although the relationships with parents remain important, youths become increasingly more independent of their caregivers, a normative process that aids the development of their sense of identity (Crone et al. 2022; Suleiman and Dahl 2019).

This change in the youth–parent relationship is paralleled by the growing importance of peer relationships, such as friendships. As compared to other age groups, adolescents have a heightened need for social belonging, increased rejection sensitivity, and heightened sensitivity to peer evaluation (Blakemore and Mills 2014; Sebastian et al. 2010; Somerville 2013). This increased peer importance translates to heightened susceptibility to peer influence on behaviors such as risk-taking and prosocial behavior (Crone, Smeijnen, et al. 2022; Laursen and Veenstra 2021; van Hoorn et al. 2016). For example, compared to other age groups, both laboratory experiments and real-life observations show that adolescents' willingness to engage in risky behaviors increases in the presence of peers and friends (Gardner and Steinberg 2005; Simons-Morton et al. 2011), and this effect is particularly pronounced when peers convey risk-accepting norms (Simons-Morton et al. 2019).

This means that when studying important developmental milestones in adolescence, such as behavioral adjustment, considering important contextual factors such as quality of social relationships with parents and peers, as they are perceived by adolescents themselves, is crucial.

1.4 | Prosocial Behavior and Externalizing Problems in Adolescence

Adolescence is a period marked by changes in both adaptive and maladaptive behaviors (Bongers et al. 2004; Padilla-Walker et al. 2018a). While adolescent research has traditionally largely focused on maladaptive outcomes, understanding the factors that shape adaptive behaviors is equally important. Examining these together provides a more comprehensive view of adolescent behavioral adjustment.

In this study, we focus on two aspects of behavioral adjustment: prosocial behavior and externalizing problems. Prosocial behavior, defined as voluntary behaviors intended to benefit others (Eisenberg et al. 2013), has been positively linked to a broad spectrum of social and psychological adjustment (e.g., Layous et al. 2012), and negatively associated with externalizing problems (Hukkelberg et al. 2019; Memmott-Elison et al. 2020). Externalizing problems largely refer to maladaptive behavior that is frequently destructive or aggressive and typically can be categorized into four behavioral clusters: aggression, opposition, status violations, and property violations (Frick et al. 1993).

While some degree of continuity in these aspects of behavioral adjustment exists across development, possibly maintained through ongoing interactions between the child and their envi-

ronment, it has been proposed that discontinuity and altered patterns may be brought about by new events and transitions, including the onset of puberty (Sørli et al. 2008). Understanding the associations between pubertal development and behavioral adjustment, and how they are influenced by the quality of social relationships with parents and peers, may thus provide valuable insights into modifiable factors that could be targeted in interventions to enhance developmental outcomes for young people.

1.5 | Theoretical Framework

Several theoretical frameworks have been proposed to understand how variation in pubertal development relates to adjustment in adolescence. One such example is the accentuation theory, which posits that earlier pubertal timing represents a life stressor that amplifies pre-existing problems (Caspi and Moffitt 1991). Prior research demonstrated that early maturing individuals with preexisting problems, behavioral or emotional, had more problem behaviors and internalizing symptoms later in adolescence (Caspi and Moffitt 1991; Senia et al. 2018). However, other literature suggests that pre-existing problem behaviors and earlier pubertal timing both predict future problem behaviors independently of each other (Beltz et al. 2014).

More recent theoretical frameworks emphasize the importance of the context in which the individual is developing. For instance, the contextual amplification hypothesis suggests that early puberty increases the risk for developing problem behaviors in the context of a harsh social environment (Laube and Fuhrmann 2020). In contrast, the differential susceptibility theory posits that individual differences in susceptibility to the environment may be heightened during earlier puberty, for better and worse (Belsky et al. 2007; Laube and Fuhrmann 2020). Thus, earlier pubertal timing may elevate the risk of maladjustment in harsh environments but enhance the likelihood of positive outcomes in supportive environments. Evidence that supports early pubertal timing as a differential susceptibility marker has almost exclusively been studied in association with maladaptive developmental outcomes, such as externalizing problems. For example, this association was amplified in negative social environments, such as peers engaging in risky and violent behaviors or harsh parenting, and weakened in the context of supportive social environments, such as positive parenting or high neighborhood efficacy (Chen and Raine 2018; Kanwar 2021; Klopach et al. 2020; Lynne et al. 2007).

To the best of our knowledge, only one study has examined whether pubertal development relates to a positive outcome, prosocial behavior, and whether this association is moderated by contextual factors—and that study focused exclusively on boys (Klopach et al. 2020). Klopach and colleagues (2020) showed that the relationship between early pubertal timing and prosocial behavior may be strengthened in the context of positive school experience and weakened in the context of harsh parenting.

In addition, several hypotheses exist regarding the duration of the impact of early puberty on behavioral adjustment. The attenuation hypothesis suggests that the effect would disappear in adulthood, implying recovery (Copeland et al. 2010). In contrast, the selective persistence hypothesis predicts long-lasting effects,

suggesting a cascade of events where behavioral problems may result in early parenthood and reduced education, which could then increase the risk of poorer mental health in adulthood (Copeland et al. 2010; Senia et al. 2018).

Taken together, the existing literature indicates that pubertal development can relate to both negative and positive developmental outcomes and that the associations may depend on the social context, in line with the differential susceptibility theory. At present, it is unclear whether the associations between pubertal development and adjustment are long-lasting or time limited, and how social factor shape these associations.

1.6 | Aims and Hypotheses

The present pre-registered study examined associations between pubertal development and both positive and negative aspects of behavioral adjustment at age 16. We also investigated whether these associations were moderated by contextual factors, namely child-to-parent disclosure and friendship satisfaction. Leveraging longitudinal data from the large UK-based Avon Longitudinal Study of Parents and Children (ALSPAC) across the ages 8 to 17 years, we investigated: (i) associations between pubertal development indices (pubertal timing and pubertal tempo) and both negative (externalizing problems) and positive (prosocial behavior) aspects of behavioral adjustment; and (ii) the moderating role of social context in these associations.

We hypothesized that earlier pubertal timing would relate to both more externalizing problems (H1) and more prosocial behavior (H2). In line with the differential susceptibility theory, we hypothesized that the link between earlier pubertal timing and increased externalizing problems would be amplified in negative social environments, such as lower child-to-parent disclosure and lower friendship satisfaction (H3) and attenuated in positive social environments, such as higher child-to-parent disclosure and friendship satisfaction (H4). In contrast, we hypothesized that the link between earlier pubertal timing and more prosocial behavior would be attenuated in negative social environments (H5) and amplified in positive social environments (H6). Given the limited empirical evidence on sex differences in the associations among pubertal maturation, externalizing problems, and prosocial behavior, we did not outline specific hypotheses for these analyses. Similarly, analyses including pubertal tempo as a predictor of behavioral adjustment were exploratory due to limited prior research.

2 | Methods

The present study and analyses were pre-registered [‘anonymous contributors’]. Any deviations from the pre-registration have been fully described.

2.1 | Sample

We used data from the Avon Longitudinal Study of Parents and Children (ALSPAC). The ALSPAC study is a multigenerational prospective birth cohort study where 14541 pregnant women residents in Avon, UK with expected dates of delivery between

TABLE 1 | Descriptive statistics for the sample and primary variables.

	N	White	Higher education	Financial hardship mean (SD)	Prosocial behavior mean (SD)	Externalizing problems mean (SD)	Child-to-Parent disclosure mean (SD)	Friendship satisfaction mean (SD)
Girls	5013	95.9%	18.0%	10.2 (4.0)	8.16 (1.8)	3.36 (2.9)	20.27 (3.34)	3.84 (0.38)
Boys	4822	95.7%	17.2%	10.2 (3.9)	7.78 (1.95)	3.79 (3.1)	19.63 (3.31)	3.77 (0.44)

Note: *N* refers to the number of individuals with available measures of pubertal timing. White refers to the race/ethnicity of the child as reported by their mothers. Higher education reported by mothers refers to having received A-levels or higher education. Financial hardship is a total score based on 8 items, with higher scores indicating greater difficulties. The score ranged from 8 to 32. *SD* = standard deviation. Outcome variables (prosocial behavior and externalizing problems) were measured at age 16 years, moderator variables (child-to-parent disclosure and friendship satisfaction) were assessed at age 13.5 years.

April 1, 1991 and December 31, 1992, were invited to participate. Through subsequent phases of recruitment, the total sample size for data collected after the age of seven increased to 15,447 pregnancies. Of these 14,901 children were alive at 1 year of age. Ethical approval for the study was obtained [Anonymized]. Informed consent for the use of data collected via questionnaires and clinics was obtained from participants following the recommendations of [anonymized] at the time. More details about this study are presented in the [Supporting Information: Section 1.1](#) and have also been described elsewhere (Boyd et al. 2013; Fraser et al. 2013).

The analytic sample comprised all individuals with at least one available measure of pubertal development ($n = 9835$), including 252 siblings, of whom 80 were twins. Participants excluded due to missing pubertal data were more likely to have mothers with lower educational attainment and to be described by their mothers as non-White; however, they did not differ from the included participants on any outcomes of interest. Details of the attrition analyses are provided in the [Supporting Information: Section 1.2](#).

Pubertal development was collected 9 times, annually from ages 8 to 17 years. Additionally, we utilized questionnaire data on behavioral adjustment collected at ages 6, 11, 13, and 16 years. Social context variables were assessed at age 13.5 years. Note that data collected at age 13.5 were collected only for a subsample of the original ALSPAC sample ($n = 5844$) and consisted of a more in-depth clinical assessment “Teen Focus 2”. Data from this subsample were used in the analyses examining the moderating role of contextual factors. Sample sizes for each analysis are listed in Table S1. Basic demographic information for the study sample is presented in Table 1.

2.2 | Measures

Please note that the ALSPAC website contains details of all the data that is available through a fully searchable data dictionary and variable search tool, and reference the following webpage: <http://www.bristol.ac.uk/alspac/researchers/our-data/>.

2.3 | Predictors

2.3.1 | Pubertal Development

The parent-report Growing Up and Changing Questionnaire (GUCQ) was used to measure perceived development of sec-

ondary sex characteristics (Golding et al. 2024; Horvath et al. 2020), including changes in height, pubic hair, and axillary hair growth, in addition to sex specific items for boys (genital development and voice changes) and girls (breast development and age at menarche). The GUCQ is based on the Tanner Stages (Marshall and Tanner 1969, 1970), and includes a series of questions accompanied by pictures, where the respondent is asked to select the category that best describes their degree of pubertal development. The GUCQ, which was administered 9 times annually from ages 8 to 17 years, is designed so that it can be completed by a parent or child alone, or by the child with help of a parent (Golding et al. 2024). For the first five waves of data collection, the GUCQ was mostly completed with help of a parent, and by the child alone at the remaining waves of data collection (for details see Elhakeem et al. 2024). The GUCQ scores were used to derive a measure of pubertal timing and pubertal tempo for each individual using growth curve analysis, which is described in the Data Analyses section.

2.4 | Outcomes

2.4.1 | Externalizing Problems

Externalizing problems were measured at age 16 and were assessed by combining the two 5-item parent-report conduct problems and hyperactivity/inattention subscales of the Strength and Difficulties Questionnaire (SDQ; (SDQ; Goodman et al. 2010) to generate a sum score. The items on the conduct subscale include: (i) has often had temper tantrums or hot tempers; (ii) is generally obedient; (iii) usually does what adults request; (iv) often fights or bullies other children or teenagers; (v) often lies or cheats; steals from home, school or elsewhere; while items on the hyperactivity/inattention subscale are: (i) has been restless, overactive; (ii) cannot stay still for long; (iii) is constantly fidgeting or squirming; (iv) is easily distracted, their concentration wanders; (v) thinks things out before acting; (vi) sees tasks through to the end, has good attention span. Response options included: Not true, somewhat true, certainly true, do not know. The standardized Cronbach's α of the externalizing scale in this study was 0.76.

2.4.2 | Prosocial Behavior

Prosocial behavior was also assessed at age 16, using the sum score of the 5-item parent-report prosocial behavior subscale of

the SDQ (Goodman et al. 2010). The parents responded to the following question: Please describe how your teenager has been in the past 6 months: (i) has been considerate of other people's feelings; (ii) has shared readily with other children and teenagers; (iii) is helpful if someone is hurt, upset or feeling ill; (iv) is kind to younger children; and (v) often volunteers to help others (parents, teachers, other teenagers), with the following response options: Not true, somewhat true, Certainly true, do not know. The standardized Cronbach's α of the prosocial scale in this study was 0.73.

2.5 | Moderator Variables

2.5.1 | Child-to-parent Disclosure

The present study used a self-report of adolescent disclosure to their caregivers who were the parents for most participants, collected at age 13.5 years during the clinical examination "Teen Focus 2". Throughout the manuscript we will therefore use the term child-to-parent disclosure. The study participants indicated the frequency of what they chose to tell their caregivers / parents: "Do you tell your carers/parents what you do during your free time?", "What do you spend your money on?", "How often during the past month were your carers/parents unaware where you were at night?", "How often do you keep secrets from your carers/parents about what you do in your free time?", "How often do you keep things from your carers/parents about what you do at nights/weekends?". The response options were given a 5-point scale ranging from 1 (never) to 5 (always). A higher sum score reflects greater adolescent disclosure to parents and may, in part, indicate higher quality of the parent-child relationship. The standardized Cronbach's α of the disclosure scale in this study was 0.77.

2.5.2 | Friendship Satisfaction

Using semi-structured interviews (collected during "Teen Focus 2"), the study participants were asked about the quality of their peer relationships at age 13.5 years. Questions were derived from the Cambridge Hormone and Mood Project (Goodyer et al. 1989). Contrary to the preregistered plan, where we planned to compute a composite score based on six distinct friendship-related items, this study utilized a single item: "Overall, how happy are you with your friends?" measured on a four-point Likert scale ranging from 1 (very happy) to 4 (unhappy). The deviation from the original plan was due to low internal consistency of the scale, as indicated by a Cronbach's α of 0.52 when all six items were included.

2.6 | Demographic Variables

Demographic variables included biological sex assigned at birth, ethnicity reported by the mothers, financial hardship, and maternal education. Financial hardship was assessed using eight items that evaluated the difficulties mothers faced in affording necessities. These items included questions about their ability to afford food, clothing, heating, rent, children's needs, educational courses, dental care, and childcare. Responses were recorded on a four-point scale and reverse-coded, such that higher scores

indicated greater financial difficulties. Maternal education was measured as the highest education achieved by the mother using the following categories: CSE/GCSE, vocational, O level, A level, Degree. Deviating from our pre-registered analysis, we did not include parental education or ethnicity as covariates in our model due to high missingness (education) and homogeneity (ethnicity) in the data. It should be noted, however, that ethnicity and socioeconomic disadvantage relate differently to pubertal development (Deardorff et al. 2021; Sun et al. 2017).

2.7 | Data Analyses

All statistical analyses were performed in R version 4.1.2 (R Core Team 2021) and Rstudio version 1.4.1717 (RStudio Team 2020). Sample sizes in the main preregistered analyses ranged from 2666 to 3900 depending on the analyses in question, as the mixed effects models performed (using the nlme r package) to explore associations between pubertal development and behavioral adjustment required complete data. An overview of the included data can be found in Table S1.

2.7.1 | Derivation of Indices of Pubertal Development

To derive measures of pubertal timing and pubertal tempo, we used SITAR (SuperImposition by Translation And Rotation), a type of growth curve analysis (Cole et al. 2010). In modeling growth processes, several approaches — including SITAR, linear spline, and natural cubic spline linear mixed-effects (LME) models — have demonstrated similar performance in describing mean developmental trajectories. As compared to linear spline LME, both SITAR and natural cubic spline models are particularly effective in identifying key growth features such as age at peak velocity (Elhakeem et al. 2022). The SITAR model is especially well-suited for modeling longitudinal pubertal development, including Tanner stages, as it accommodates individual variation in size, timing, and intensity of growth and allows inclusion of individuals who do not have complete data on all the repeated assessments (Cole et al. 2010, 2014; Elhakeem et al. 2024). SITAR as implemented in the R package sitar (Cole 2014), is a shape invariant model that fits a cubic spline mean growth curve and allows the modeling of several individual-level random effects that reflect departures of individual growth curves from the mean curve (Cole et al. 2010), allowing us to derive individual differences in pubertal timing and pubertal tempo.

First, we fitted a separate SITAR model for the following pubertal measures selected for this study: pubic hair development, axillary hair development, height, breast development stage (girls only), voice breaking and genital development (boys only) to identify the best fitting growth trajectory for each pubertal measure. In all models, age was modelled as log(age) and the models were fitted separately for girls and boys, in line with prior research (Elhakeem et al. 2024). Each SITAR model included two random effects: timing and intensity. For height, we additionally included size as a random effect to account for individual differences in maximum height. The individual-level timing and intensity values were used as the measures of pubertal timing and pubertal tempo, respectively. Within the SITAR framework, timing is expressed as the age at peak velocity (APV), that is, the point of

peak pubertal growth. Timing is geometrically expressed as left to right departures of the individual growth curves from the mean growth curve. Thus, in the present study, negative values indicate earlier pubertal timing, while positive values reflect later pubertal timing. The mean age of pubertal timing (i.e., the average age at peak growth) for each pubertal indicator can be found in Table S2. The second random effect modelled in this study was intensity, or pubertal tempo, expressed by SITAR as peak velocity (PV), that is, the intensity reflects an individual's growth rate compared to the average growth rate and is measured as a fraction or as percentage. Geometrically, intensity corresponds to stretching or shrinking of the age scale (which makes each individual growth curve steeper or flatter than the average). In the context of this study, negative values reflect slower pubertal growth/tempo while positive values reflect faster growth/tempo than the average.

Second, building on the analytical steps applied by Elhakeem et al. (2024), we performed model comparisons whereby for each pubertal measure (i.e., one for breast development, one for pubic hair development etc.), different models were fitted with 2 to 5 knots (which determines the wiggleness of the curve) in the mean growth curve and included up to two random effects (for timing and intensity). The best fitting model was chosen based on recommended criteria (Elhakeem et al. 2024), including the lowest Bayesian Information Criteria (BIC) value. Model selection procedures are described in greater detail in [Supporting Information: Section 1.4.1](#) and Table S3.

Third, we extracted individual-level values for age at peak velocity (APV; pubertal timing) and peak velocity (PV; pubertal intensity/tempo) from the SITAR models for each pubertal measure. Some models that included multiple random effects failed to converge; in these cases, we retained only the available random effects from the best-fitting models. As a result, information on pubertal tempo was available for pubic hair, height, and breast development in girls, and for axillary and pubic hair development in boys. For pubertal timing, the models provided estimates for axillary hair, pubic hair, and breast development in girls, and for axillary hair, pubic hair, voice breaking, and height in boys.

Finally, we calculated overall pubertal timing and pubertal tempo scores. For girls, the total timing score was calculated as the average of the following: centered age at menarche (not modeled with SITAR because it was reported as a single value) and APV values derived from Tanner stage breast development, pubic hair, and axillary hair development. For boys, the total timing score was calculated as the average of APV values derived from Tanner stage genital development, voice breaking, pubic hair, axillary hair development, and height. Similarly, total pubertal tempo in girls was calculated as the average of PV values derived from Tanner stage breast development, height, and pubic hair development, while for boys the pubertal tempo score was calculated as the average of PV values derived from Tanner stage pubic and axillary hair development.

In addition to the preregistered analyses, we conducted exploratory analyses distinguishing between timing and tempo of two biologically distinct processes within puberty: adrenarche (earlier phase) and gonadarche (later phase) (Counts et al. 1987). Full details of score derivation and results are provided in [Supporting Information: Section 1.4.2](#).

2.7.2 | Linear-Mixed Effects Models

To test our hypotheses, a series of mixed effects models were performed using the nlme package (Pinheiro et al. 1999) in R. Family was included as a random effect to account for relatedness in the sample. The total pubertal timing and pubertal tempo scores generated from the SITAR analyses were used as predictor variables. Exploratory analyses were performed by means Pearson's correlations to assess correlations between total pubertal timing and total pubertal tempo.

2.8 | Main Analyses

First, we tested whether pubertal timing was associated with externalizing problems (H1) and prosocial behavior (H2) by regressing externalizing problems and prosocial behavior measured at age 16 years on the total pubertal timing score. Second, significant associations were followed up by including an interaction term to explore the potential moderating role of social context: child-to-parent disclosure and friendship satisfaction, respectively (H3-H6). Third, significant associations (H1 and H2) were also followed up by testing whether the presence of externalizing problems and prosocial behavior earlier in development impacted our associations of interest. Specifically, we included a measure of externalizing problems and prosocial behavior from age 6 as covariates in our models. This step was included to isolate the effect of pubertal development on behavioral adjustment in late adolescence from pre-existing differences.

Contrary to the preregistration, models were run separately for boys and girls due to differences in the distribution of pubertal timing scores between sexes generated by the SITAR models (see Figure S1 for differences in dispersion of pubertal timing scores).

As preregistered, exploratory analyses were also performed with the conduct subscale of SDQ as a predictor. See [Supporting Information: Section 1.4.3](#) for details. We applied False Discovery Rate (FDR) correction for multiple testing using the Benjamini-Hochberg procedure, with an FDR level of 0.05 (see [Supporting Information: Section 1.4.4](#)).

The same analyses were repeated using the total pubertal tempo as the main predictor. All beta coefficients reported in the manuscript are standardized estimates unless otherwise specified.

3 | Results

3.1 | Associations Between Pubertal Timing and Pubertal Tempo

In girls, the total pubertal timing score and the total pubertal tempo score were not correlated ($r = -0.01, p = 0.596$). In boys, total pubertal timing score and total pubertal tempo were positively and moderately correlated ($r = 0.41, p < 0.001$). Correlations among timing and tempo of the individual indicators of pubertal development are described in [Supporting Information: Section 1.4.5](#).

TABLE 2 | Associations between pubertal timing and pubertal tempo and externalizing problems and prosocial behaviors.

Pubertal measure		Externalizing problems at 16 years				Prosocial behavior at 16 years			
		<i>n</i>	<i>B</i> (<i>SE</i>)	<i>p</i>	95% CI	<i>n</i>	β (<i>SE</i>)	<i>p</i>	95% CI
Timing	Girls	2895	0.01 (0.05)	0.808	[−0.10, 0.12]	2900	0.00 (0.03)	0.996	[−0.07, 0.07]
Tempo		2891	−0.07 (0.05)	0.231	[−0.18, 0.04]	2896	−0.03 (0.03)	0.451	[−0.09, 0.04]
Timing	Boys	2671	0.03 (0.06)	0.585	[−0.09, 0.16]	2671	0.01 (0.04)	0.738	[−0.06, 0.09]
Tempo		2666	−0.00 (0.06)	0.959	[−0.13, 0.12]	2666	−0.03 (0.04)	0.465	[−0.11, 0.05]

Note: β is beta coefficient, *SE* is standard error, *p* is an uncorrected *p*-value, 95% CI is 95% confidence intervals, and *n* is sample size.

3.2 | Pubertal Development and Behavioral Adjustment Age 16 Years

Contrary to H1 and H2, we found no associations between pubertal timing and either externalizing problems or prosocial behavior at age 16 years in boys and girls. Similarly, pubertal tempo was not associated with externalizing problems or prosocial behavior at age 16 years (Table 2), and no associations were found between pubertal development and conduct problems (see Table S4).

3.3 | Post Hoc Analyses

3.3.1 | Validation of the Pubertal Indices

Since pubertal timing and its associations with internalizing problems in girls have been widely studied, we used internalizing problems (measured by the SDQ) as a validation outcome to assess the predictive validity of our pubertal indices. Demonstrating expected associations with internalizing problems provides confidence that the pubertal measures derived from SITAR capture meaningful variation in pubertal development. In line with existing research (Marceau et al. 2011; Pham et al. 2025), earlier pubertal timing (as indicated by a negative timing score) and faster pubertal tempo (as indicated by a positive intensity score) were associated with higher levels of internalizing problems in girls at age 16; $\beta = -0.016$, *SE* = 0.025, *p* = 0.007 for pubertal timing and $\beta = 0.012$, *SE* = 0.05, *p* = 0.003 for pubertal tempo. See Tables S5 and S6 for details.

3.3.2 | Associations Between Pubertal Development and Behavioral Adjustment Earlier in Development

After validating our measure of pubertal timing and tempo, we explored whether the hypothesized associations with externalizing problems and prosocial behavior were present earlier in development. Relevant behavioral adjustment data were available for participants at ages 11 and 13 years. To minimize exploratory analyses, we examined earlier ages only for outcome variables that showed stronger preliminary correlations with pubertal measures than at age 16 years (see Table S7 for correlation coefficients). Therefore, in girls, we examined associations between

pubertal timing and externalizing problems and prosocial behavior at age 13 years. In boys, we investigated associations between both pubertal timing and tempo and prosocial behavior at age 11 years, and pubertal timing and externalizing problems at age 11.

3.3.3 | Pubertal Development and Behavioral Adjustment at Age 11 in the Social Context

At age 11 years, neither pubertal tempo nor timing were associated with behavioral adjustment in boys. More details are presented in Tables S8 and S11.

3.3.4 | Pubertal Development and Behavioral Adjustment at Age 13 in the Social Context

At age 13, earlier pubertal timing was associated with more externalizing problems ($\beta = -0.013$, *SE* = 0.05, *p* = 0.046) in girls, and later timing was associated with more prosocial behavior ($\beta = 0.07$, *SE* = 0.03, *p* = 0.046). Both associations survived FDR-correction. There was a unique effect of pubertal timing on prosocial outcomes at age 13 years even when accounting for the level of prosocial behavior at age 6 years. The effect of pubertal timing on externalizing problems at age 13 years was no longer significant when accounting for externalizing problems at age 6 years. Details are presented in Tables S10 and S11. Entering child-to-parent disclosure and friendship satisfaction in subsequent models rendered the main effect of pubertal timing on these developmental outcomes non-significant (see Table S9).

In summary, pubertal development was not related to externalizing problems or prosocial behavior at age 16, so H1 and H2 were not supported, and H3-H6 were thus not tested at this age. Exploratory analyses to validate our pubertal measures did, however, show that earlier pubertal timing and faster pubertal tempo were associated with more internalizing problems in girls at age 16. Further exploratory work identified earlier developmental associations; in 13-year-old girls, later pubertal timing was linked to more prosocial behavior, and earlier timing was associated with more externalizing problems, with the latter becoming non-significant after adjusting for prepubertal levels of externalizing problems. Additionally, these associations at age 13 years were no longer significant once socio-contextual variables were entered into the models.

4 | Discussion

This preregistered study examined how pubertal timing and pubertal tempo—derived from up to nine time points between ages 8 and 17 years—relate to externalizing problems and prosocial behavior at age 16 years, and whether these associations are moderated by the quality of relationships with parents (child-to-parent disclosure) and peers (friendship satisfaction). Pre-registered analyses found no associations for either boys or girls at age 16. Exploratory analyses revealed that earlier pubertal timing was related to more externalizing problems and later pubertal development was associated with more prosocial behavior in girls aged 13 years. However, these associations were no longer significant when child-to-parent disclosure or friendship satisfaction were explored as potential moderators of the associations between pubertal timing and these behavioral outcomes.

4.1 | Pubertal Development and Behavioral Adjustment

The lack of associations between pubertal indicators and externalizing problems or prosocial behaviors at age 16 years was surprising and contrasts with previous studies (e.g., Carlo et al. 2012; Klopach et al. 2020; Kowalski et al. 2021). Some of the differences may be due to methodological variations, particularly the use of different measures of behavioral adjustment. For instance, the measure of social competence in the study by Klopach et al. (2020) centers on friendships. The measure used by Carlo et al. (2012) is more similar, as it also measures prosocial behavior; however, these associations were limited to household helping and did not extend to peer-directed helping behavior. This implies that understanding the relationship between pubertal development and prosocial behavior may depend on factors such as the type of prosocial behavior and the recipient of the prosocial act (Crone and Achterberg 2022).

Differences in methodology may also explain the null findings with externalizing problems at age 16 years. Some studies conceptualized externalizing problems as more serious conduct, such as unlawful behavior (Castellanos-Ryan et al. 2013; Klopach et al. 2020). While our lack of association contradicts previous findings using similar measures of behavioral adjustment (Beltz et al. 2014; Marceau et al. 2011), this discrepancy is unlikely due to our longitudinal SITAR-derived pubertal indices. Validation analyses show these indices are associated with internalizing problems, in line with existing literature (MacSweeney et al. 2023; Pham et al. 2025).

4.2 | Continuity of Puberty Effects on Behavioral Adjustment

Our exploratory findings offer valuable insights that inform existing theoretical frameworks by demonstrating a clear positive continuity between prepubertal and pubertal levels of behavioral adjustment. For example, earlier pubertal timing was associated with more externalizing problems in girls at age 13; however, this association was no longer significant after adjusting for externalizing problems at age 6. These findings align with Beltz

et al. (2020), who reported that pubertal timing did not predict adolescent externalizing problems after accounting for childhood behavior problems. However, Beltz et al. (2020) also observed timing effects on other outcomes, including earlier age at first sex (both sexes), higher substance use (girls), and more conduct disorder symptoms (boys), which were independent of age 7 problem behaviors. Together, this work highlights the importance of outcome specificity in pubertal timing effects.

Beyond externalizing problems, we found that later pubertal timing was associated with more prosocial behavior in girls. This association in girls remained significant after controlling for pre-pubertal levels of prosocial behavior. This is an important finding, as no previous study, to our knowledge, has accounted for pre-existing differences in prosocial behavior. Pubertal development explaining additional variance in behavioral adjustment, above and beyond the prepubertal levels, may be indicative of a second window of risk and opportunity in adolescence.

Contrary to our expectations, our findings indicate that early pubertal timing did not confer heightened environmental sensitivity in this sample and context. However, our findings underscore the importance of the social context in adolescent development, consistent with the broader premise of contextual amplification and differential susceptibility frameworks. In girls, the associations between pubertal development and behavioral adjustment at age 13 years were no longer significant when child-to-parent disclosure and friendship satisfaction were included as potential moderators of the association between pubertal developmental and behavioral adjustment. This highlights the continued importance of parent–child relationships despite growing autonomy during adolescence (Suleiman and Dahl 2019), and illustrates the well-established importance of friendships in this developmental stage (Alsarrani et al. 2022; Blakemore 2018).

4.2.1 | Developmental Trajectories

Our results highlight the importance of using longitudinal data in developmental sciences. However, the heterogeneous associations we observed show that pubertal indices do not uniformly relate to psychosocial outcomes across development, a nuance that should be considered in future work. For instance, the finding that pubertal development is associated with externalizing problems and prosocial behavior in middle adolescence, but with internalizing problems in late adolescence, may be explained by the different developmental trajectories of these constructs, whereby externalizing problems and prosocial behavior peak considerably earlier than those of internalizing problems (Bevilacqua et al. 2021; Gautam et al. 2024). This suggests that there may be sensitive windows during which associations with pubertal timing are more likely to be detected.

4.2.2 | Directions for Future Research

Despite the null findings in our preregistered analyses, our exploratory results provide valuable insights into the predictive roles of pubertal timing and tempo on psychosocial development from early to late adolescence (from ages 11 to 16 years). Pubertal

timing emerged as the most consistent predictor across middle and late adolescence, whereas faster pubertal tempo was only linked to heightened internalizing problems in girls during late adolescence. Future research should build on these insights by controlling for prepubertal levels of outcome variables to isolate developmental effects and by testing the accentuation theory to examine whether trajectories steepen among early-maturing adolescents. Additionally, studies should adopt a developmental lens when selecting measures of prosocial behavior, given evidence that associations vary by measure and context (Crone and Achterberg 2022; El Mallah 2020). For instance, prosocial tendencies may increase toward close friends but decline toward unfamiliar peers as ingroup-outgroup differentiation intensifies across adolescence. Finally, mapping social contexts and their dynamic changes remains crucial, as our findings underscore the importance of fostering supportive relationships—including those with parents—throughout adolescence.

4.2.3 | Strengths and Limitations

Although the present study benefits from rich longitudinal data over nine timepoints, the findings of this study should be interpreted considering certain limitations. First, the sample is representative of a single region in the UK, which may restrict the generalizability of the results to broader populations. Mothers of children who provided pubertal data tended to have higher education and were more likely to identify their children as White, which may have introduced bias. Second, the cohort under investigation consists of adolescents born in the 1990s. This temporal context may limit the applicability of the findings to contemporary youth. There are ongoing debates about whether pubertal timing has been gradually decreasing over the past half-century (Walvoord 2010). Additionally, while this research primarily focused on social contexts defined by the quality of child-to-parent disclosure and friendship satisfaction—factors that undoubtedly remain relevant—future research should broaden its scope to include emerging social and societal contexts, particularly those shaped by social media and other digital environments that are integral to the lives of today's adolescents. Third, we cannot exclude the possibility that children who reported poorer parent-child relationship (as indexed by lower score on disclosure to parents) had less reliable puberty data, as most puberty questionnaires between ages 8 and 12 were completed with the help of a parent. Fourth, the timing of assessment in the present study poses limitations for causal interpretation. The social environment was assessed at age 13.5 years, a decision that allowed these variables to be positioned after the average pubertal onset in the sample and before the assessment of key behavioral adjustment outcomes. However, this timing also means that the assessed social environment may partly reflect earlier developmental processes, including pubertal development, as well as a continuation of the broader social context. This may be particularly pronounced for participants with late pubertal timing. Together, these features complicate efforts to establish a clear temporal separation between pubertal timing and tempo, social contextual factors, and behavioral adjustment; we therefore emphasize that the findings should not be interpreted as causal. Fifth, due to poor internal consistency of the friendship scale, friendship satisfaction was only measured with a single item, which does not capture the multidimensional

nature of friendship, as originally intended, and the results should therefore be interpreted with caution. Finally, while we conceptualized the social environment as a moderator of the association between pubertal development and behavioral adjustment, an alternative explanation is possible. Speculatively, parental factors may function as shared antecedents, influencing both pubertal development and behavioral outcomes. For example, prior research suggests that parental characteristics in early childhood can predict earlier pubertal onset (DiLalla et al. 2021), which could partly explain why associations between pubertal timing and behavior attenuate when parental variables are included in the models. Future research should examine these potential shared pathways to clarify causal mechanisms.

5 | Conclusion

To conclude, we did not find evidence for associations between pubertal timing and tempo and prosocial behavior or externalizing problems at age 16. However, exploratory analyses revealed heterogeneous associations between pubertal development and outcomes across different stages of adolescence. In girls, earlier pubertal timing was linked to more externalizing problems and less prosocial behavior at younger ages, while faster pubertal tempo and earlier timing were associated with heightened internalizing problems during late adolescence. These patterns underscore the developmental specificity of puberty's impact on behavioral adjustment. Notably, most of the associations were no longer significant after accounting for prepubertal levels of the same outcomes, or the quality of social relationships was included as a potential moderator. Together, these findings highlight the need for longitudinal designs that incorporate prepubertal behaviors and contextual factors to fully capture the complex interplay between pubertal development and adolescent adjustment over time.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the University of Bristol. Restrictions apply to the availability of these data, which were used under license for this study. Data are available from <https://www.bristol.ac.uk/alspac/researchers/access/> with the permission of the University of Bristol.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Supporting File: sode70068-sup-0001-SupMat.docx