Research Square

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Puberty as a Predictor of Changes in the Dual Systems Imbalance Gap: The Moderating Role of Autism Spectrum Disorder

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Abstract

Examine the direct effects of puberty on dual systems imbalance for male and female youth. Test for a moderating effect of autism spectrum disorder. The Adolescent Brain Cognitive Development data were analyzed. Ordinary least squares regression was used to test for direct and moderated effects of interest. Entering puberty was associated with significantly greater dual systems imbalance characterized by greater sensation-seeking and lower impulse control for male youth. Autism spectrum disorder significantly moderated this relationship for male youth, resulting in lower and more negative dual systems imbalance for post-pubertal male youth with autism and the opposite observed for male youth without autism. No significant direct or moderated effects were observed for female youth. Puberty only increases the dual systems imbalance gap for male youth without autism. Male youth with autism may be at lower risk for involvement in risky behavior because of an attenuated gap.

Introduction

The dual systems model has risen to prominence as a developmental framework for understanding the elevated propensity for involvement in risky behavior during adolescence (Vazsonyi et al., 2017; Wasserman et al., 2017; Wojciechowski, 2020). This framework centers on the imbalance in the development of key cognitive constructs of impulse control and sensation-seeking and the brain regions that govern them (Steinberg et al., 2008; Steinberg, 2010). While a great deal of research has examined drivers of variation in development of these constructs and their imbalance (Hannula, 2019; Wojciechowski, 2022; Wojciechowski, 2024), there remain important questions in this area. Puberty marks a key stage in the life-course when these processes are perhaps most salient. Puberty not only marks the beginning of adolescence when these developmental processes appear to be more relevant for understanding behavior (Steinberg et al., 2008; Steinberg, 2010), but also because puberty triggers many of the cognitive changes that underpin this risk. While pubertal development is broadly understood as the trigger that may lead to onset of this rapid increase in imbalance in development of sensation-seeking and impulse control, there still exists variation around these averages that necessitate further investigation. There is limited understanding of how the timing of puberty may influence these developmental shifts in cognition and also how distinct subgroups may experience these shifts differently. Though it would be expected that earlier puberty would result in greater dual systems imbalance earlier in the life-course, the differential relevance that early puberty may have for neurodivergent populations in this regard remains understudied.

Autism spectrum disorder (ASD) represents a neurodivergent condition generally present from birth characterized by social communication difficulties, repetitive behaviors, rigid adherence to routine, and restricted interests (American Psychiatric Association, 2013). Being a neurodevelopmental disorder, the root of these symptoms exist specifically with differences in brain development. This highlights to potential that youth with ASD may demonstrate differences in dual systems development and the manner in which puberty influences this cognitive development. Prior research has indicated that individuals with ASD specifically demonstrate variation in cognitive development relative to neurotypical peers also (Clark et al., 2017; Joseph, 2002; Simonoff et al., 2020), highlighting the potential relevance of the dual systems model as it pertains to the relationship between ASD and pubertal development. Despite these links identified in the prior literature, this area remains understudied. The present study sought to address these gaps in the extant literature by examining early pubertal development as a predictor of dual systems imbalance and determine whether ASD moderates this relationship for male and female youth separately.

The Dual Systems Model and Pubertal Development

The dual systems model has been observed to have relevance for understanding involvement in a range of risky behaviors during adolescence (Vazsonyi et al., 2017; Wasserman et al., 2017; Wojciechowski, 2020). Puberty plays a key role in this relationship, as puberty triggers important neurological development that underpins this elevated propensity for involvement in risky behaviors during this life-course stage. A major issue of concern in this regard is that not all youth enter puberty at the same age nor do they progress through puberty at the same rate. Early developing youth have been observed to be at elevated risk for early involvement in antisocial behavior (Downing & Bellis, 2009; Park et al., 2017). This is particularly problematic because early onset of antisocial behavior is a risk factor for chronic issues with such behaviors (Lee, 2025; Piquero & Chung, 2001; Tärnhäll et al., 2023). This indicates a need to better understand how early pubertal development may trigger these changes in dual systems development.

Sensation-seeking and impulse control are the key cognitive constructs of interest to the dual systems model. These constructs and the brain regions governing them do not develop at the same rate. This leads to imbalance in the development of sensation-seeking and impulse control and this imbalance is the reason why it is posited that risk for involvement in antisocial behavior is elevated

during adolescence (Steinberg et al., 2008; Steinberg, 2020). Sensation-seeking refers to drives to seek out novel and thrilling experiences. The socioemotional network of the brain governs sensation-seeking and is comprised in-part by the dopaminergic system. As the name implies, the dopaminergic system is responsible for the release and experience of the neurotransmitter dopamine. Dopamine is the neurotransmitter associated with feelings of pleasure, reward, and reinforcement (Berke, 2018; Walsh, 2009). Upon beginning puberty, the dopaminergic system demonstrates a rapid pace of development. This results in the laying of novel neural pathways for the release of dopamine. This development then leads to heightened stimulation in response to excitatory stimuli previously unexperienced by children. In turn, this increases sensation-seeking as this dopamine response reinforces engagement in stimulating behaviors and results in youth seeking out such experiences again. The development of these systems continues throughout adolescence before plateauing sometime around the entry to adulthood. This is also around the time that desistance occurs for many youth (Le Blanc, 2020; Loeber, 2012).

Impulse control refers to the capacity to stop and consider potential consequences of an action prior to engagement. The cognitive control network in the brain, comprised in-part by the prefrontal cortex, governs the exertion of impulse control. The prefrontal cortex is particularly relevant here, as it helps to facilitate communication across brain regions in a manner that allows for the ability to stop and think before acting. The prefrontal cortex demonstrates a much slower and steadier pattern of development across adolescence. This is one of the final brain regions to reach full maturity also, generally taking until the mid-20s to reach this point (Spencer-Smith & Anderson, 2009). As such, youth do not fully develop impulse control capabilities until much later in life than they develop the strong sensation-seeking drives. This results in adolescents having strong drives to seek out risky behaviors with only limited capacity to stop and think about the potential consequences for the entirety of this period of the life-course.

The analogy of giving teenagers the keys and accelerator to a fast car years before giving them the steering wheel and brakes has been offered to describe this phenomenon (Gopnik, 2012). While this imbalance in development is a generally universal pattern observed among adolescents, there is still between-person variation in the degree of imbalance that is experienced (Meeus et al., 2021; Wojciechowski, 2024). Even as involvement in some degree of risky behavior is somewhat normative during adolescence (Moffitt, 1993), earlier and involvement in more serious behaviors presents increased risk for chronic involvement and social and legal consequences (Lee, 2025; Piquero & Chung, 2001; Tärnhäll et al., 2023). This highlights the fact that some youth will be at greater risk for involvement in antisocial behavior during adolescence relative to their peers even as absolute risk for involvement in these behaviors is elevated for the vast majority of adolescents. This indicates a need to better understand drivers of differential development of imbalance during adolescence. This would allow for more effective targeting of treatment resources to help mitigate risk for progression to more serious forms of antisocial behavior.

Pubertal Development, Autism Spectrum Disorder, and the Dual Systems Model

Pubertal development and ASD may be particularly relevant for understanding variation in dual systems model development. Because puberty triggers important developmental changes pertaining to the dual systems model, beginning puberty earlier and progressing through puberty at a quicker pace may lead youth to be at increased risk for earlier onset of involvement in antisocial behavior. Puberty is associated with the rapid development of sensation-seeking. Once this development begins, it should progress in tandem with pubertal development. With impulse control still expected to develop at much slower and steadier pace across adolescence, it would then be expected that these early developing youth would demonstrate earlier widening of the gap between sensation-seeking and impulse control. This would then result in these earlier developing youth greater dual systems imbalance characterized by greater sensation-seeking and lower impulse control. When examining between-person differences in dual systems imbalance, this would then result in these early developing youth having greater imbalance scores than their later developing peers. Because greater dual systems imbalance like this is a risk factor for involvement in risky behavior (Murray et al., 2021; Wojciechowski, 2024), this earlier pubertal development triggering cognitive changes may contribute to the elevated risk that early developing youth demonstrate for earlier involvement in such behaviors (Downing & Bellis, 2009; Park et al., 2017). That said, there also remain concerns about additional factors that may play a role in determining the degree to which pubertal development impacts dual systems imbalance in this regard.

ASD presents one factor that may moderate the relationship between early pubertal development and dual systems imbalance. ASD, as defined by the Diagnostic and Statistical Manual for Mental Disorders is a neurodevelopmental disorder (American Psychiatric Association, 2013). The variation in cognitive development demonstrated by youth with ASD relative to their neurotypical peers extends to dual systems model constructs of impulse control and sensation-seeking (Mirabella, 2021; Wojciechowski, 2026a).

Interestingly, these differences in from neurotypical peers provides a more limited view on just how ASD may impact development of dual systems imbalance as a whole. Individuals with ASD often demonstrate difficulties with exertion of impulse control (American Psychiatric Association, 2013; Mirabella et al., 2020). A recent review on impulse control difficulties across neurodevelopmental disorders noted important heterogeneity in the mechanisms underpinning such difficulties across disorders (Mirabella, 2021). This review of the literature noted that impulse control issues among individuals with ASD generally manifest earlier in life and that the capacity to exert impulse control may develop more slowly among individuals with ASD relative to neurotypical peers. Further, issues with executive function are common among individuals with ASD and that this may provide a neurological mechanism explaining these impulse control issues (Demetriou et al., 2018; O'Hearn et al., 2008). However, research has also indicated that this may be dependent on the specific form of impulse control in question. Some research has indicated that youth with ASD only differ from neurotypical peers in terms of proactive control, whereas there were no differences between the groups observed for reactive control (Schmitt et al., 2018). The opposite has also been observed (Mirabella et al., 2020). While a full examination of these specific forms of impulse control was beyond the scope of this study, the extant literature overall suggests that individuals with ASD may have more limited impulse control than neurotypical peers early in life. This may have implications for how pubertal development may exacerbate cognitive differences in this regard given that impulse control is one half of the equation for understanding dual systems imbalance. This may be especially pertinent considering that puberty generally triggers rapid development of the other half of this equation, that is, sensation-seeking.

Sensation-seeking may also manifest itself differently among individuals with ASD vs. their neurotypical peers. Prior research has indicated that youth with ASD may report lower sensation-seeking compared to neurotypical youth (Crasta et al., 2024; van den Boogert et al., 2021; Wojciechowski, 2026a). For example, Crane et al. (2009) observed that individuals with ASD reported significantly lower sensation-seeking scores compared to neurotypical peers and that this partially explained the relationship between attention and social responsiveness. This is a particularly important study in this regard because it highlights how the lower sensation-seeking among individuals with ASD may be connected with the sensory processing that are also characteristic of the disorder. Individuals with ASD may become overwhelmed with sensory stimuli (Boldsen, 2022; Jones et al., 2003). This then may lead youth with ASD to have weaker drives to seek out sensory stimulation compared to neurotypical peers, thus, resulting in lower sensation-seeking scores relative to this group. This brings into question whether pubertal development affects the development of sensation-seeking in the same manner for each of these groups of youth. While puberty generally precipitates rapid development of sensation-seeking among youth (Steinberg et al., 2008; Steinberg, 2010), this development may be less dramatic for individuals with ASD. If youth with ASD are overwhelmed by sensory stimuli, then they may not be reinforced by dopamine reactions to novel and thrilling experiences in the same manner that their neurotypical peers are. This may also help to explain the rigid adherence to routine and limited interests that are common among individuals with ASD also (American Psychiatric Association, 2013). If routine and these limited interests provide a more predictable level of reinforcement for individuals with ASD instead of potentially overwhelming reward provided by novel experiences, this may help to explain why these symptoms are common in ASD and why sensation-seeking tends to be lower in this population. That said, there remains more limited research on how puberty may affect the development of sensation-seeking among youth with ASD. Only one study was identified that explicitly compared the sensation-seeking of youth with ASD that was specifically focused on the role of pubertal development in this regard. Bitsika & Sharpley (2018) observed that girls who had reached menarche actually exhibited lower sensation-seeking scores than girls who had yet to reach menarche in their sample. This may provide indication that dopaminergic system development throughout puberty may indeed result in elevating sensory issues among ASD youth and lead to diminished sensation-seeking as posited above. However, this study was limited by a focus only on girls and lacked comparison to neurotypical youth, thus, indicating a need for continued research in this area.

When considered together, the extant literature provides a mixed picture regarding how dual systems imbalance may look among youth with ASD vs. neurotypical youth and how puberty may impact any observed variation in imbalance between these two groups. While impulse control maybe slower to develop among ASD youth and this may lead to general impairment, sensation-seeking may not develop to the same rapid and elevated extent following puberty among these youth relative to their neurotypical counterparts. This limits the capacity for predicting how variation in dual systems imbalance will be demonstrated between neurotypical and neurodivergent youth with ASD. One final consideration in this area is related to the potential for sex differences in these processes. Male and female youth demonstrate different phenotypic changes during puberty, making direct comparison of these groups difficult. For this same reason, examining these processes with a sample comprised of both male and female youth may obscure important differences in these relationships. This indicates the need to examine the impact of the interactive effect of pubertal development and ASD status on dual systems imbalance separately for male and female youth. Identification of differential impact of pubertal development on dual systems imbalance based on whether youth have or do not have ASD may allow for more effective targeting of

treatment to potentially mitigate propensity for involvement in risky behavior during adolescence. Examining sex differences in this regard may further allow for more effective targeting in this regard. These processes have yet to be examined in this manner, providing motivation for the current study. This study sought to address the gaps in the extant literature by addressing the following research questions:

Research Question 1: How do early pubertal development and ASD diagnosis influence dual systems imbalance?

Research Question 2: How does early pubertal development influence dual systems imbalance development for youth with and without an ASD diagnosis?

Research Question 3: Do these processes differ for male and female youth?

Methods

Data

The present study utilized data from the first three waves of the Adolescent Brain Cognitive Development (ABCD) study. The first three waves were used in analyses because this facilitated establishment of appropriate temporal ordering between independent and dependent variables while accounting for the limits of timing of measurement of key constructs of interest. The ABCD dataset is comprised of the responses of 11,880 youth in the United States aged 8–10 at baseline measurements. This is an ongoing longitudinal panel study, with plans to continue following youth up through emerging adulthood. The purpose of the ABCD study was to identify the drivers of onset and differential development of mental health and substance use issues and identify key correlates. A probability cluster sampling methodology as used to identify sample schools in catchment areas surrounding the 21 participating study sites. Upon identification of these sample schools, recruitment information was dispersed to interested parents/guardians of children attending these schools and families could opt into the study if interested in participating. This resulted in a diverse sample of youth at initial measurements, albeit potentially not representative of the United States general youth population as a whole due to the nature of participant recruitment in the catchment areas only. Participants were surveyed on an annual basis and provided brain imaging data for the study also, though only the survey data were used in the present study. Minor participants provided assent to participate in the study, with parents/guardians providing concurrent informed consent. The ABCD data collection endeavor received institutional review board approval and the present study was exempt from full ethical review because it entailed secondary analysis of deidentified survey data.

Measures

Dual Systems Imbalance

The dependent variable examined in these analyses was dual systems imbalance at Wave 3. The UPPS Impulsive Behavior Scale was used to measure relevant constructs at Wave 3 (Whiteside et al., 2005). The dual systems imbalance construct examined in analyses was a composite construct comprised of data derived from subscale items from this instrument. The sensation-seeking subscale was used to measure sensation-seeking for the study. The lack of premeditation scale was used to measure impulse control for the study, as these tow constructs were defined analogously as the capacity to stop and think prior to acting. Series of four ordinal items were used to assess each of these constructs within each subscale (Sensation-seeking: e.g., I like new, thrilling things, even if they are a little scary; Impulse control: e.g., I like to stop and think about things before I do it). Mean scores were computed from these subscale items so that every participant had single impulse control and sensation-seeking scores at Wave 3. Higher scores on each measure corresponded to greater sensation-seeking and lower impulse control. These mean scores were then standardized by subtracting the sample means and dividing by the standard deviation for each participant. This standardization allowed for the creation of dual systems imbalance scores for each participant by adding the standardized sensation-seeking and impulse control scores together. This additive score provided a measure of the degree of difference between sensation-seeking and impulse control due to the reverse coding of the impulse control scores. Higher and more positive scores on this dual systems imbalance measure would then be indicative of dual systems imbalance characterized by elevated sensation-seeking and diminished impulse control. Lower and negative scores would indicate imbalance also, but this imbalance would be characterized by greater impulse control and lower sensation-seeking which would be expected to provide a protective effect. Scores near zero then indicated scores that were closer to balance in the development of these constructs during childhood and adolescence.

Pubertal Development

One of the main independent variables examined in the present study was pubertal development at Wave 2. The Wave 2 measure was chosen because it provided the most proximal measure to the measurement of the dependent variable while still establishing temporal ordering. An ordinal variable that assessed the progression through the Tanner stages of pubertal development at this wave was used in the ABCD data collection (Marshall & Tanner, 1969; Marshall & Tanner, 1970). These Tanner stages differed for male vs. female youth because of the distinct phenotypic changes exhibited by each group at each of the five stages. That said, the present study utilized a binary variable that delineated participants by whether or not they had progressed past the prepubertal first stage into at least the second stage which signals the beginning of puberty (0 = Prepubertal; 1 = Puberty started). While the distinct phenotypic markers of pubertal development differ between male and female youth across these stages, progression to the second stage marked the beginning of puberty for youth of either sex.

Autism Spectrum Disorder

The key moderating variable examined in the present study was ASD diagnostic status at baseline. ASD diagnosis was reported by parents at baseline and coded into a binary variable that delineated youth with an ASD diagnosis at baseline from those who had no such diagnosis (0 = No; 1 = Yes).

Control Variables

Several additional control variables were also included in analyses to best mitigate bias in estimation of relationships of interest. Race/ethnicity comprised the first set of these control variables, as prior research has identified racial/ethnic differences in dual systems model development (Pederson et al., 2012). Race was measured at baseline using a binary variable that delineated White and Racially Minoritized participants into distinct categories (0 = White; 1 = Racially Minoritized). Latinx ethnicity was also controlled for in analyses. A binary variable was used to delineate participants who identified as Latinx vs. Non-Latinx at baseline (0 = Non-Latinx; 1 = Latinx).

Familial income at baseline was also controlled for in these analyses because past research has indicated that children's cognition may be influenced by social class (Seidler & Ritchie, 2018). Participants' parents were asked to report on their overall annual income for the study. This data was then used to compute an ordinal variable measuring total familial income annually, with higher scores corresponding to greater familial income.

It was also necessary to control for age at Wave 3 in these analyses because cognitive development progresses across the life-course. As such, this necessitated statistical control to account for older vs. younger participants. Age was measured at Wave 3 in single-year intervals.

Exposure to violence history at Wave 2 was also included as a control variable in these analyses because past research has identified experiencing such exposures as a risk factor for atypical cognitive development (Monahan, 2015; Kerig, 2019). The Adverse Life Events Scale was used to assess this construct at Wave 2 (Tiet et al., 1998). This instrument utilized a series of binary items that asked participants whether they had ever experienced a variety of forms of exposure to violence in their lifetimes (e.g., Witnessed or caught in a natural disaster that caused significant property damage or personal injury). These individual binary items were then collapsed into a single binary item that delineated participants who reported experiencing any form of exposure to violence in their lifetimes from those who did not (0 = No; 1 = Yes).

Community socioeconomic disadvantage was also controlled for in these analyses. This is because past research has indicated that community conditions like this may influence brain development among youth (Kulla et al., 2024). The Area Deprivation Index was linked to the ABCD study data to provide a means of assessing the degree of socioeconomic disadvantage in the home communities of participants. The Area Deprivation Index is a composite score comprised of various census-based indicators of community deprivation (e.g., median family income, percentage of homeowners, percentage of population with at least a high school diploma). A weighted score comprised of these indicators was computed from these indicators to provide an overall indicator of the degree of disadvantage present in participants' home communities. Higher scores on this measure corresponded to greater socioeconomic disadvantage.

The final control variable included in analyses was dual systems imbalance at Wave 1. This variable was included in analyses to ensure that any relationships observed between the independent and dependent variables of interest in this study were not simply due to pre-existing relationships in these constructs driven by continuity of earlier measurement. This is to say that the predicted relationship between puberty and dual systems imbalance may actually be the reverse and this may drive a significant relationship between these constructs if pre-existing levels of the dependent variable are not accounted for. As such, this Wave 1 measure of dual systems imbalance was included in analyses. This variable was computed in a manner analogous with the process described for creating the dependent variable of interest, but using the UPPS Impulsive Behavior Scale measures of sensation-seeking and impulse control at Wave 1 instead of Wave 3.

Analytic Strategy

The present study utilized a series of ordinary least squares (OLS) regression models to examine the direct and moderated relationships of interest. OLS regression was deemed as an appropriate modeling choice because of the adherence of the dual systems imbalance dependent variable to the standard normal distribution and the other various assumptions of the OLS model. Coefficients were interpreted as the predicted difference in dual systems imbalance scores at Wave 3 given a one-unit increase in the independent variable of interest, net of all other control variables in the model. Two models were estimated for male and female youth each. Model 1 examined the direct effect of pubertal development and ASD on dual systems imbalance net of all control variables in the model. Model 2 then included an additional variable modeling the multiplicative interaction between ASD and pubertal development, again, net of all control variables in the model. Because of the binary nature of both the ASD and pubertal development variables of interest, it was not necessary to mean-center these variables to avoid multicollinearity of direct and moderated effects of interest. A Little's test was used to determine whether data for variables included in analyses were missing completely at random. Findings from this preliminary test indicated that data were not missing completely at random, necessitating an approach to manage missingness (χ^2 = 11071.490; p<.001). Multiple imputation was used to manage these missing data, with missingness regressed on variables with complete data in analyses (Race, Wave 1 age). A total of 20 imputations were carried out and pooled for each variable with missing data.

Results

Table 1 provides descriptive statistics for all variables included in the models. Table 2 then provides regression results for female participants, whereas Table 3 provides these same results for male participants.

Table 1
Descriptive Statistics for Male and Female Youth

	Male (N = 6,190)			Female (N = 5,678)		
	Mean/Proportion	**Standard Deviation**	**Minimum/Maximum**	**Mean/Proportion**	**Standard Deviation**	**Minimum/Maximum**
Dual Systems Imbalance at Wave 3	.218	1.485	-3.742 6.101	− .240	1.502	-3.742 6.101
Pubertal Stage at Wave 2*	1.947	.790	1 5	2.656	.894	1 5
Autism Spectrum Disorder Diagnosis at Wave 1*	No = 97.20% Yes = 2.80%			No = 99.50% Yes = 0.50%		
Race (0 = White; 1 = Racially Minoritized)*	White = 66.89% Minoritized = 33.11%	---	---	White = 64.56% Minoritized = 35.44%	---	---
Latinx Ethnicity (0 = No; 1 = Yes)	Non-Latinx = 79.40% Latinx = 20.60%	---	---	Non-Latinx = 79.23% Latinx = 20.77%	---	---
Parental Annual Income at Baseline	7.234	2.421	1 10	7.213	2.425	1 10
Age Wave 2*	11.581	.689	10 13	11.565	.706	10 13
Parental Monitoring Wave 3*	4.422	.489	1 5	4.554	.427	1.6 5
Lifetime Exposure to Violence at Wave 2 (0 = No; 1 = Yes)*	No = 67.18% Yes = 32.82%	---	---	No = 73.66% Yes = 26.34%	---	---
Community Socioeconomic Disadvantage at Wave 1	94.477	21.025	1.067 125.749	94.822	21.314	1.067 125.749
Dual Systems Imbalance at Wave 1	.235	1.451	-3.723 5.797	− .256	1.424	-3.723 5.797

*=Boy vs. girls T-test statistically significant at p<.05 level

Table 2
Ordinary Least Squares Regression Modeling of Pubertal Stage and Autism Spectrum Disorder Diagnosis on Dual Systems Imbalance at Wave 3 for Female Youth (Multiple Imputed N = 5,667)

	Model 1			Model 2		
	Coefficient	**p-Value**	**95% Confidence Interval**	**Coefficient**	**p-Value**	**95% Confidence Interval**
Begun Puberty at Wave 2 (0 = No; 1 = Yes)	.028	.627	− .085 .141	.030	.598	− .083 .144
Autism Spectrum Disorder Diagnosis at Wave 1 (0 = No; 1 = Yes)	.448	.087	− .064 .961	1.018	.090	− .163 2.199
Puberty X Autism	---	---	---	− .640	.347	-1.989 .708
Race (0 = White; 1 = Racially Minoritized)	− .058	.176	− .141 .026	− .058	.174	− .141 .026
Latinx Ethnicity (0 = No; 1 = Yes)	.063	.196	− .032 .158	.063	.196	− .032 .158
Parental Annual Income at Wave 1	.009	.381	− .011 .029	.009	.382	− .011 .029
Age Wave 3	.084	.002	.031 .137	085	.002	.032 .137
Lifetime Exposure to Violence at Wave 2 (0 = No; 1 = Yes)	.205	< .001	.120 .290	.205	< .001	.120 .290
Community Socioeconomic Disadvantage at Wave 1	< .001	.685	− .001 .002	< .001	.682	− .001 .002
Dual Systems Imbalance at Wave 1	.458	< .001	.431 .484	.458	< .001	.431 .484
Constant	-1.270	< .001	-1.929 − .611	-1.278	< .001	-1.938 − .618

Table 3
Ordinary Least Squares Regression Modeling of Pubertal Stage and Autism Spectrum Disorder Diagnosis on Dual Systems Imbalance at Wave 3 for Male Youth (Multiple Imputed N = 6,189)

	Model 1			Model 2		
	Coefficient	**p-Value**	**95% Confidence Interval**	**Coefficient**	**p-Value**	**95% Confidence Interval**
Begun Puberty at Wave 2 (0 = No; 1 = Yes)	.088	.042	.003 .174	.102	.019	.017 .188
Autism Spectrum Disorder Diagnosis at Wave 1 (0 = No; 1 = Yes)	− .270	.013	− .482 − .058	.091	.631	− .281 .464
Puberty X Autism	---	---	---	− .510	.029	− .969 − .051
Race (0 = White; 1 = Racially Minoritized)	− .090	.025	− .169 − .011	− .090	.025	− .169 − .011
Latinx Ethnicity (0 = No; 1 = Yes)	.010	.821	− .080 .100	.011	.808	− .079 .101
Parental Annual Income at Wave 1	.019	.033	.002 .036	.019	.034	.001 .036
Age Wave 3	.098	< .001	.048 .149	.098	< .001	.048 .149
Lifetime Exposure to Violence at Wave 2 (0 = No; 1 = Yes)	.142	< .001	.063 .221	.141	< .001	.063 .220
Community Socioeconomic Disadvantage at Wave 1	− .001	.542	− .002 .001	− .001	.502	− .003 .001
Dual Systems Imbalance at Wave 1	.447	< .001	.421 .474	.448	< .001	.422 .474
Constant	-1.178	< .001	-1.818 − .538	-1.180	< .001	-1.820 − .540

Model 1 results for female participants indicated that neither pubertal status nor ASD diagnosis were significant predictors of dual systems imbalance in this mode. That said, the relationship between ASD and dual systems imbalance was marginally significant for female participants here (Coefficient=.448; p<.087). Being older, experiencing exposure to violence, and greater dual systems imbalance at Wave 1 were all significant predictors of greater dual systems imbalance characterized by greater sensation-seeking and lower impulse control at Wave 3 in this model. Model 2 results for female participants indicated that neither ASD nor pubertal status were significant predictors of dual systems imbalance at Wave 3 in this model. Further, the interaction between ASD and pubertal status was nonsignificant in this model also. Being older, experiencing exposure to violence, and greater dual systems imbalance scores at Wave 1 significantly predicted greater and more positive dual systems imbalance scores at Wave 3 in this model.

Model 1 results for male participants indicated that participants who had begun puberty reported significantly greater and more positive dual systems imbalance scores compared to those who had not begun puberty in this model (Coefficient=.088; p<.042). Male participants with an ASD diagnosis at baseline reported significantly lower and more negative dual systems imbalance scores compared to male participants without an ASD diagnosis in this model (Coefficient=-.270; p<.013). Greater familial income, being older, experiencing exposure to violence, and greater and more positive dual systems imbalance at Wave 1 also all predicted greater and more positive dual systems imbalance at Wave 3 in this model. White participants also reported greater dual systems imbalance characterized by greater sensation-seeking and lower impulse control compared to Racially Minoritized participants in this model. Model 2 results indicated that inclusion of the interaction term of interest attenuated the direct effect of ASD on dual systems imbalance to non-significance, though the direct effect of pubertal status remained significant (Coefficient=.102; p<.019). The interaction between ASD and pubertal status in this model was significant and negative also (Coefficient=-.510; p<.029). White participants reported significantly greater and more positive dual systems imbalance scores in this model relative to Racially Minoritized participants also. Experiencing exposure to violence, being older, lower familial income, and greater dual systems imbalance at Wave 1 were also all significant predictors of greater and more positive dual systems imbalance at Wave 3 in this model.

Additional analyses visualized the significant interaction effect between pubertal status and ASD diagnosis for male participants using the *margins* and *marginsplot* commands in Stata. Figure 1 provides visual depiction of these marginal effects. This figure indicated that that there was a dual systems imbalance scores were greater following puberty for male youth without ASD. The opposite was observed for male youth with ASD, as post-pubertal male youth in this group reported dramatically lower dual systems imbalance scores than those in the prepubertal group. Post-puberty dual systems imbalance scores were positive for non-ASD male youth and negative for ASD male youth and the difference in these scores between these two subgroups was statistically significant.

Discussion

Findings from this study provided important insight into the relevance of ASD for understanding how early pubertal development influences dual systems imbalance. Early pubertal development was a significant predictor of greater dual systems imbalance characterized by elevated sensation-seeking and diminished impulse control for male youth only. ASD was also a significant predictor of lower dual systems imbalance scores among male youth only. ASD diagnosis significantly moderated the relationship between early pubertal development and dual systems imbalance for male youth only. This moderation effect was negative, as youth with ASD demonstrated lower dual systems imbalance scores than their neurotypical peers. Interestingly, the predicted marginal dual systems imbalance score for youth with ASD was negative, indicating that these youth did demonstrate some mean level of imbalance, but it was more characterized by elevated impulse control and lower sensation-seeking scores following the onset of puberty. These findings highlight the particular relevance that early pubertal development and ASD diagnosis have for understanding the differential development of dual systems imbalance among male youth specifically. There were no significant findings pertaining to female youth in this regard, highlighting the potential that sex-specific programming may be a more cost-effective means of addressing these specific issues related to cognitive development. There are a number of important implications of these findings.

Having begun puberty was observed to influence greater dual systems imbalance among male youth, but not female youth. These findings are particularly relevant given that male youth generally demonstrate elevated propensity for involvement in antisocial behavior during adolescence compared to female youth (Durrant, 2019; Lauritsen et al., 2009). With the dual systems model identified as a relevant for understanding for risky and offending behaviors (Vazsonyi et al., 2017; Wasserman et al., 2017; Wojciechowski, 2020), this may provide a mechanism by which the gender gap in offending may be explained. These findings also highlight how dual systems development may differ for male and female youth overall. While the dual systems model had initially focused on typical development of these processes universally (Steinberg et al., 2008; Steinberg, 2010), more recent research has indicated that male and female youth demonstrated different developmental patterns of impulse control and sensation-seeking (Hannula, 2019;

Wojciechowski, 2026b). The present study provided findings consistent with this more recent research, as imbalance in the development of sensation-seeking and impulse control only significantly widened following puberty for male youth. This highlights the potential that programming focused on fostering stronger impulse control and mitigating sensation-seeking tendencies among male youth may aid both in reducing offending rates overall, but may also mitigate the gender gap in offending.

Another finding of this study pertained to the negative direct effect of ASD on dual systems imbalance among male youth, but not female youth. Male youth with ASD not only reported lower dual systems imbalance scores than their neurotypical peers on average, but additional analyses indicated that these scores were negative in and of themselves at Wave 3 for this subgroup (Mean=-.121). This indicates that ASD may actually foster dual systems development that is more prosocial in nature, at least in terms of involvement in risky behaviors. There are certainly positive aspects of the typical dual systems development associated with identity exploration and formation that may come with trying new experiences in a manner consistent with sensation-seeking (Klimstra et al., 2010; Meeus, 2011). As such, ASD should not necessarily be seen as a protective factor because of this limited imbalance in the development of these constructs, but rather, as an explanation for some of the differences that male youth with ASD may demonstrate in their social development. Some research has indicated that ASD is a protective factor against offending, though this evidence remains mixed overall (Cheely, 2012; King & Murphy, 2014; Rutten et al., 2017). However, youth with ASD may also struggle with friendship formation and relationships (American Psychiatric Association, 2013). Both of these idiosyncrasies of ASD may be traced back to this variation in cognitive development, at least for male youth. These youth may not have the same drive to seek out novel and thrilling experiences that may result in them getting in trouble, but these diminished drives may also result in a stunting of their social development. Wojciechowski (2026a) does provide one unique examination of these processes that are consistent with these findings. This study examined sensation-seeking and impulse control as mediators of the relationship between ASD and deviant peer association. Findings indicated that youth with ASD reported lower deviant peer association and that this was significantly mediated by lower sensation-seeking. That said, this overall remains speculative and in need of additional research.

It is also important to note that there was no significant relationship between ASD and dual systems imbalance observed for female youth in this study. However, this relationship was positive and marginally significant for this subgroup (Coefficient=.448; p<.087). While optimal confidence cannot be had in this finding, it would be a mistake not to discuss this result given that it was opposite of that of male youth and relatively close to the traditional p<.05 threshold for significance. This is especially concerning given the potential for power issues due to the small N of female youth with ASD (N = 28). This much lower prevalence of ASD among female youth in the sample relative to male youth (N = 173) may be a function of underdiagnosis of the disorder in female youth that is well documented (American Psychiatric Association, 2013; Haney, 2016). In any case, this finding would seem to suggest a sex-specific effect of ASD wherein sensation-seeking is only dampened among male youth and is instead amplified among female youth in comparison to their neurotypical peers. While a more complete investigation of these differences was beyond the scope of this study, this highlights the need for additional research to examine these sex-differences using a sample that do not suffer from these power issues. This would allow for a more complete understanding of the potential three-way interaction between sex, ASD, and pubertal development.

The final significant finding of note from this study was the significant interaction between pubertal status and ASD for predicting dual systems imbalance among male youth. This significant and negative interaction indicated that the onset of puberty had opposing effects on dual systems imbalance for male youth with and without ASD. For male youth without ASD, beginning puberty was associated with slightly higher sensation-seeking. For male youth with ASD, there was a much stronger negative effect of puberty on dual systems imbalance. As noted above, this negative effect actually led to mean levels of sensation-seeking that were characterized more by weaker sensation-seeking and greater impulse control. In the context of the framework of the dual systems model, the Non-ASD group demonstrated a pubertal effect on imbalance that was much more consistent with the postulations of the theory. The significant moderation effect here highlights the necessity of looking beyond the typical developmental patterns of sensation-seeking and impulse control, as this obscures important within-sample heterogeneity in this area. The vast changes in imbalance scores that was observed among male youth with ASD potentially demonstrates an increase in sensory processing difficulties due to the rapid development of sensation-seeking following puberty. While there is currently a dearth of research on the role that puberty may play in this regard, the sensory processing issues among youth with ASD are well documented and it is foreseeable that novel dopamine responses that come with puberty may lead to sensory overload. This overload may lead male youth with ASD to withdraw from seeking novel experiences following puberty and may help to explain limited interests and rigid routines, as these things may provide more predictable reward response to stimulation. While this may ultimately result in narrower dual systems imbalance gaps for male youth with ASD, this still raises concerns about how this may impact these adolescents' social development. If these youth are not

seeking out novelty in their experiences, this may inhibit relationship formation and exertion of autonomy in social spaces. While these narrowed imbalance gaps may be protective against involvement in antisocial behavior among male youth with ASD in a manner consistent with some of the extant literature (Cheeley et al., 2012; King & Murphy, 2014), prosocial youth development must also be considered holistically. This serves to highlight some of the distinct needs that male youth with ASD may have as they mature and indicates the need for additional research in this area to better understand how this differential cognitive development post-puberty may have broader implications beyond behavioral risk. Future research should also seek to better understand the role sex plays in this regard given the nonsignificant interaction effect and opposite direct effect of ASD on dual systems imbalance for female youth.

While the present study provided unique insight into the relevance of pubertal development and ASD for understanding dual systems development, there remain several important limitations. The first of these limitations pertains to the measurement of ASD. The ASD measure used in the present study is a binary measure delineating youth with and without an ASD diagnosis at baseline as reported by parents/guardians. While this provides a straightforward measure of ASD diagnostic status, there is the potential for significant measurement error in this regard. First, being in the ASD group in the sample is dependent on whether youth have access to mental healthcare that could result in a diagnosis. If this access is restricted for any reason, this means that additional youth with ASD in the sample may not receive a diagnosis. Prior research has also indicated that ASD diagnosis is missed in female youth disproportionately (American Psychiatric Association, 2013; Haney, 2016). This could then result in an undercount of the number of female youth with ASD in the sample. Indeed, the ASD diagnosis prevalence rate for female youth in the sample is much lower than that of male youth in the sample (Male N = 173; Female N = 28). This diminished power may help to explain some of the null findings observed for ASD effects for female youth in the sample. Related to this issue, if there is systematic bias in the female youth that are vs. aren't diagnosed with ASD in the sample, this may help to explain the direct effect of ASD on dual systems imbalance that is in the opposite direct of that for male youth. A final issue in this regard pertains to the binary nature of the ASD measure. While this provides a distinct categorization of youth with and without a diagnosis, it says nothing about the seriousness of ASD symptomatology as it may pertain to the relationships of interest. ASD is a spectrum disorder with a number of distinct continuums upon which a variety of symptoms may be experienced. No two individuals with ASD present analogously and even individuals who do not meet criteria for diagnosis may demonstrate some degree of ASD symptomatology. This means that the present analyses can say nothing of symptoms severity along any of these dimensions of the disorder and this may obscure a more complicated set of relationships between ASD, pubertal development, sex, and dual systems imbalance. These issues highlight the need for additional research in this area with data that better addresses these issues.

Another limitation of this study pertains to the biological sex measure utilized in analyses to delineate male and female youth. While this sex measure does appropriately discriminate between male and female youth, there does not currently exist any variable assessing gender identity in the data nor is there any variable that assess biological sex outside of the male/female binary. While it is likely a relatively small proportion of the population who are born intersex (Sax, 2002), the inability to assess this nuance of biological sex may have led to some measurement error. Perhaps more concerning, both in the scope of this study and beyond, is the lack of a gender identity variable. Previous iterations of the ABCD dataset did indeed provide one such measure of gender identity, delineating boy, girl, and nonbinary youth into distinct categories. Further, these previous iterations also offered a measure of whether participants were transgender or cisgender. However, these variables were omitted from the latest data releases with the explanation that this was done to align the study with the directives of the current Trump administration. This is problematic for the present study given that transgender and nonbinary youth may experience puberty differently than their cisgender peers (Horton, 2024; Schwartz et al., 2022). While the number of youth who reported identifying as transgender and/or nonbinary at baseline measurement was relatively small and unlikely to affect findings overall, this still raises concerns over precision of these analyses and also the larger issue of political influence on the scientific process. This indicates a broader need to address these concerns in future data releases so as not to miss important variation on gender identity that may impact findings.

Declarations

Funding Statement: This research received no funding.

Human Ethics Statement: The ABCD data collection endeavor received institutional review board approval from the University of Pittsburgh. The present study was exempt from full ethical review because it entailed secondary analysis of deidentified survey data.

Consent to Participate Statement: All minor participants provided assent to participate accompanied by concurrent parent/guardian informed consent.

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Figures

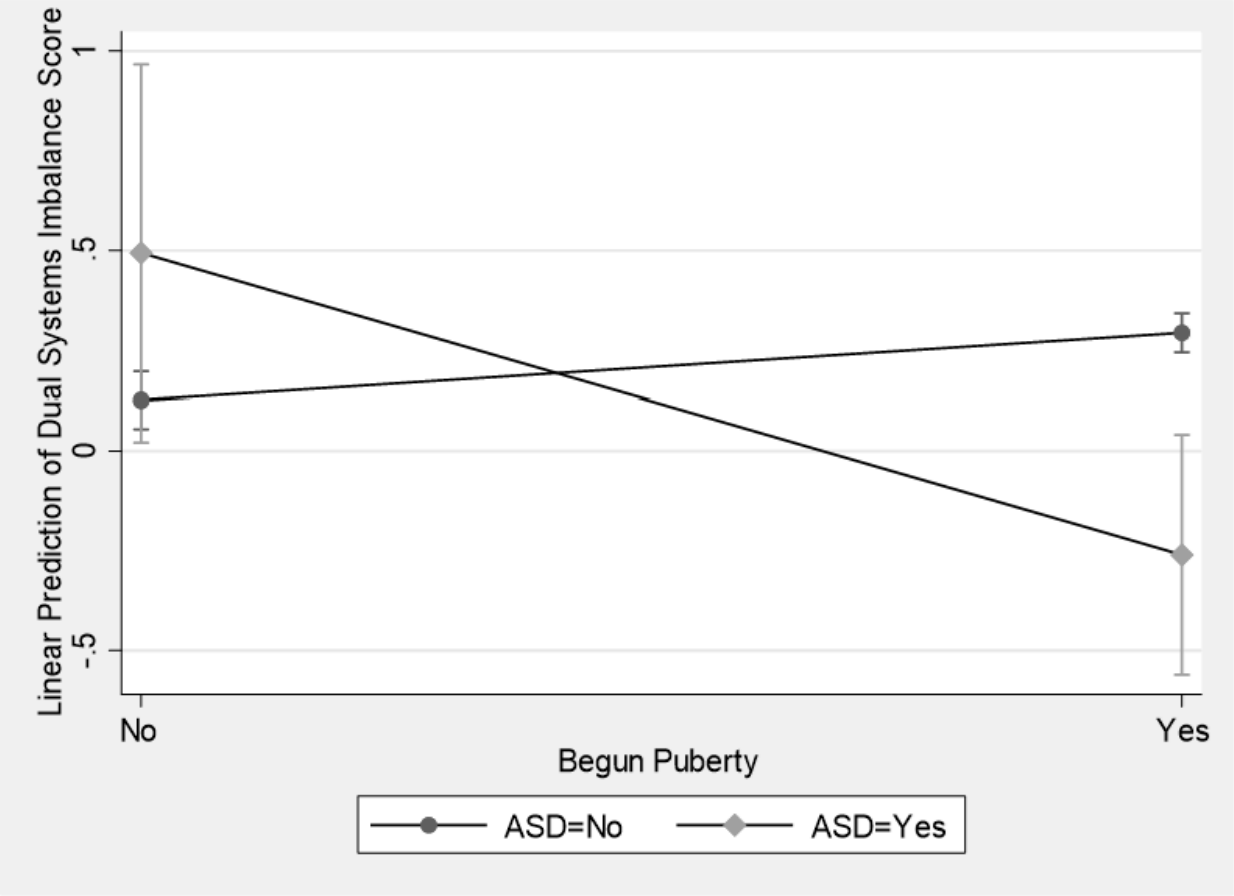


Figure 1

Marginal Effects of Interaction Between Autism Spectrum Disorder Diagnostic Status and Pubertal Status for Predicting Dual Systems Imbalance