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Adolescent Maturity and the Brain: The Promise and Pitfalls of Neuroscience Research in Adolescent Health Policy

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Abstract

Longitudinal neuroimaging studies demonstrate that the adolescent brain continues to mature well into the 20s. This has prompted intense interest in linking neuromaturation to maturity of judgment. Public policy is struggling to keep up with burgeoning interest in cognitive neuroscience and neuroimaging. However, empirical evidence linking neurodevelopmental processes and adolescent real-world behavior remains sparse. Nonetheless, adolescent brain development research is already shaping public policy debates about when individuals should be considered mature for policy purposes. With this in mind, in this article we summarize what is known about adolescent brain development and what remains unknown, as well as what neuroscience can and cannot tell us about the adolescent brain and behavior. We suggest that a conceptual framework that situates brain science in the broader context of adolescent developmental research would help to facilitate research-to-policy translation. Furthermore, although contemporary discussions of adolescent maturity and the brain often use a deficit-based approach, there is enormous opportunity for brain science to illuminate the great strengths and potentialities of the adolescent brain. So, too, can this information inform policies that promote adolescent health and well-being.

Keywords

Adolescent; Health policy; Neuroscience; Neuroimaging; Judgment

In the last decade, a growing body of longitudinal neuroimaging research has demonstrated that adolescence is a period of continued brain growth and change, challenging longstanding assumptions that the brain was largely finished maturing by puberty [1–3]. The frontal lobes, home to key components of the neural circuitry underlying “executive functions” such as planning, working memory, and impulse control, are among the last areas of the brain to mature; they may not be fully developed until halfway through the third decade of life [2]. This finding has prompted interest in linking stage of neuromaturation to maturity of judgment. Indeed, the promise of a biological explanation for often puzzling adolescent health risk behavior has captured the attention of the media, parents, policymakers, and clinicians alike. Although such research is currently underway, many neuroscientists argue that empirical support for a causal

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relationship between neuromaturational processes and real-world behavior is currently lacking [4].

Despite the lack of empirical evidence, there has been increasing pressure to bring adolescent brain research to bear on adolescent health-and-welfare policy. For example, in the policy process, adolescent brain immaturity has been used to make the case that teens should be considered less culpable for crimes they commit; however, parallel logic has been used to argue that teens are insufficiently mature to make autonomous choices about their reproductive health [5]. This apparently conflicting use of neuroscience research evidence highlights the need for brain scientists, neurocognitive psychologists, and adolescent health professionals to work together to ensure appropriate translation of science for policy. Failing to proactively define or engage in a discussion about the role of neuroimaging research in policy may catalyze a course of action many adolescent health professionals would not endorse.

In this review, we begin by outlining historical attempts to use developmental benchmarks as measures of adolescent maturity. (When we refer to “maturity” we do not intend to suggest the end of development, but rather use this as shorthand for the achievement of adult-like capacities and privileges.) We then briefly summarize what is known about adolescent brain development, and what is unknown. (For in-depth reviews of adolescent brain development, and more nuanced discussions of research findings, which are beyond the scope of this review, see [6] and [7]). We provide an overview of what neuroimaging research can and cannot tell us about the adolescent brain and behavior. We then highlight the current use of the brain sciences in adolescent health policy debates. Finally, we outline a strategy for increasing the utility of brain science in public policy to promote adolescents’ well-being.

A Historical Perspective on Development and Maturity

Throughout history there have been biological benchmarks of maturity. For example, puberty has often been used as the transition point into adulthood. As societal needs have changed, so too have definitions of maturity. For example, in 13th century England, when feudal concerns were paramount, the age of majority was raised from 15 to 21 years, citing the strength needed to bear the weight of protective armor and the greater skill required for fighting on horseback [8]. More recently, in the United States the legal drinking age has been raised to 21, whereas the voting age has been reduced to 18 years so as to create parity with conscription [9]. Similarly, the minimum age to be elected varies by office in the U.S.: 25 years for the House of Representatives, 30 years for the Senate, and 35 years for President. However, individuals as young as 16 can be elected Mayor in some municipalities. The variation evident in age-based definitions of maturity illustrates that most are developmentally arbitrary [9]. Nonetheless, having achieved the legal age to participate in a given activity (e.g., driving, voting, marrying) often comes to be taken as synonymous with the developmental maturity required for it.

Age-based policies are not exceptional; policies are frequently enacted in the face of contradictory or nonexistent empirical support [10]. Although neuroscience has been called upon to determine adulthood, there is little empirical evidence to support age 18, the current legal age of majority, as an accurate marker of adult capacities. Less clear is whether neuroimaging, at present, helps to inform age-based determinations of maturity. If so, can generic guidelines be established, or is individual variation so great as to preclude establishing a biological benchmark for adult-like maturity of judgment?

Brain Development in Adolescence

Current studies demonstrate that brain structures and processes change throughout adolescence and, indeed, across the life course [11]. These findings have been facilitated by imaging technologies such as structural and functional magnetic resonance imaging (sMRI and fMRI, respectively). Much of the popular discussion about adolescent brain development has focused on the comparatively late maturation of the frontal lobes [12], although recent work has broadened to the increasing “connectivity” of the brain.

Throughout childhood and into adolescence, the cortical areas of the brain continue to thicken as neural connections proliferate. In the frontal cortex, gray matter volumes peak at approximately 11 years of age in girls and 12 years of age in boys, reflecting dendritic overproduction [7]. Subsequently, rarely used connections are selectively pruned [6] making the brain more efficient by allowing it to change structurally in response to the demands of the environment [13]. Pruning also results in increased specialization of brain regions [14]; however, the loss of gray matter that accompanies pruning may not be apparent in some parts of the brain until young adulthood [2,15,16]. In general, loss of gray matter progresses from the back to the front of the brain with the frontal lobes among the last to show these structural changes [3,6].

Neural connections that survive the pruning process become more adept at transmitting information through myelination. Myelin, a sheath of fatty cell material wrapped around neuronal axons, acts as “insulation” for neural connections. This allows nerve impulses to travel throughout the brain more quickly and efficiently and facilitates increased integration of brain activity [17]. Although myelin cannot be measured directly, it is inferred from volumes of cerebral white matter [18]. Evidence suggests that, in the prefrontal cortex, this does not occur until the early 20s or later [15,16].

The prefrontal cortex coordinates higher-order cognitive processes and executive functioning. Executive functions are a set of supervisory cognitive skills needed for goal-directed behavior, including planning, response inhibition, working memory, and attention [19]. These skills allow an individual to pause long enough to take stock of a situation, assess his or her options, plan a course of action, and execute it. Poor executive functioning leads to difficulty with planning, attention, using feedback, and mental inflexibility [19], all of which could undermine judgment and decision making.

Synaptic overproduction, pruning and myelination—the basic steps of neuromaturation—improve the brain’s ability to transfer information between different regions efficiently. This information integration undergirds the development of skills such as impulse control [20]. Although young children can demonstrate impulse control skills, with age and neuro-maturation (e.g., pruning and myelination), comes the ability to *consistently* use these skills [21].

Evidence from animal studies suggests that the neural connections between the amygdala (a limbic structure involved in emotional processing, especially of fear and vigilance) and the cortices that comprise the frontal lobes become denser during adolescence [22]. These connections integrate emotional and cognitive processes and result in what is often considered to be “emotional maturity” (e.g., the ability to regulate and to interpret emotions). The evidence suggests that this integration process continues to develop well into adulthood [23]. Steinberg, Dahl, and others have hypothesized that a temporal gap between the development of the socioemotional system of the brain (which experiences an early developmental surge around puberty) and the cognitive control system of the brain (which extends through late adolescence) underlies some aspects of risk-taking behavior [24,25]. This temporal gap has been compared with starting the engine of a car without the benefit of a skilled driver [25].

Adolescent Neuropsychology: Linking Brain and Behavior

As detailed above, across cultures and millennia, the teen years have been observed to be a time of dramatic changes in body and behavior. During adolescence, most people successfully navigate the transition from dependence upon caregivers to self-sufficient adult members of society. Where specifically, along the maturational path of cognitive and emotional development, individuals should be given certain societal rights and responsibilities continues to be a topic of intense interest. Increasingly, neuroscience has been called on to inform this question.

Impulse control, response inhibition, and sensation seeking

Among the many behavior changes that have been noted for teens, the three that are most robustly seen across cultures are: (1) increased novelty seeking; (2) increased risk taking; and (3) a social affiliation shift toward peer-based interactions [13]. This triad of behavior changes is seen not only in human beings but in nearly all social mammals [13]. Although the behaviors may lead to danger, they confer an evolutionary advantage by encouraging separation from the comfort and safety of the natal family, which decreases the chances of inbreeding. The behavior changes also foster the development and acquisition of independent survival skills [13].

Studying the link between behavioral changes and brain changes has been greatly facilitated by recent advances in neuroimaging technology and behavioral assessments. One challenge has been to identify the fundamental units of emotion and cognition and how they combine to determine more complicated “real-world” behaviors. For instance, younger adolescents are less likely than older adolescents to wait a given period of time to receive a larger reward [26]. This tendency can be studied using experiments in which the subject is asked questions such as whether they would rather receive $800 now or $1,000 in 12 months. By varying the amount of monetary difference and/or time between the transactions, an “indifference point” can be calculated to quantify an individual’s tendency to prefer the “here and now” to some future reward. There is an extensive literature characterizing effects of age, gender, intelligence quotient (IQ), and other variables on this phenomenon, which is termed “delay discounting” [26,27]. However, more recent work has demonstrated that delay discounting is determined in part by the more fundamental traits of impulse control and future orientation, each with their own neural representations and developmental trajectories [28]. Furthermore, future orientation itself is a multidimensional construct involving cognitive, affective, and motivational systems.

Studies using fMRI are beginning to contribute to this parsing of behavior into more fundamental units by characterizing different neural representations and maturational courses for separate but related concepts such as impulse control and sensation seeking. Whereas sensation seeking changes seem to reflect striatal dopamine changes related to the onset of puberty, impulse control, as discussed previously, is more protracted and related to maturational changes in the frontal lobe [21].

“Hot” and “cold” cognition

Perhaps because of the relative ease of quantifying hormonal levels in animal models, it is tempting to attribute all adolescent behavioral changes to “raging hormones.” More nuanced investigations of adolescent behavior seek to understand the specific mechanisms by which hormones affect neural circuitry and to discern these processes from nonhormonal developmental changes. An important aspect of this work is the distinction between “hot” and “cold” cognition. Hot cognition refers to conditions of high emotional arousal or conflict; this is often the case for the riskiest of adolescent behaviors [29]. Most research to date has captured information in conditions of “cold cognition” (e.g., low arousal, no peers, and hypothetical situations). Like impulse control and sensation seeking, hot and cold cognition are subserved by different neuronal circuits and have different developmental courses [30]. Thus, adolescent maturity of judgment and its putative biological determinants are difficult to disentangle from socioemotional context.

What We Do Not Know About Brain Development in Adolescence

In many respects, neuroimaging research is in its infancy; there is much to be learned about how changes in brain structure and function relate to adolescent behavior. As of yet, however, neuroimaging studies do not allow a chronologic cut-point for behavioral or cognitive maturity at either the individual or population level. The ability to designate an adolescent as “mature” or “immature” neurologically is complicated by the fact that neuroscientific data are continuous and highly variable from person to person; the bounds of “normal” development have not been well delineated [5].

Neuroimaging has captured the public interest, arguably because the resulting images are popularly seen as “hard” evidence whereas behavioral science data are seen as subjective. For example, in one study, subjects were asked to evaluate the credibility of a manufactured news story describing neuroimaging research findings. One version of the story included the text, another included an fMRI image, and a third summarized the fMRI results in a chart accompanying the text. Subjects who saw the brain image rated the story as more compelling than did subjects in other conditions [31]. More strikingly, simply referring verbally to neuroimaging data, even if logically irrelevant, increases an explanation’s persuasiveness [32].

Despite being popularly viewed as revealing the “objective truth,” neuroimaging techniques involve an element of subjectivity. Investigators make choices about thickness of brain slices, level of clarity and detail, techniques for filtering signal from noise, and choice of the individuals to be sampled [5]. Furthermore, the cognitive or behavioral implications of a given brain image or pattern of activation are not necessarily straightforward. Researchers generally take pains to highlight the correlative nature of the relationship; however, such statements are often misinterpreted as causal [5]. Establishing a causal relationship is more complicated than it might, at first, seem. For example, there is rarely a one-to-one correspondence between a particular brain region and its discrete function; a given brain region can be involved in many cognitive processes, and many types of cognitive processes may be subserved by a particular brain structure [33].

Some neuroscientists lament that the technology has been used too liberally to draw conclusions where there is little empirical basis for interpreting the results. For example, a 2007 *New York Times* Op-Ed piece reported the results of a study in which fMRI was used to view the brains of 20 undecided voters while they watched videos of presidential candidates; they had previously rated the candidates on a scale of 1 to 10 from “very unfavorable” to “very favorable” [34]. The results of the brain scans were interpreted as reflecting the inner thoughts of the participants. For instance, “[w]hen viewing images of [Senator Clinton], these voters exhibited significant activity in the anterior cingulate cortex, an emotional center of the brain that is aroused when a person feels compelled to act in two different ways but must choose one. It looked as if they were battling unacknowledged impulses to like [Senator] Clinton” [34]. The editorial drew a swift response from several neuroscientists who believed that, in addition to subverting the standard peer review process before presenting data to the public, the investigators did not address the issue of reverse inference [35]. In neuroimaging terms, reverse inference is using neuroimaging data to infer specific mental states, motivations, or cognitive processes. Because a given brain region may be activated by many different processes, careful study design and analysis are imperative to making valid inferences [36, 37]. In symbolic logic terminology, reverse inference errors are related to the “fallacy of affirming the consequent” (e.g., “All dogs are mammals. Fred is a mammal. Therefore, Fred is a dog.”).

In sum, neuroimaging modalities involve an element of subjectivity, just as behavioral science modalities do. A concern is that high-profile media exposures may leave the mistaken impression that fMRI, in particular, is an infallible mind-reading technique that can be used to establish guilt or innocence, infer “true intentions,” detect lies, or establish competency to drive, vote, or consent to marriage.

The adolescent brain in context

Neuroimaging technologies have made more information available about the structure and function of the human brain than ever before. Nonetheless, there is still a dearth of empirical evidence that allows us to anticipate behavior in the real world based on performance *in the scanner* [5]. Linking brain scans to real-world functioning is hampered by the complex integration of brain networks involved in behavior and cognition. Further hindering extrapolation from the laboratory to the real world is the fact that it is virtually impossible to parse the role of the brain from other biological systems and contexts that shape human behavior [6]. Behavior in adolescence, and across the lifespan, is a function of multiple interactive influences including experience, parenting, socioeconomic status, individual agency and self-efficacy, nutrition, culture, psychological well-being, the physical and built environments, and social relationships and interactions [38–42]. When it comes to behavior, the relationships among these variables are complex, and they change over time and with development [43]. This causal complexity overwhelms many of our “one factor at a time” explanatory and analytic models and highlights the need to continually situate research from brain science in the broader context of interdisciplinary developmental science to advance our understandings of behavior across the lifespan [44].

Adolescent Maturity and Policy in the Real World: Scientific Complexity Meets Policy Reality

The most prominent use of neuroscience research in adolescent social policy was the 2005 U.S. Supreme Court Case, *Roper vs. Simmons*, which has been described as the *“Brown v. Board of Education* of ‘neurolaw,”’ recalling the case that ended racial segregation in American schools [45]. In that case, 17-year-old Christopher Simmons was convicted of murdering a woman during a robbery. Ultimately, he was sentenced to death for his crime. Simmons’ defense team argued that he did not have a specific, diagnosable brain condition, but rather that his still-developing adolescent brain made him less culpable for his crime and therefore not subject to the death penalty. *Amicus* briefs were filed by, among others, by the American Psychological Association (APA) and the American Medical Association (AMA) summarizing the existing neuroscience evidence and suggesting that adolescents’ still-developing brains made them fundamentally different from adults in terms of culpability.

The AMA brief argued that: “[a]dolescents’ behavioral immaturity mirrors the anatomical immaturity of their brains. To a degree never before understood, scientists can now demonstrate that adolescents are immature not only to the observer’s naked eye, but in the very fibers of their brains”’ [46]. (Notably, the brief submitted by the AMA et al., implied a causal link among brain structure, function, and behavior in adolescence [5]). The neuroscientific evidence is thought to have carried significant weight in the Court’s decision to overturn the death penalty for juveniles [47].

In a dissenting opinion in that case, Justice Antonin Scalia reflected on a 1990 brief filed by the APA in support of adolescents' right to seek an abortion without parental consent *(Hodgson v. Minnesota).* In this case, the APA argued that adolescent decision making was virtually indistinguishable from adult decision making by the age of 14 or 15. Scalia pointed out this seeming inconsistency: "[The APA] claims in this case that scientific evidence shows persons under 18 lack the ability to take moral responsibility for their decisions, [the APA] has previously taken precisely the opposite position before this very Court. Given the nuances of scientific methodology and conflicting views, courts—which can only consider the limited evidence on the record before them, are ill equipped to determine which view of science is the right one" [48]. Although one can make the case that the "cold cognitive" context in which abortion-related decisions are made encourages more mature judgment than the "hot cognitive" context of a murder, Scalia's comments highlight the peril of leaving nonscientists to arbitrate and translate neuroscience for policy.

The Supreme Court used neuroimaging research to protect juveniles from the death penalty based on reduced capacity and consequently reduced culpability. A year after *Roper vs. Simmons* was decided, the same logic was extended to limit adolescent sexual behavior. In 2006, the State of Kansas used its interpretation of adolescent neuroscience research to expand the state's child abuse statute to include any consensual touching between minors under the age of 16 years. Although scientists may be reticent to apply their research to policy, in some cases, policy makers are doing it for them.

Some argue that one must only look to the use of early-life brain science to anticipate what happens when brain science is overgeneralized [49]. In the early 1990s, there were several high-profile studies that suggested that there was rapid growth brain growth and plasticity in the first 3 years of life and, therefore, that "enriched" environments could hasten the achievement of some developmental milestones [50]. This research was used to perpetuate the idea that videos, classical music, and tailored preschool educational activities could give a child a cognitive advantage before the door of neural plasticity swung shut forever [49]. One could imagine that such a perspective would discourage the allocation of resources for school-aged children and adolescents because, if this were true, after early childhood it would simply be "too late." The use of neuroscientific research to support "enriched" environments demonstrates that if neuroscientists do not direct the interpretation and application of their findings (or the lack of applicability), others will do it for them, perhaps without the benefit of their nuanced understanding. A proactive approach to research and research-to-policy translation that includes neuroscientists, adolescent health professionals, and policy makers is an important next step.

Toward a Policy-Relevant Neuroscientific Research Agenda

Public policy is struggling to keep up with burgeoning interest in cognitive neuroscience and neuroimaging [51]. In a rush to assign biological explanations for behavior, adolescents may be caught in the middle. Policy scholar Robert Blank comments, "We have not kept up in terms of policy mechanisms that anticipate the implications beyond the technologies. We have little evidence that there is any anticipatory policy. Most policies tend to be reactive" [51]. There is a need to situate research from the brain sciences in the broader context of adolescent developmental science, and to find ways to communicate the complex relationships among biology, behavior, and context in ways that resonate with policymakers and research consumers.

Furthermore, the time is right to advance collaborative, multidisciplinary research agendas that are explicit in the desire to link brain structure to function as well as adolescent behavior and implications for policy [52].

Ultimately, the goal is to be able to articulate the conditions under which adolescents' competence, or demonstrated maturity, is most vulnerable *and* most resilient. Resilience, it seems, is often overlooked in contemporary discussions of adolescent maturity and brain development. Indeed, the focus on pathologic conditions, deficits, reduced capacity, and age-based risks overshadows the enormous opportunity for brain science to illuminate the unique strengths and potentialities of the adolescent brain. So, too, can this information inform policies that help to reinforce and perpetuate opportunities for adolescents to thrive in this stage of development, not just survive.

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