Cell Press

Neuron
NeuroView

Insights about Adolescent Behavior, Plasticity, and Policy from Neuroscience Research

Adriana Galván[1,*]
[1]Department of Psychology University of California, Los Angeles, Los Angeles, CA 90095, USA
*Correspondence: agalvan@ucla.edu
http://dx.doi.org/10.1016/j.neuron.2014.06.027

Adolescent brain research has offered an explanation of adolescent behavior relevant for parents, society, and policymakers. As the science continues to evolve, it will advance understanding of adolescent potential and individual variation to further generate developmentally appropriate expectations, policies, and sanctions.

The explosion of research on the adolescent brain in recent years has triggered enthusiastic attention from the media, policymakers, and legal scholars alike. Initial media portrayals of this research fueled the perception that the developing brain was an enigma to be reckoned with and that it rendered adolescents fragile, troubled, and irrational. Fortunately, scientists have increasingly rectified this perception through empirical research showing that the ontogenetic changes in the adolescent brain are adaptive for the individual and beneficial for society. Nonscientists are now connecting with developmental cognitive neuroscience researchers to enact meaningful voices in shaping social policy and legal sanctions related to adolescents. Although still relatively new compared to the plethora of research on earlier and later stages of development, adolescent brain research has thus far been impactful in at least three ways. First, it has neurobiologically differentiated adolescents from children and adults. Second, it has helped explain adolescent behavior. Third, it demonstrates that the brain is adaptively plastic well beyond the early postnatal years. These advancements have been essential to the mission of generating developmentally appropriate expectations, policies, and sanctions for adolescents. More broadly, the research has generated a fresh perspective on this powerful period of life.

Adolescence: A Distinct Neurodevelopmental Stage

At no other time in life is there greater intrinsic motivation to explore new experiences than during adolescence (Crone and Dahl, 2012). Youth are often at the forefront of new ideas, impassioned defenders of ideals, fervid leaders, and the ones having the most fun in the quest for autonomy. These characteristics are what make adolescents adolescents—despite better cognitive, intellectual, and reasoning abilities than children, adolescents are not simply "mini-adults" and despite immature emotion regulation, inexperience, and dependence on caregivers, adolescents are not overgrown children. Instead, they are in a distinct developmental stage that facilitates the adaptive transition from a state of dependence on caregivers to one of relative independence. However, along the road to autonomy, the very same characteristics that catalyze independence may lead adolescents to stumble into harmful behaviors—ones that have been the focus of our society's perception of the teenage years. Historically, lawmakers have tended to binarize age boundaries between "minors," who are presumed to be vulnerable, dependent, and incompetent to make decisions, and adults, who are viewed as autonomous, responsible, and entitled to exercise legal rights and privileges (Bonnie and Scott, 2013). However, neuroscience research conducted over the past two decades has demonstrated that the adolescent brain is anatomically and functionally unique. Using neuroimaging tools, researchers have examined the human brain in vivo to identify adolescent-specific neurobiological changes.

Research by Casey et al. (1997) was the first to empirically connect protracted neural development with immature cognitive regulation in humans. The prefrontal cortex, a region important in self-control and rational decision making, is the last brain region to mature, well into the mid-20s and long past the normative developmental trends of other brain regions. This protracted development is paralleled by significant increases in neurocognitive maturation and is functionally meaningful because it places adolescents in the unique neurocognitive position of being more cognitively sophisticated than younger children but not quite as experienced, wise, and mature as adults. Several recent studies have demonstrated that the relatively unstable nature of the prefrontal cortex in adolescents renders it more susceptible to emotional, arousing, or distracting information than in adults (e.g. Somerville et al., 2011; Geier et al., 2010). In fact, whereas adolescents and adults perform comparably on cognitive tests and logical reasoning, adolescents are not as equally mature when it comes to capacities such as impulse control, reward sensitivity, and resistance to peer influence (Steinberg, 2013). Numerous studies have shown that the adolescent brain functions differently based on context—in "cold" or unarousing situations, adolescent behavior and brain function is very similar to that of adults, but under "hot" or arousing conditions, adolescent behavior is more impulsive and emotional (Somerville et al., 2011; Figner et al., 2009). The application to real life is clear: policies about adolescents need to take into consideration the capricious nature of adolescent behavior.

The prefrontal susceptibility to arousing information has previously been described as a "hijacking" of the regulatory system by the affective system (Casey and Caudle, 2013). During adolescence, affective neural systems, including the striatum and amygdala, undergo a fluctuating course of development. These systems are most excitable and responsive to the environment during adolescence, rendering adolescents more reward-seeking, risk-sensitive, and emotionally reactive than younger or older individuals (Galván, 2013). Adolescents exhibit enhanced activation of the ventral striatum in response to rewards, an effect that is linked to increased risky behavior (Galván et al., 2007). This hyperactivation persists through the late adolescent years and into early adulthood (Lamm et al., 2014), underscoring the protracted development of the reward system. Using connectivity methods, researchers have recently shown that this developmental trajectory also applies to communication between neural networks: prefrontal regulation of affective regions that is normative in adults has not yet reached equilibrium in adolescents (Somerville et al., 2011). The brain continues to increase in the efficiency of connections between these systems in adolescence, strengthening pathways that are called upon routinely. In general, maturation of functional connections is driven by the integration of regions that are distal from each other into functional networks by strengthening of long-range functional connections (Dosenbach et al., 2010). This plasticity helps sculpt each individual's brain in an experience-dependent manner.

Plasticity = Possibility

The brain is remarkably malleable. In response to new experiences, social interactions, and learning opportunities, the brain reshapes and refines itself adaptively to fit the needs of the individual. This phenomenon is particularly true during periods of rapid development like adolescence. Although plasticity during this window renders the adolescent more vulnerable to negative influence, it also makes adolescence an ideal time to positively influence or redirect problem behaviors. Policymakers are increasingly using developmental neuroscience research to determine how well adolescents will respond to justice-system interventions (Bonnie and Scott, 2013). As such, greater efforts to determine not only which interventions are most effective but when they are most likely to change or influence behavior are necessary; this knowledge can inform targeted interventions to prevent recidivism, encourage prosocial behavior, or spark an interest in a positive activity.

Experience-based neural plasticity occurs across the entire lifespan but one unanswered question is whether adolescence is a "sensitive period" for neural development. Do events experienced during this developmental window have a uniquely consequential effect on future outcomes and behavior? In the coming decade, one goal of developmental cognitive neuroscience research will be to resolve this question. Evidence from animal models suggests that experience during the juvenile years is uniquely powerful in shaping brain architecture and behavior (Linkenhoker et al., 2005) such that habits that are established during adolescence not only sculpt the brain contemporaneously but have long-lasting effects into adulthood.

To test this empirically in humans would require large longitudinal studies in which participants who experienced an experimental manipulation at baseline were compared longitudinally to individuals who did not experience the manipulation. This type of experiment is incredibly challenging and expensive to conduct but indirect evidence suggests that adolescence is a sensitive period. First, passionate involvement in new psychosocial or spiritual experiences can generate lifelong behavioral transformations; adolescence has thus been coined a sensitive period for sociocultural processing (Blakemore and Mills, 2014). Second, Falconi et al. (2014) concluded that early adolescence is a sensitive developmental period for males. They applied time series methods to cohort mortality data and found that population stressors experienced during ages 10–14 are more strongly associated with a decrease in lifespan compared with those experienced during infancy, ages 1–9, and ages 15–19 (Falconi et al., 2014). Third, recent cross-sectional research from our laboratory demonstrates that the adolescent brain is more susceptible to input than adults. Given the alarming high proportion of adult smokers (80%) who began smoking before age 18, we hypothesized that the adolescent brain may be uniquely susceptible to cigarette cues. Our fMRI study suggests that one reason cigarette ads may be more influential in youth is because they exhibit a greater neural response in reward-related circuitry when presented with smoking cues, an effect that subsequently predicts cigarette craving (K. Do and A.G., unpublished data). Collectively, these strands of evidence indicate that adolescence is indeed a sensitive period and may explain why adolescents are more behaviorally and neurobiologically sensitive to environmental inputs than adults.

The Implications of Adolescent Brain Research on Policy

Juvenile Justice

"Raging hormones" has long been a narrative used to explain the emotional, impulsive, and passionate behavior often observed in adolescents. While hormonal changes that emerge during puberty clearly contribute to these behaviors (Crone and Dahl, 2012), maturation of frontostriatal circuitry is equally influential. Knowledge of these ontogenetic neural changes has increasingly played a role in remarkable policy and legal decisions related to juveniles. The U.S. Supreme Court's ruling on criminal behavior in juveniles (*Roper v. Simmons*, 2005, 125 S. Ct. 1183; *Graham v. Florida*, 2010, 130 S. Ct. 2011; *Miller v. Alabama*, 2012, 132 S. Ct. 2455) is perhaps the most impactful consequence of this research. Neuroscience data have been used to support the position that adolescents are less mature than adults in ways that mitigate their criminal culpability (Steinberg, 2013). In *Roper v. Simmons*, in which capital punishment was found to be unconstitutional for individuals under the age of 18 years, the Court highlighted behavioral differences between adolescents and adults with little mention of adolescent brain development. However, in more recent cases, including *Graham v. Florida*, which banned the implementation of life without parole for juveniles who are convicted of crimes other than homicide, and the joined cases of *Miller v. Alabama* and *Jackson v. Hobbs* (2012, 132 S. Ct. 1733), in which the Court held that it is unconstitutional for states to mandate life without parole for juveniles, opinions