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

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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 were directly informed by neuroscience research.

Three general characteristics of adolescent behavior, all substantiated by neuroscientific evidence, have influenced the Court. First, in several rulings the Court commented on the role of developing regulatory systems in limiting behavioral regulation, the following of which is one such example, "It is increasingly clear that adolescent brains are not yet fully mature in regions and systems related to higher-order executive functions such as impulse control, planning ahead, and risk avoidance" (*Miller v. Alabama*). Second, the Court has noted that juveniles differ from adults in being "more vulnerable or susceptible to negative influences and outside pressures, including peer pressure" (*Roper v. Simmons*). Recent neuroscience research has substantiated this opinion. In a clever experiment in which participants of different ages played a risky computer game in the presence of peers and while undergoing a brain scan, Chein and colleagues (Chein et al., 2011) demonstrated that adolescents not only take greater risks than adults in the presence of peers but that they exhibit increased activation in reward circuitry. Third, the Court opined that "the character of a juvenile is not as well formed as that of an adult. The personality traits of juveniles are more transitory, less fixed (*Roper v. Simmons*)," an opinion consonant with the plasticity of the adolescent brain and the likelihood of behavioral changes across development. The recognition that [juveniles show] "heightened capacity for change" (*Miller v. Alabama* and *Jackson v. Hobbs*) is particularly important because it has implications for the sanctions imparted on youth convicted of criminal activity.

Teenage Driving

The influence of brain research on the Supreme Court is highly significant but it will, thankfully, only impact a relatively small proportion of youth in the United States. A more wide-reaching influence of this research is on teenage driving regulations. Motor vehicle crashes are the leading cause of death for U.S. teens (Centers for Disease Control and Prevention, 2012). Per mile driven, teen drivers are three times more likely than drivers aged 20 and older to be in a fatal crash. Fatalities are even higher among adolescent drivers who are male, driving with adolescent passengers, or newly licensed (Centers for Disease Control and Prevention, 2012). Knowledge about the protracted development of the adolescent brain, and in particular, research on the limited cognitive control and hyperactive affective system, played a key role in generating driving policies for young drivers. Most states impose Graduated Driver Licensing (GDL) laws. GDL is a licensing system for novice drivers that has proven effective at reducing adolescent drivers' fatal and injury crashes by 38% and 40%, respectively (Baker et al., 2007). It has three stages of licensure: (1) a learner's permit that allows driving only while supervised by a fully licensed adult driver; (2) a probationary license that prohibits unsupervised nighttime driving and imposes passenger limits; and (3) a full license at 18 years old. These stages reflect our current understanding of adolescent brain and behavior development: the first recognizes that adolescents are inexperienced with behavioral regulation compared to adults and therefore benefit from adult supervision. The second stage reflects the empirical and anecdotal knowledge that adolescents are more susceptible to distraction, particularly social distraction, than adults. Finally, the very nature of being a graduated policy is reflective of the understanding that the adolescent brain changes in response to experience, ontogeny, and skill and that changing neural systems are directly related to increasing sophistication in behavior and decision making.

New Directions for Policy

The implications of neuroscience research will become increasingly relevant in domains other than the legal system and driving privileges. Recent attention on the potentially deleterious effects of sports-related concussions on brain development and injury is one such example. In the last year alone, several events, including the first-ever White House summit on the issue, lawsuits between the National Football League and former players, and a $10 million grant by Steve Tisch, co-owner of the New York Giants, to the UCLA School of Medicine, has fueled a national conversation about this important public health concern. In particular, there is a focus on characterizing the extent of brain damage in young athletes. A recent investigation reported over 200 sports-related deaths of young athletes between 2008 and 2011 (http://www.nata.org) and during 2001–2009, an estimated 2,651,581 youth less than 19 years old were treated annually for sports- and recreation-related injuries (Centers for Disease Control and Prevention, 2011). The grant to UCLA is to train pediatric neurologists specializing in sports concussions and research on how to prevent, diagnose, and treat the injuries among young athletes. This clinically relevant research will undoubtedly benefit from basic neuroscience research on the adolescent brain, which has already demonstrated both its vulnerability and resilience. A deeper understanding of the substantive neurobiological and psychological impact of sports-related injuries on the developing brain will help inform strategies to reduce, prevent, and treat avoidable tragedies.

Individual Differences

Despite the research advances, one issue that will continue to arise is how to incorporate the vast individual variation in adolescent behavior and neurodevelopment. Clearly, scientists recognize that behavior and brain development are highly variable across individuals but most research on the adolescent brain and all research that has been referenced in legal and policy contexts is based on group data. This is largely because of methodological constraints that necessitate inference based on a large number of research participants. One looming question that makes translation from laboratories to courtrooms challenging, therefore, is whether generic guidelines about maturation can be established based on neuroscience research or is individual variation so great as to preclude the establishment of a biological benchmark for adult-like maturity and judgment? Using multivariate pattern analysis methods, recent work has suggested that the field has made progress in using brain scans to assess functional maturation of individual brains (Dosenbach et al., 2010). Importantly, this report highlights that variability of brain maturation is as great within ages as it is between ages. For instance, within the 15 year olds in their sample, there is considerable variability in the brain maturation index (ranging from ~0.4 functional connectivity maturation index [fcMI] to 2.2 fcMI) that is as large a range as between the 10 year olds and the adults in their late 20s (Dosenbach et al., 2010, Figure 1). This example underscores how imprecise age is as an index of cognitive maturation. Despite this, it is the only index currently used to determine eligibility for most privileges in this country, including driving, voting, marrying, purchasing alcohol and cigarettes, and serving in the military. Parents and scholars know that having reached the age at which involvement in an activity is legal is not necessarily equated with the developmental maturity the activity requires. In the future, perhaps it will be wiser to consider establishing guidelines based on skill rather than age, a marker that will differ among individuals based on underlying brain development.

Conclusion

This is an exciting time for research on the adolescent brain. Never before has there been so much communication between diverse disciplines and scholars in applied fields. Nonetheless, a significant challenge is to meaningfully apply evolving research that changes as rapidly as neuromethodological tools materialize to immediate legal and policy puzzles. Science is an arduous and lengthy process that sometimes challenges existing literature. Although this method leads to credible scientific conclusions, it makes it more difficult for law and policymakers to apply the science to practice. It is therefore the responsibility of scientists to ensure that the research is appropriately interpreted and that nonscientists integrate multiple strands of research into a solid grasp of the data.

Like development itself, the science on the adolescent brain is a moving target. With every study, methodological advance, and collaboration with nonscientists, the field continues to grow. By appreciating that the adolescent brain is a sponge thirsty and receptive for new knowledge rather than one that is of strictly nefarious intent helps redirect social awareness of this significant period of life. By recognizing the power of youth, we empower youth themselves. As long as all parties involved recognize both the strengths and limitations of adolescent brain research as it applies to real-life questions and problems, it will continue to make important contributions to the lives of youth.

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