Title:

Is early good or bad? Early puberty onset and its consequences for learning

Authors:

Laube, C.[1, 2] & Fuhrmann, D.[3, 4 *]

1. Max Planck Institute for Human Development, Berlin, DE
2. Fresenius University of Applied Sciences, Berlin, DE
3. MRC Cognition and Brain Sciences Unit, University of Cambridge, Cambridge, UK
4. Department of Psychology, Institute for Psychiatry, Psychology and Neuroscience, King's College London, London, UK

* Corresponding author: delia.fuhrmann@kcl.ac.uk

Abstract:

Entering puberty at a relatively young age is often thought to be associated with negative outcomes, such as poorer cardiovascular and psychosocial health. However, the literature on the relationship between early puberty, learning and academic achievement is inconclusive. Previous work suggests both positive and negative outcomes of early puberty. We here review recent findings on the relationship between early puberty and cognitive outcomes and integrate these findings into larger theoretical frameworks of pubertal development. We argue that differences in observed outcomes may be explained by domain- and context-specific effects. Early maturation may be linked to positive as well as negative cognitive outcomes, depending on the domain studied, and appears to be influenced by the wider social context, with less supportive environments associated with poorer outcomes for early maturers.

Highlights:

- Early puberty can be associated with both negative and positive cognitive outcomes.
- The effects of early puberty are domain specific. Early maturation may be associated with lower self-control but better attention.
- The effects of early maturation appear to be mediated or moderated by social contexts.
- Recent work suggests that supportive contexts may allow early maturers to benefit from new learning opportunities associated with early entry into adolescence.

Is early good or bad? Early puberty onset and its consequences for learning

Puberty is a watershed in the life course. It is characterized by a rapid increase in gonadal hormones, initiating the development of secondary sexual characteristics (Shirtcliff, Dahl, & Pollak, 2009). The onset of puberty marks the beginning of adolescence, with its profound physical, social and cognitive changes (Crone & Dahl, 2012) and unique developmental tasks such as establishing strong peer relationships and the need to make reproductive decisions (Suleiman & Harden, 2016). Puberty onset may spark the opening of a sensitive period for development (Fuhrmann, Knoll, & Blakemore, 2015; Piekarski, Johnson, et al., 2017) and increase plasticity for traits relevant to these new developmental tasks (Scherf, Behrmann & Dahl, 2012). Depending on the social or cognitive domain studied, the rate of learning may increase (Knoll et al., 2016) or decrease (Pattwell et al., 2012) during this time compared to earlier or later in development (Laube, van den Bos, & Fandakova, 2020), providing preliminary evidence for changes in plasticity around the onset of puberty.

The timing of puberty onset has changed over the last few decades (Sørensen et al., 2012) and differs between individuals (Parent et al., 2003). This may have implications for sensitive periods of development because individual differences in puberty onset are thought to predict cognitive outcomes, such as inhibitory control (Laube, Lorenz, & van den Bos, et al., 2020; Piekarski, Boivin, & Wilbrecht, 2017). Whether these outcomes are generally better or worse after early puberty onset is controversial, however.

Our objective is to review the recent literature on the effects of early onset of puberty on cognitive development, learning and academic achievement. We systematize recent findings on the effects of early puberty on cognition and integrate them into long-standing theoretical ideas on pubertal timing effects. We show that the literature on the effects of pubertal timing is mixed, with some studies finding negative associations between early puberty onset and cognitive outcomes, other studies finding positive associations and still others finding null results. We will argue that these mixed findings may be a result of domain- and context-specific effects of puberty and cognition that reflect adaptive life history strategies.

Natural variation in pubertal onset

The age of onset of breast development - the first hallmark sign of puberty for girls - has declined during the last two decades, from about 11 years to well below 10 years worldwide (Eckert-Lind et al., 2020). Similarly, the age at menarche - signaling full sexual maturity and the end of puberty – has decreased from 17-18 years of age in the early 19th century to about 13 years in the 1960s, when the trend plateaued in both Europe and North America (Sørensen et al., 2012; but see Walvoord, 2010). Findings are more mixed for boys. The male marker of pubertal onset - genital development (defined as testicular volume of more than 3ml) – has remained relatively stable in North America at about 11.5 years (Biro, Lucky, Huster, & Morrison, 1995; but see Euling et al., 2008). In Europe, in contrast, a recent Danish study documented a decrease in age at pubertal onset of 3

months over a 15-year period (Sorensen et al., 2010). Similarly, Ohlsson et al. (2019) showed a secular trend for earlier pubertal timing in Swedish boys.

Within these secular trends, individual differences are pronounced. In America, puberty onset ranges from ages 8.0 to 14.9 years for girls and ages 9.7 to 14.1 years for boys (Lee, 1980), with similar age ranges currently considered typical in Britain (NHS, 2020). These individual differences in pubertal onset are thought to contribute to individual differences in health and cognitive outcomes (Laube et al. 2020). Entering puberty earlier compared to one's peers is often thought to be associated with an increased risk for psychopathological symptoms during adolescence (Ullsperger & Nikolas, 2017), as well as cardiovascular disease, type-two-diabetes and breast cancer in adulthood (Bodicoat et al., 2014; Day, Elks, Murray, Ong, & Perry, 2015; Prentice & Viner, 2013). Early puberty onset has also been associated with worse performance on attention and executive functioning tasks (Stumper, Mac Giollabhui, Abramson, & Alloy, 2020), as well as lower academic attainment (Cavanagh, Riegle-Crumb, & Crosnoe, 2007). Theories of puberty development therefore generally seek to explain *negative* effects of early puberty (e.g. Caspi & Moffitt, 1991). In contrast, several recent studies (e.g. Chaku & Hoyt, 2019; Koerselmann & Pekkarinen, 2017) and theories (e.g. Belsky, Bakermans-Kranenburg, & Van Ijzendoorn, 2007), have suggested potential *positive* associations between early puberty and socio-cognitive outcomes (Chaku & Hoyt, 2019; Koerselmann & Pekkarinen, 2017). Others still suggest that early puberty is merely a symptom of pre-existing differences and has no effect in and of itself (cf. stress acceleration hypothesis; Callaghan & Tottenham, 2016). Below we outline several of these theories, discuss their relative support by recent empirical findings and extract key predictions for cognitive trajectories (Figure 1).

Theories on the effects of pubertal timing

The literature on pubertal timing is rich in hypotheses predicting different developmental trajectories and mechanisms by which early puberty onset affects developmental trajectories (Figure 1). These hypotheses can be grouped into three theoretical strands: The first predicts that early puberty amplifies preexisting childhood characteristics (e.g. the accentuation hypothesis, Caspi & Moffitt, 1999). The second predicts that early maturation fundamentally changes developmental trajectories (e.g. hormonal influences hypothesis, Schulz, Molenda-Figueira, & Sisk, 2009). The third predicts that the impact of early puberty is context-dependent (e.g. differential susceptibility hypothesis, Belsky, Bakermans-Kranenburg, & Van Ijzendoorn, 2007).

Theory Strand 1: Early puberty amplifies pre-existing problems

The first theory strand suggests that early puberty amplifies pre-existing problems. A primary example of this line of thought is the accentuation hypothesis (Caspi & Moffitt, 1991). This hypothesis suggests that pre-pubertal emotional and behavioral problems are exacerbated at the onset of puberty (Figure 1A). Early physical maturation is here framed

as a life stressor that adds to and magnifies existing childhood problems. The accentuation hypothesis predicts that maladaptive behaviors are thought to become magnified by early puberty, compared to later maturing peers. In line with these considerations, current research shows that early pubertal timing amplifies the link between childhood problems and adolescent substance use (Beltz, Corley, Wadsworth, DiLalla, & Berenbaum, 2019; Senia, Donnellan, & Neppl, 2018). Effects may not persist into adulthood, however (Senia et al., 2018). Presently, there is little evidence for this hypothesis for cognitive outcomes.

Theory Strand 2: Early puberty alters developmental trajectories

The hormonal influence hypothesis (Schulz, Molenda-Figueira, & Sisk, 2009) and maturation disparity hypothesis (Brooks-Gunn, Petersen, & Eichorn, 1985) predict that early puberty fundamentally changes developmental trajectories (Figure 1B). These theories are complimentary to the accentuation hypothesis, as they, too, predict mainly poorer outcomes for early maturers.

The hormonal influence hypothesis suggests that the brain‘s sensitivity to pubertal hormones decreases with age. Therefore, puberty and the associated hormonal changes assert a stronger effect on behavior and cognition earlier than later in development. This hypothesis stands in the tradition of theories predicting a decrease in plasticity over the lifespan (Kühn & Lindenberger, 2015; Oberman & Pascual-Leone, 2013). It suggests that an early increase in pubertal hormones contributes to a premature decrease in plasticity and thus closure of sensitive periods for cognitive development in childhood (Juraska & Willing, 2017; Piekarski, Boivin, et al., 2017; Piekarski, Johnson, et al., 2017; Figure 1B).

Recent animal studies provide causal evidence that pubertal hormones impact on plasticity and can have negative effects on learning. Pubertal hormones have been shown to affect inhibitory interneurons like parvalbumin-positive large basket cells and brain-derived neurotrophic factor expression, as well as γ-aminobutyric acid (GABA) neurotransmission. All of these mechanisms contribute to the opening and closure of sensitive periods (Hill, Wu, Kwek, & Van den Buuse, 2012; Piekarski, Boivin, et al., 2017; Wu, Du, Van den Buuse, & Hill, 2014). Their effects are region-specific and may be particularly pronounced in the frontal cortex and hippocampus (see Laube et al., 2020). Pubertal hormones may also be related to decreases in cognitive performance, potentially decreasing capacity for learning (Nguyen et al., 2017; Piekarski, Boivin, et al., 2017). Piekarski and colleagues (2017), for instance, manipulated pubertal onset via pre-pubertal hormone treatment and found that mice with peri-pubertal exposure to gonadal hormones required more trials to reach criterion performance in a reversal-learning task compared to controls.

While the hormonal influence hypothesis is mainly concerned with the biological effects of early puberty, the maturation disparity hypothesis highlights social effects of early maturation. Early maturers may have less opportunity to prepare cognitively and socially for the changes and challenges of puberty and adolescence. Due to a more mature physical appearance, early maturers may be treated as older than they actually are, or affiliate with older peers, without necessarily having had time to develop the relevant

cognitive and social skills to navigate a more mature world (Caspi, Lynam, Moffitt, & Silva, 1993). In line with this prediction, Acacio-Claro, Koivusilta, Doku and Rimpelä (2019) sampled a total of 37,876 adolescents and found that those with early puberty timing showed more stress symptoms, and were less likely to share problems with their family. Early maturation was not associated with lower academic achievement in this study, however. Delayed, rather than early puberty was related to lower school achievement in boys, although this effect dissipated in adulthood.

In a similarly critical vein, Chaku and Hoyt (2019) argued that early maturation may present opportunities as well as obstacles. Early maturers may be exposed to new roles and responsibilities before the majority of their peers, giving them unique, and prolonged opportunities for cognitive growth and social advantage. This suggestion is in line with recent theoretical suggestions highlighting that adolescence may form another sensitive period after early childhood, particularly for higher-order cognitive functions in adolescence (Fuhrmann et al., 2015; Larsen & Luna, 2018). Early pubertal onset may then prolong this sensitive phase.

Koerselman and Pekkarinen (2017) provided some evidence for potential benefits associated with earlier puberty. They showed larger gains in mathematics and reading test scores between ages seven and 16 for children with early, compared to late, pubertal development. In a recent, seven-year longitudinal study with 1,099 young people aged 9.5-15.5 years of age, Chaku & Hoyt (2019) also showed that early maturing girls showed both increases in attention, as well as less self-control over the course of adolescence, highlighing the complexities of developmental outcomes of pubertal timing.

Theory Strand 3: Early puberty increases susceptibility to context

In contrast to Theory Strands 1 and 2, Theory Strand 3 highlights context-dependencies. The contextual amplification hypothesis predicts that harsh social environments combined with early puberty increase the cumulative risk of problematic behavior (Figure 1, C1 and C2). Consistent with this account, several studies have shown that environmental factors such as family environment and parenting styles moderate the association between early pubertal timing and problematic behavior (for a review, see Ge, Natusaki, Jin & Biehl, 2011), although there is little data on cognitive outcomes.

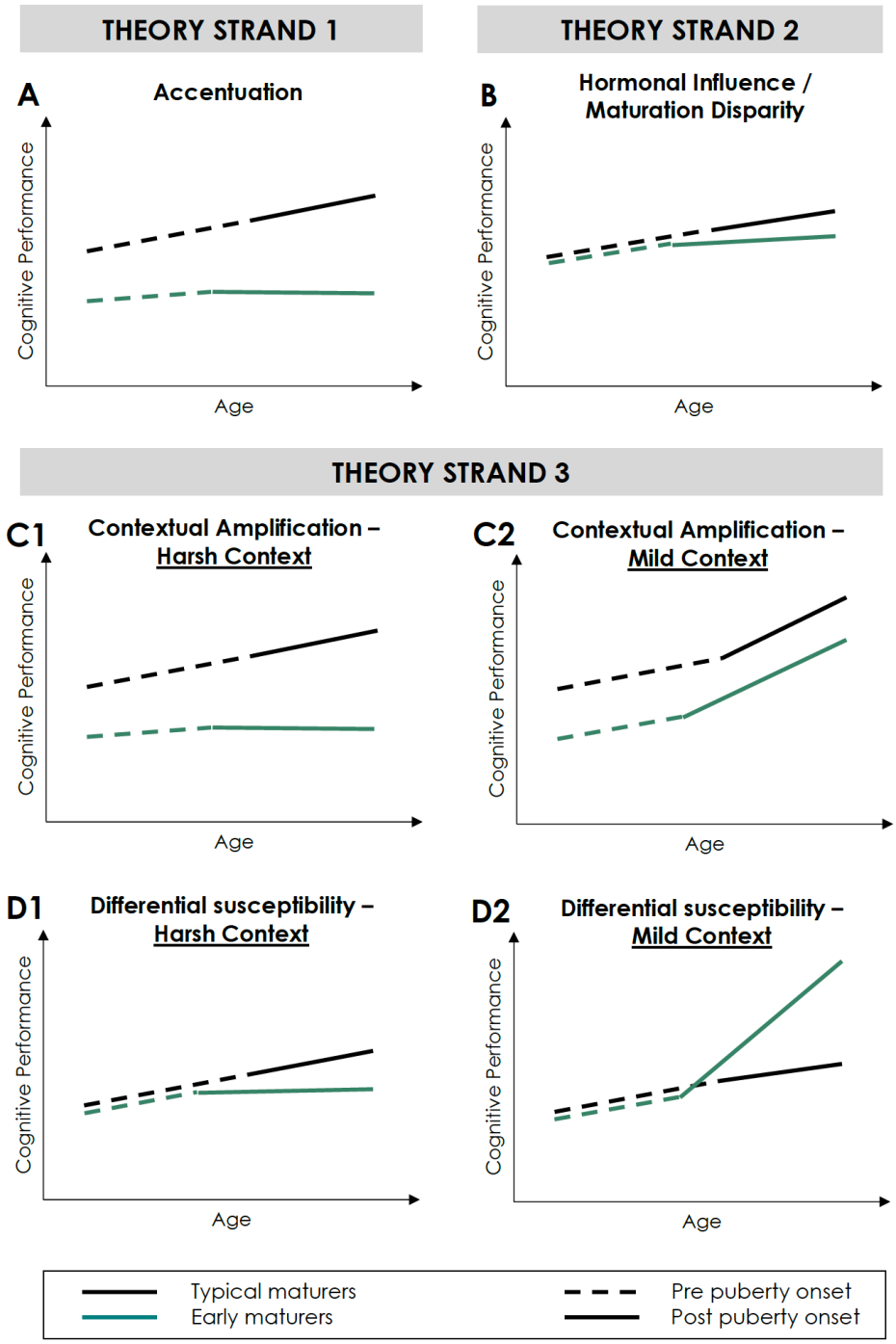

Figure 1. Cognitive trajectories for early maturers (shown in green) and typical maturers (shown in black), as predicted by three different theoretical frameworks of early puberty (Theory Strand 1: Early puberty amplifies pre-existing problems; Theory Strand 2: Early puberty alters developmental trajectories; Theory Strand 3: Early puberty increases susceptibility to context). We considered the following frameworks within these Strands: accentuation hypothesis (Caspi & Moffitt, 1991), hormonal influence hypothesis (Schulz, Molenda-Figueira, & Sisk, 2009), maturation disparity hypothesis (Brooks-Gunn, Petersen, & Eichorn, 1985), contextual amplification hypothesis (Ge, Natusaki, Jin & Biehl, 2011) and differential susceptibility hypotheses (Belsky, Bakermans-Kranenburg, & Van Ijzendoorn, 2007). Trajectories pre puberty onset are shown as dashed lines, trajectories post puberty onset is shown as solid lines.

The differential susceptibility hypothesis (Belsky, Bakermans-Kranenburg, & Van Ijzendoorn, 2007) suggests that early pubertal timing increases the susceptibility to both positive and negative environmental influences (Figure 1, D1 and D2). That is, early maturers may show heightened susceptibility to supportive and nurturing influences, as well as to harsh and adverse ones. Chen & Raine (2017) tested this hypothesis in a sample of 411 community-recruited youth aged 11-12. They found that harsh parenting predicted more aggressive behavior in early, but not late maturing individuals. Conversely, positive parenting was associated with less aggressive behavior, but only among early maturing individuals. Similarly, a study by Klopack, Sutton, Simons, & Simons (2019) showed that the social context including factors such as parenting, peers and neighborhood were related to social competence, and delinquent behavior in late adolescence, depending on the nature of relationships. The authors also found a significant, albeit weak, association between early and average pubertal onset and higher educational level in adulthood. We note that there is little data on cognitive outcomes.

Overall, all Theory Strands predict a change in developmental trajectories after early puberty (Figure 1). Animal studies support the accentuation hypothesis. They clearly show that pubertal hormones are implicated in mechanisms of plasticity, with mainly negative effects on cognitive outcomes (Piekarski, Boivin, et al., 2017; Piekarski, Johnson, et al., 2017). However, findings in the human literature are more mixed, demonstrating both costs (Cavanagh et al., 2007; Nguyen et al., 2017) and benefits (Chaku & Hoyt, 2019; Korselmann & Pekkarinen, 2017) or no clear effects at all (Acacio-Claro et al., 2019). These mixed results are more easily accommodated by theories predicting a context-dependent effect of early puberty. For humans, social context, may play a larger role in determining lifespan outcomes than for other animals (see Textbox Questions for Future Research).

Pubertal timing in the larger social context

In 1964, Douglas and Ross showed that these effects may differ between adolescents from different social background. Using the British National Survey of Health and Development (N = 5,000), the authors showed that early maturers of both genders showed superior performance in intelligence and attainment assessments at ages 8, 11 and 15 years. The authors noted, however, that this effect did not hold for participants from working class backgrounds. Early maturing boys and girls from a working class background left education earlier than their later maturing peers. This study was one of the first to highlight that the detrimental effects of puberty observed in some studies may not be solely due to direct effects of pubertal timing on cognition and achievement. Rather, socio-cultural effects may mediate the effects of early puberty on cognition.

Lower educational attainment after early maturation may partly be due to motivational effects (Martin and Steinbeck, 2017). Martin and Steinbeck (2017) found that a more advanced pubertal status did not directly predict academic achievement, but rather academic motivation, which included factors such as academic self-efficacy and

valuing of school. Academic motivation was found to be significantly lower for more mature participants, which was, in turn, related to lower academic achievement. These motivational differences may be related to pubertal, hormone-related increases in impatience observed both at a behavioral (Cardoos et al., 2017; Laube, Suleiman, Johnson, Dahl, & van den Bos, 2017) and neural level (Laube, Lorenz, & van den Bos, 2020; Op De MacKs et al., 2011). These motivational differences may also reflect reasonable, and possibly adaptive, responses to living in more uncertain social contexts (Frankenhuis & Nettle, 2019). For instance, there are studies showing that women from more advantaged backgrounds on average benefit from delayed childbearing in terms of both infant health (Cohen, 2016) and employment (Florian, 2018). For women from more disadvantaged backgrounds, however, early childbearing may, on average, be associated with reduced infant health (Cohen, 2016). This may be an adaptive response to stress effects accumulating over the years and impacting maternal health more at older ages (Cohen, 2016).

Carter, Mustafaa, & Leath (2018) highlighted another potential route by which the social environment may affect cognitive outcomes. The authors showed elementary school teachers' drawings of black and white girls at varying stages of pubertal development. Teachers were then asked to predict future academic success and social functioning. Teachers expected more physically developed girls to show lower academic performance and more social problems for both ethnicities. This effect was more pronounced for black than white girls, however. These results support the notion that academic achievement may be shaped by expectations and reactions of society towards early physical maturation. Overall, these findings suggest that biological processes interact with socio-cultural context and expectations.

Conclusion

Early puberty is often thought to be associated with negative outcomes. However, recent work on the relationship between early puberty and cognition highlights domain- and context-specific effects. Early maturation may be related to positive outcomes for domains such as attention and negative outcomes for domains such as self-control, though general laws governing cognitive strengths and weaknesses after early puberty still need to be specified. It has become clear that early maturation may not necessarily affect cognition and academic outcomes directly. Rather, negative effects of early puberty may be related to academic motivation and reactions from the social environment to early maturation. Future research can help us understand what social contexts are related to positive outcomes and how interventions can harness developmental plasticity and sensitive periods in adolescence to foster positive social environments for early maturers (see Textbox Questions for future research).

Questions for future research

Domain specificity: What cognitive domains are spared or positively impacted by early maturation? What domains are negatively impacted?

Context dependencies: What kind of context fosters cognitive health for early maturers? What kind of context impacts early maturers positively? What influence do familial, school and peer factors have?

Plasticity and sensitive periods: How malleable are early maturers to interventions (e.g. cognitive training)? At what point in life are they most susceptible to interventions?

Testing mechanisms: Can we use animal models to isolate causal mechanisms (e.g. specific hormones and neural pathways) that lead to changes in plasticity after early maturation?

Testing theoretical predictions: What maturation hypothesis best predicts longitudinal trajectories of cognitive development?

Generating new theoretical predictions: Can we test the costs and benefits of early maturation on cognitive outcomes using, for instance, life history theory and optimality models?

Acknowledgements:

We thank Oisin Butler and Rogier Kievit for helpful comments on the manuscript.

References and recommended reading

Papers of particular interest, published within the period of review, have been highlighted as:

* of special interest

** of outstanding interest

** Acacio-Claro, P. J., Koivusilta, L. K., Doku, D. T., & Rimpelä, A. H. (2019). Timing of puberty and reserve capacity in adolescence as pathways to educational level in adulthood—a longitudinal study. *Annals of Human Biology*, *46*(1), 35–45. https://doi.org/10.1080/03014460.2019.1596311

This longitudinal study followed 37,876 adolescents into adulthood and found that early puberty was related to more stress symptoms, less physical activity and less openness with family and friends. However, this directionality did not hold for academic achievement, where delayed pubertal timing increased the probability of having low-to-middle education in adulthood. This effect dissipated by adulthood, however. This study highlights mixed findings in large samples, as well as the importance of following participants into adulthood. The latter allows us to assess long-term consequences of early puberty and gives us the opportunity to assess outcomes at a point in development at which early and late maturers can be matched for both puberty stage and age.

Belsky, J., Bakermans-Kranenburg, M. J., & Van Ijzendoorn, M. H. (2007). For better and for worse: Differential susceptibility to environmental influences. *Current Directions in Psychological Science*, *16*(6), 300–304. https://doi.org/10.1111/j.1467-

8721.2007.00525.x

Beltz, A. M., Corley, R. P., Wadsworth, S. J., DiLalla, L. F., & Berenbaum, S. A. (2019). Does puberty affect the development of behavior problems as a mediator, moderator, or unique predictor? *Development and Psychopathology*, 1–13. https://doi.org/10.1017/S095457941900141X

Biro, F. M., Lucky, A. W., Huster, G. A., & Morrison, J. A. (1995). Pubertal staging in boys. *The Journal of Pediatrics*, *127*(1), 100–102. https://doi.org/10.1016/S0022-3476(95)70265-2

Bodicoat, D. H., Schoemaker, M. J., Jones, M. E., McFadden, E., Griffin, J., Ashworth, A., & Swerdlow, A. J. (2014). Timing of pubertal stages and breast cancer risk: The Breakthrough Generations Study. *Breast Cancer Research*, *16*(1), 1–8. https://doi.org/10.1186/bcr3613

Brooks-Gunn, J., Petersen, A. C., & Eichorn, D. (1985). The study of maturational timing effects in adolescence. *Journal of Youth and Adolescence*, *14*(3), 149–161. https://doi.org/10.1007/BF02090316

Cardoos, S. L., Ballonoff, A., Johnson, M., Bos, W. Van Den, Hinshaw, S. P., & Dahl, R. E. (2017). Psychoneuroendocrinology Social status strategy in early adolescent girls : Testosterone and value-based decision making. *Psychoneuroendocrinology*, *81*, 14–21. https://doi.org/10.1016/j.psyneuen.2017.03.013

Carter, R., Mustafaa, F. N., & Leath, S. (2018). Teachers' Expectations of Girls' Classroom Performance and Behavior: Effects of Girls' Race and Pubertal Timing. *Journal of Early Adolescence*, *38*(7), 885–907. https://doi.org/10.1177/0272431617699947

Casey, B. J. (2014). Beyond Simple Models of Self-Control to Circuit-Based Accounts of Adolescent Behavior. *Annual Review of Psychology*, (July 2014), 1–25. https://doi.org/10.1146/annurev-psych-010814-015156

Caspi, A., Lynam, D., Moffitt, T. E., & Silva, P. A. (1993). Unraveling girls' delinquency: Biological, dispositional, and contextual contributions to adolescent misbehavior. *Developmental Psychology*, *29*(1), 19–30. https://doi.org/10.1037//0012-1649.29.1.19

Caspi, A., & Moffitt, T. E. (1991). Individual differences are accentuated during periods of social change: The sample case of girls at puberty. *Journal of Personality and Social Psychology*, *61*(1), 157–168. https://doi.org/10.1037//0022-3514.61.1.157

Callaghan, B. L., & Tottenham, N. (2016). The stress acceleration hypothesis: Effects of early-life adversity on emotion circuits and behavior. Current Opinion in Behavioral Sciences, 7, 76–81. doi:10.1016/j.cobeha.2015.11.018

Cavanagh, S. E., Riegle-Crumb, C., & Crosnoe, R. (2007). Puberty and the education of girls. *Social Psychology Quarterly*, *70*(2), 186–198. https://doi.org/10.1177/019027250707000207

** Chaku, N., & Hoyt, L. T. (2019). Developmental Trajectories of Executive Functioning and Puberty in Boys and Girls. *Journal of Youth and Adolescence*, *48*(7), 1365–1378. https://doi.org/10.1007/s10964-019-01021-2

A longitudinal study with 1099 youg people showing that early puberty is related to better attention skills for both boys and girls. In addition, early puberty onset predicted less self-control in girls, highlighing the complexities of puberal processes and its

diverse effects on development.

Chen, F. R., & Raine, A. (2017). Effects of harsh parenting and positive parenting practices on youth aggressive behavior: The moderating role of early pubertal timing. *Aggressive Behavior*, *44*(1), 18–28. https://doi.org/10.1002/ab.21720

Cohen, P. N. (2016). Maternal age and infant mortality for white, black, and Mexican mothers in the United States. *Sociological Science,* 3, 32-38.

Crone, E. a, & Dahl, R. E. (2012). Understanding adolescence as a period of social-affective engagement and goal flexibility. *Nature Reviews. Neuroscience*, *13*(9), 636–650. https://doi.org/10.1038/nrn3313

Day, F. R., Elks, C. E., Murray, A., Ong, K. K., & Perry, J. R. B. (2015). Puberty timing associated with diabetes, cardiovascular disease and also diverse health outcomes in men and women: The UK Biobank study. *Scientific Reports*, *5*(April), 1–12. https://doi.org/10.1038/srep11208

Douglas, J. W. B., & Ross, J. M. (1964). Age of Puberty Related To Educational Ability, Attainment and School Leaving Age. *Journal of Child Psychology and Psychiatry*, *5*(3–4), 185–196. https://doi.org/10.1111/j.1469-7610.1964.tb02140.x

* Eckert-Lind, C., Busch, A. S., Petersen, J. H., Biro, F. M., Butler, G., Bräuner, E. V., & Juul, A. (2020). Worldwide Secular Trends in Age at Pubertal Onset Assessed by Breast Development among Girls: A Systematic Review and Meta-analysis. *JAMA Pediatrics*, 1–11. https://doi.org/10.1001/jamapediatrics.2019.5881

A comprehensive review and meta-analysis of 38 international studies assessing age at pubertal onset in healthy girls.

Euling, S. Y., Herman-Giddens, M. E., Lee, P. A., Selevan, S. G., Juul, A., Sørensen, T. I. A., … Swan, S. H. (2008). Examination of US puberty-timing data from 1940 to 1994 for secular trends: Panel findings. *Pediatrics*, *121*(SUPPL.3). https://doi.org/10.1542/peds.2007-1813D

Florian, S. M. (2018). Motherhood and employment among whites, Hispanics, and blacks: a life course approach. *Journal of Marriage and Family*, 80(1), 134-149.

Frankenhuis, W. E. & Nettle, D. (2020). The strengths of people in poverty. C*urrent Directions in Psychological Science*, 29(1), 16-21. doi:10.1177/0963721419881154

Fuhrmann, D., Knoll, L. J., & Blakemore, S. J. (2015). Adolescence as a Sensitive Period of Brain Development. *Trends in Cognitive Sciences*, *19*(10), 558–566. https://doi.org/10.1016/j.tics.2015.07.008

Ge, X., Natsuaki, M. N., Jin, R., & Biehl,M. (2011). A contextual amplification hypothesis: Pubertal timing and girls' emotional and behavioral problems. In M. Kerr, H. Stattin, R. C. M. E. Engels, G. Overbeek, & A.-K. Andershed (Eds.), *Understanding girls' problem behavior: How girls' delinquency develops in the context of maturity and health, co-occurring problems, and relationships* (pp. 11–30). London, UK: Wiley.

Hill, R. A., Wu, Y. W. C., Kwek, P., & Van den Buuse, M. (2012). Modulatory Effects of Sex Steroid Hormones on Brain-Derived Neurotrophic Factor-Tyrosine Kinase B Expression during Adolescent Development in C57Bl/6 Mice. *Journal of Neuroendocrinology*, *24*(5), 774–788. https://doi.org/10.1111/j.1365-2826.2012.02277.x

Juraska, J. M., & Willing, J. (2017). Pubertal onset as a critical transition for neural

development and cognition. *Brain Research*, *1654*, 87–94. https://doi.org/10.1016/j.brainres.2016.04.012

Klopack, E. T., Sutton, T. E., Simons, R. L., & Simons, L. G. (2019). Disentangling the Effects of Boys' Pubertal Timing: The Importance of Social Context. *Journal of Youth and Adolescence*. https://doi.org/10.1007/s10964-019-01141-9

Knoll, L. J., Fuhrmann, D., Sakhardande, A. L., Stamp, F., Speekenbrink, M., & Blakemore, S.-J. (2016). A Window of Opportunity for Cognitive Training in Adolescence. *Psychological Science*, *27*(12), 1620–1631. https://doi.org/10.1177/0956797616671327

Koerselman, K., & Pekkarinen, T. (2017). The Timing of Puberty and Gender Differences in Educational Achievement. *IZA Discussion Paper;10889*, (10889).

Kühn, S., & Lindenberger, U. (2015). Research on Human Plasticity in Adulthood: A Lifespan Agenda. *Handbook of the Psychology of Aging: Eighth Edition*, 105–123. https://doi.org/10.1016/B978-0-12-411469-2.00006-6

Larsen, B., & Luna, B. (2018). Adolescence as a neurobiological critical period for the development of higher-order cognition. *Neuroscience and Biobehavioral Reviews*, *94*(March), 179–195. https://doi.org/10.1016/j.neubiorev.2018.09.005

Laube, C., Lorenz, R., & van den Bos, W. (2020). Pubertal testosterone correlates with adolescent impatience and dorsal striatal activity. *Developmental Cognitive Neuroscience*, *42*(February 2019), 100749. https://doi.org/10.1016/j.dcn.2019.100749

Laube, C., Suleiman, A. B., Johnson, M., Dahl, R. E., & van den Bos, W. (2017). Dissociable effects of age and testosterone on adolescent impatience. *Psychoneuroendocrinology*, *80*, 162–169. https://doi.org/10.1016/j.psyneuen.2017.03.012

Laube, C., van den Bos, W., & Fandakova, Y. (2020). The relationship between pubertal hormones and brain plasticity: Implications for cognitive training in adolescence. *Developmental Cognitive Neuroscience*, *42*(January), 100753. https://doi.org/10.1016/j.dcn.2020.100753

Lee, P. A. (1980). Normal ages of pubertal events among American males and females. *Journal of Adolescent Health Care, 1*(1), 26-29, doi: 10.1016/S0197-0070(80)80005-2

Li, S. C., Lindenberger, U., Hommel, B., Aschersleben, G., Prinz, W., & Baltes, P. B. (2004). Transformations in the Couplings Among Intellectual Abilities and Constituent Cognitive Processes Across the Life Span. *Psychological Science*, *15*(3), 155–163. https://doi.org/10.1111/j.0956-7976.2004.01503003.x

Martin, A. J., & Steinbeck, K. (2017). The role of puberty in students' academic motivation and achievement. *Learning and Individual Differences*, *53*, 37–46. https://doi.org/10.1016/j.lindif.2016.11.003

Nguyen, T. V., Lew, J., Albaugh, M. D., Botteron, K. N., Hudziak, J. J., Fonov, V. S., … McCracken, J. T. (2017). Sex-specific associations of testosterone with prefrontal-hippocampal development and executive function. *Psychoneuroendocrinology*, *76*, 206–217. https://doi.org/10.1016/j.psyneuen.2016.12.005

NHS (2020). Stages of puberty: what happens to boys and girls. Retrieved from https://www.nhs.uk/live-well/sexual-health/stages-of-puberty-what-happens-to-

boys-and-girls

Oberman, L., & Pascual-Leone, A. (2013). Changes in plasticity across the lifespan: Cause of disease and target for intervention. *Progress in Brain Research*, *207*, 91–120. https://doi.org/10.1016/B978-0-444-63327-9.00016-3

* Ohlsson, C., Bygdell, M., Celind, J., Sondén, A., Tidblad, A., Sävendahl, L., & Kindblom, J. M. (2019). Secular Trends in Pubertal Growth Acceleration in Swedish Boys Born from 1947 to 1996. *JAMA Pediatrics*, *173*(9), 860–865. https://doi.org/10.1001/jamapediatrics.2019.2315

This paper provides recent data on a secular trend for ealier pubertal timing among boys.

Op De MacKs, Z. a., Moor, B. G., Overgaauw, S., Gürolu, B., Dahl, R. E., & Crone, E. a. (2011). Testosterone levels correspond with increased ventral striatum activation in response to monetary rewards in adolescents. *Developmental Cognitive Neuroscience*, *1*(4), 506–516. https://doi.org/10.1016/j.dcn.2011.06.003

Parent, A. S., Teilmann, G., Juul, A., Skakkebaek, N. E., Toppari, J., & Bourguignon, J. P. (2003). The Timing of Normal Puberty and the Age Limits of Sexual Precocity: Variations around the World, Secular Trends, and Changes after Migration. *Endocrine Reviews*, *24*(5), 668–693. https://doi.org/10.1210/er.2002-0019

Pattwell, S. S., Duhoux, S., Hartley, C. A., Johnson, D. C., Jing, D., Elliott, M. D., … Lee, F. S. (2012). Altered fear learning across development in both mouse and human. *Proceedings of the National Academy of Sciences of the United States of America*, *109*(40), 16318–16323. https://doi.org/10.1073/pnas.1206834109

Piekarski, D. J., Boivin, J. R., & Wilbrecht, L. (2017). Ovarian Hormones Organize the Maturation of Inhibitory Neurotransmission in the Frontal Cortex at Puberty Onset in Female Mice. *Current Biology*, *27*(12), 1735-1745.e3. https://doi.org/10.1016/j.cub.2017.05.027

This animal study provides causal evidence that early puberty onset leads to early increases in inhibitory neurotransmission in the frontal cortex. This suggests that earlier puberty may advance cortical maturation and thus regulate sensitive periods for cognitive development. In addition, the authors demonstrate that mice with peri-pubertal exposure to gonadal hormones required more trials to reach criterion performance in a reversal-learning task compared to controls.

Piekarski, D. J., Johnson, C. M., Boivin, J. R., Thomas, A. W., Lin, W. C., Delevich, K., … Wilbrecht, L. (2017). Does puberty mark a transition in sensitive periods for plasticity in the associative neocortex? *Brain Research*, *1654*, 123–144. https://doi.org/10.1016/j.brainres.2016.08.042

Prentice, P., & Viner, R. M. (2013). Pubertal timing and adult obesity and cardiometabolic risk in women and men: A systematic review and meta-analysis. *International Journal of Obesity*, *37*(8), 1036–1043. https://doi.org/10.1038/ijo.2012.177

Rubia, K., Smith, A. B., Woolley, J., Nosarti, C., Heyman, I., Taylor, E., & Brammer, M. (2006). Progressive increase of frontostriatal brain activation from childhood to adulthood during event-related tasks of cognitive control. *Human Brain Mapping*, *27*(12), 973–993. https://doi.org/10.1002/hbm.20237

Scherf, K. S., Behrmann, M., & Dahl, R. E. (2012). Facing changes and changing faces in

adolescence: A new model for investigating adolescent-specific interactions between pubertal, brain and behavioral development. *Developmental Cognitive Neuroscience, 2*, 199–219. doi:10.1016/j.dcn.2011.07.016

Schulz, K. M., Molenda-Figueira, H. a., & Sisk, C. L. (2009). Back to the future: The organizational–activational hypothesis adapted to puberty and adolescence. *Hormones and Behavior*, *55*(5), 597–604. https://doi.org/10.1016/j.yhbeh.2009.03.010

Senia, J. M., Donnellan, M. B., & Neppl, T. K. (2018). Early pubertal timing and adult adjustment outcomes: Persistence, attenuation, or accentuation? *Journal of Adolescence*, *65*(March), 85–94. https://doi.org/10.1016/j.adolescence.2018.03.003

Shirtcliff, E. a., Dahl, R. E., & Pollak, S. D. (2009). Pubertal development: Correspondence between hormonal and physical development. *Child Development*, *80*(2), 327–337. https://doi.org/10.1111/j.1467-8624.2009.01263.x

Sørensen, K., Mouritsen, A., Aksglaede, L., Hagen, C. P., Mogensen, S. S., & Juul, A. (2012). Recent secular trends in pubertal timing: Implications for evaluation and diagnosis of precocious puberty. *Hormone Research in Paediatrics*, *77*(3), 137–145. https://doi.org/10.1159/000336325

Stumper, A., Mac Giollabhui, N., Abramson, L. Y., & Alloy, L. B. (2020). Early Pubertal Timing Mediates the Association between Low Socioeconomic Status and Poor Attention and Executive Functioning in a Diverse Community Sample of Adolescents. *Journal of Youth and Adolescence*. https://doi.org/10.1007/s10964-020-01198-x

Suleiman, A., & Harden, K. P. (2016). The importance of sexual and romantic development in understanding the developmental neuroscience of adolescence. *Developmental Cognitive Neuroscience, 17*, 145-147. https://doi.org/10.1016/j.dcn.2015.12.00

Ullsperger, J. M., & Nikolas, M. A. (2017). Supplemental Material for A Meta-Analytic Review of the Association Between Pubertal Timing and Psychopathology in Adolescence: Are There Sex Differences in Risk? *Psychological Bulletin*, *143*(9), 903–938. https://doi.org/10.1037/bul0000106.supp

Walvoord, E. C. (2010). The timing of puberty: Is it changing? Does it matter? *Journal of Adolescent Health*, *47*(5), 433–439. https://doi.org/10.1016/j.jadohealth.2010.05.018

Wu, Y. W. C., Du, X., Van den Buuse, M., & Hill, R. A. (2014). Sex differences in the adolescent developmental trajectory of parvalbumin interneurons in the hippocampus: A role for estradiol. *Psychoneuroendocrinology*, *45*, 167–178. https://doi.org/10.1016/j.psyneuen.2014.03.016