The Relevance of Immaturities in the Juvenile Brain to Culpability and Rehabilitation

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The overreaching aim of this Article is to describe how developmental cognitive neuroscience can inform juvenile law. Fundamental to culpability and responsibility is the ability to effectively execute voluntary executive behavior. Executive function, including cognitive control and working memory, has a protracted development with key aspects continuing to mature through adolescence. These limitations in executive control are due in great part to still maturing brain processes. Gray and white matter changes are still becoming established in adolescence, enhancing efficiency and the speed of brain processing supporting executive control. Dopamine, a neurotransmitter that underlies reward processing and learning, peaks in adolescence—supporting known increases in sensation seeking but also in adaptable learning. Functional Magnetic Resonance Imaging ("fMRI") studies show that adolescent limitations in recruiting brain systems that support response planning, error processing, the ability to sustain an executive state, and top-down prefrontal executive control of behavior underlie limitations in executive control in adolescence. Moreover, adolescents show over-reactivity to reward incentives, thus engaging response systems that may contribute to impulsive responses in situations with high motivation. Neurobiological evidence indicating that adolescence is a transitional stage of limited executive control in the context of increased vulnerability to sensation seeking can inform culpability, long-term sentencing, and greater amenability for rehabilitation. Finally, it is important to note that executive control, while limited in its efficiency, is available in adolescence, and given time to deliberate with guidance from mature adults, adolescents can make responsible decisions.

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Introduction

Legal systems across societies recognize the juvenile period to be a stage of development that is distinct from adulthood. The line is typically drawn at eighteen years of age. The reasons for this distinction have been largely based on intuitive knowledge and experience with juveniles who can exhibit limited understanding of responsible behavior. The field of psychology has provided more direct evidence for a true limitation in the ability to generate responsible behavior in a consistent manner. More recently, with the advent of noninvasive neuroimaging methods, neuroscience has been able to provide neurobiological evidence for immaturities in the juvenile brain that undermine the ability to generate responsible behavior in a consistent manner. This Article reviews that neuroimaging evidence in the context of its relevance to juvenile law, specifically with respect to culpability and the potential for rehabilitation. The general definition of a juvenile describes an "immature" individual who has not reached full potential. Law is more specific, indicating that, due to this immaturity, the individual is not of an age to be held responsible for criminal acts in the same manner as an adult. The actual age is typically set at eighteen years, although this can vary from sixteen to nineteen years. Cognitive control, the ability to *voluntarily* generate behavior that has been planned in a goal-directed manner while controlling compelling but goal-incompatible responses, speaks to core aspects of responsible behavior and culpability. This Article explores the development of cognitive control as that development supports the ability to exert responsible behavior by describing the brain processes underlying the transitional period marked by the beginning of puberty and extending to the late teens and early twenties.

I. Development of Voluntary Guided Behavior

Culpability requires the demonstration of responsibility for a willful act. Responsibility refers to the ability to be accountable for one's deliberate actions and implies a capacity for rational actions and moral decisions. As such, responsibility and culpability are complex concepts that engage multiple behavioral and cognitive processes. The ability to generate actions that are willful and planned requires psychological abilities that are supported by complex brain mechanisms. Executive function and cognitive control are terms used in psychology and neuroscience to describe the ability to generate actions that are voluntary and goal-directed. Executive functions are the abilities that support voluntary goal-directed behavior and include sustained attention, response planning, retaining plans in working memory, self-monitoring, attention shifting, and inhibition of distracting impulses.[1] Executive function is supported by exerting cognitive control: the ability to voluntarily generate goal-directed behavior while controlling compelling but goal-inappropriate responses.[2] These cognitive processes are core to abstract reasoning, mental flexibility, rule-guided behavior, and mentalizing (the ability to infer the mental state of others), which are higher order cognitive processes related to responsibility.

Our behaviors are guided by either external or internal cues. Behaviors guided by external cues are necessary to a prompt response to environmental stimuli. These behaviors include learned responses, automatic responses, and reactions to sensory stimuli, but also impulsive responses guided by emotional stimuli. These responses are necessary for effective interactions with our environment and range from reactively looking at a light in our field of view, to braking at a red stop light, to experiencing anger when we feel provoked. Another category of behaviors are guided by an internal plan where there is an overarching goal that requires a planned response overriding more prepotent, externally guided, reactive responses. These behaviors range from following instructions to stop a reactive response (do not look at a light) to suppressing an immediate but risky behavior in favor of a delayed yet ultimately more rewarding response. Reactive responses engage sensory systems and emotional systems that interact with motor systems for a quick response. Planned responses rely on brain networks guided by the prefrontal cortex that support the ability to hold a plan on line and coordinate "top-down" control of reactive behavior. Top-down control

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1. Tara Niendam et al., *Meta-Analytic Evidence for a Superordinate Cognitive Control Network Subserving Diverse Executive Functions*, 12 Cognitive, Affective & Behav. Neurosci. 241, 241–68 (2012); Bruce F. Pennington & Sally Ozonoff, *Executive Functions and Developmental Psychopathology*, 37 J. Child Psychol. & Psychiatry & Allied Disciplines 51, 51–87 (1996).

2. Niendam et al., *supra* note 1, at 241–68.

refers to information processing generated from executive regions that exert control on response-generating brain regions. In contrast, bottom-up processing refers to the path of information processing that sends sensory information to executive regions. Internally generated behaviors refer to executive function abilities because of their planned, goal-driven nature and because they require control processes. These executive behaviors are relevant to issues of culpability and responsibility.

The basic ability to generate planned voluntary responses is available early in life but strengthens with development. There is evidence of executive behavior guided by the prefrontal cortex at as young as seven months of age, but it is limited in the frequency and contexts in which it can be applied.[3] More complex executive behaviors associated with the prefrontal cortex continue to emerge through childhood.[4] The availability of prefrontally guided behaviors early in development indicates that later development is characterized by refinement of existing processes and not the emergence of new ones. By adolescence, executive functions are available and what improves is the ability to exert sufficient cognitive control to apply executive functions in a reliable manner.

Fundamental to executive function are the abilities to inhibit responses and to use working memory, the on line capability to retain a goal and plan on line to guide behavior. The ability to inhibit task-irrelevant reactive responses in favor of task-appropriate responses is central to voluntary control of behavior.[5] Tests that probe the maturation of the ability to inhibit responses measure a subject's capacity not to make reactive responses to a compelling stimulus, such as a suddenly appearing light (antisaccade task), or to a trained response (such as in a go-no-go task, in which a subject is asked not to press a button in the context of repeated button press responses). The ability to voluntarily inhibit a response is available early in infancy.[6] What improves through

3. A. Diamond & P.S. Goldman-Rakic, *Comparison of Human Infants and Rhesus Monkeys on Piaget's AB Task: Evidence for Dependence on Dorsolateral Prefrontal Cortex*, 74 EXPERIMENTAL BRAIN RES. 24, 24–40 (1989).

4. Patricia L. Davies & James D. Rose, *Assessment of Cognitive Development in Adolescents by Means of Neuropsychological Tasks*, 15 DEVELOPMENTAL NEUROPSYCHOL. 227, 227–48 (1999); Harvey S. Levin et al., *Developmental Changes in Performance on Tests of Purported Frontal Lobe Functioning*, 7 DEVELOPMENTAL NEUROPSYCHOL. 377, 377–95 (1991).

5. JOAQUIN FUSTER, THE PREFRONTAL CORTEX (2d ed. 1989); Matthew C. Davidson et al., *Development of Cognitive Control and Executive Functions from 4 to 13 Years: Evidence from Manipulations of Memory, Inhibition, and Task Switching*, 44 NEUROPSYCHOLOGIA 2037, 2037–78 (2006); Earl K. Miller & Jonathan D. Cohen, *An Integrative Theory of Prefrontal Cortex Function*, 24 ANN. REV. NEUROSCI. 167, 167–202 (2001).

6. Dima Amso & Scott P. Johnson, *Selection and Inhibition in Infancy: Evidence from the Spatial Negative Priming Paradigm*, 95 COGNITION B27, B27–36 (2005); Martha Ann Bell & Nathan A. Fox, *The Relations Between Frontal Brain Electrical Activity and Cognitive Development During Infancy*, 63 CHILD DEV. 1142, 1142–63 (1992); Diamond & Goldman-Rakic, *supra* note 3, at 24–40.

development is the *rate* of correct inhibitory responses, not the ability to generate a correct inhibitory response.[7] The ability to flexibly and consistently inhibit responses requires the engagement of large brain networks that need to maintain a ready manner in which to inhibit responses. The process that supports the *flexible and consistent use* of the ability to inhibit responses is what becomes better established in adulthood. Inhibitory control requires top-down modulation of response-related processes guided by a goal while simultaneously suppressing reactive responses. Studies using simple tasks that measure the rate of correct voluntary inhibitory responses indicate that there is a dramatic improvement through childhood and adolescence.[8] In optimal circumstances, adult level cognitive control is evident by fifteen years of age. In an MRI scanner, where anxiety increases, performance deteriorates compared to adults,[9] suggesting that while they have access to adult level inhibitory control, it is still immature and susceptible to errors. Given known increased reactivity to socioemotional stimuli, this could undermine the ability to apply inhibitory control.

Similar to response inhibition, working memory—the ability to keep a representation of a goal and plan for a voluntary response[10]—also shows continued improvements through adolescence.[11] Working memory tasks require subjects to keep a goal in working memory over a delay period that sometimes includes an interfering stimulus or manipulation requirement. While adolescents can guide their responses by the

7. Anne-Claude Bedard et al., *The Development of Selective Inhibitory Control Across the Life Span*, 21 DEVELOPMENTAL NEUROPSYCHOL. 93, 93–111 (2002); Beatriz Luna et al., *Maturation of Cognitive Processes from Late Childhood to Adulthood*, 75 CHILD DEV. 1357, 1357–72 (2004); K. Richard Ridderinkhof et al., *A Study of Adaptive Behavior: Effects of Age and Irrelevant Information on the Ability to Inhibit One's Actions*, 101 ACTA PSYCHOLOGICA 315, 315–37 (1999); Benjamin R. Williams et al., *Development of Inhibitory Control Across the Life Span*, 35 DEVELOPMENTAL PSYCHOL. 205, 205–13 (1999); Larry A. Wise et al., *Decrement in Stroop Interference Time with Age*, 41 PERCEPTUAL & MOTOR SKILLS 149, 149–50 (1975); Wery P.M. van den Wildenberg & Maurits W. van der Molen, *Developmental Trends in Simple and Selective Inhibition of Compatible and Incompatible Responses*, 87 J. EXPERIMENTAL CHILD PSYCHOL. 201, 201–20 (2004); Katerina Velanova et al., *The Maturation of Task Set-Related Activation Supports Late Developmental Improvements in Inhibitory Control*, 29 J. NEUROSCI. 12558, 12558–67 (2009).

8. Junko Fukushima et al., *Development of Voluntary Control of Saccadic Eye Movements: I. Age-Related Changes in Normal Children*, 22 BRAIN & DEV. 173, 173–80 (2000); C. Klein & F. Foerster, *Development of Prosaccade and Antisaccade Task Performance in Participants Aged 6 to 26 Years*, 38 PSYCHOPHYSIOLOGY 179, 179–89 (2001); Luna et al., *supra* note 7, at 1357–72.

9. Velanova et al., *supra* note 7, at 12558–67.

10. Alan D. Baddeley & Graham Hitch, *Working Memory*, *in* 8 THE PSYCHOLOGY OF LEARNING AND MOTIVATION 47–89 (Gordon H. Bower ed., 1986).

11. Andreas Demetriou et al., *The Development of Mental Processing: Efficiency, Working Memory, and Thinking*, 67 MONOGRAPHS SOC'Y FOR RES. CHILD DEV. i, 1–167 (2002); Luna et al., *supra* note 7, at 1357–72.

information in working memory,[12] the accuracy of this response continues to improve through the teenage years.[13] These results suggest that, although the ability to initiate a voluntary response guided by working memory reaches maturity in adolescence, corrective responses that afford precision continue to improve after adolescence. Thus, the ability to use working memory precisely and flexibly develops through adolescence.

Taken together, studies looking at developmental improvements in executive function indicate that basic cognitive abilities are available early in life, while sophisticated use of these abilities improves through adulthood. There are mechanisms separate from central working memory processes that can also limit performance, including processing interference and failure to use strategies. Due to immaturities in inhibition, children have more interference from distractors than adults, undermining the ability to show mature working memory performance in tasks that present competing stimuli.[14] Hence, executive function abilities are present and available by adolescence. What continues to improve into adolescence is the ability to perform complex tasks, be more precise, and control distraction—resulting in more efficient and adaptable voluntary behavior. Abstract thought and decisionmaking benefit from an efficient and adaptable working memory system, and immaturities in this system can therefore limit decisionmaking.

II. Structural Maturation of the Adolescent Brain

In parallel to improvements in executive function, the brain structurally matures to support optimal executive function. The brain is composed of gray and white matter. Gray matter, which appears gray in color, is the cortical ribbon surrounding the outer layer of the brain and nuclei within the brain. This is where neurons—the brain cells that process information—reside. White matter, which appears white, is where the wiring that connects neurons is found throughout the brain. Maturational changes in both gray and white matter persist through adolescence. The gross morphology of the brain is in place by adolescence, with brain weight reaching 95% of adult levels by seven to eleven years of

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12. Monica Luciana et al., *The Development of Nonverbal Working Memory and Executive Control Processes in Adolescents*, 76 Child Dev. 697, 697–712 (2005); Linda Van Leijenhorst et al., *Developmental Trends for Object and Spatial Working Memory: A Psychophysiological Analysis*, 78 Child Dev. 987, 987–1000 (2007).

13. Luna et al., *supra* note 7, at 1357–72; David H. Zald & William G. Iacono, *The Development of Spatial Working Memory Abilities*, 14 Developmental Neuropsychol. 563, 563–78 (1998).

14. David F. Bjorklund & Katherine Kipp Harnishfeger, *The Resources Construct in Cognitive Development: Diverse Sources of Evidence and a Theory of Inefficient Inhibition*, 10 Developmental Rev. 48, 48–71 (1990); Frank N. Dempster, *Memory Span: Sources of Individual and Developmental Differences*, 89 Psychol. Bull. 63, 63–100 (1981).

age.[15] Specialization of the core gross morphology of the brain, however, continues through adolescence as brain structure adapts and optimizes to support its specific environmental demands. The structure of neuronal cells of the brain, their interconnectivity, as well as the neurochemistry used for information transmission continue to change through adolescence. Next, we review brain maturational changes in gray and white matter as well as neurochemical changes that have relevance to responsible behavior, including synaptic pruning, myelination, and dopamine availability.

A. Synaptic Pruning

Neurons perform information processing through their synaptic connections with other neurons. The synaptic connections multiply in the first two years of life. Subsequently, through childhood and into adolescence, the synaptic connections that are used remain, and those that are not used are eliminated or "pruned."[16] Synaptic pruning is believed to be a mechanism of plasticity that allows the brain to most optimally adjust to the individual's environment. The loss of unused synaptic connections and the strengthening of the remaining connections optimize neuronal processing, enhancing computational capacity, and the speed of information processing needed for reasoning and optimal decisionmaking.

The early morphological studies on post mortem brains indicate that different parts of the brain prune on different schedules. Synaptic connections reach adult levels in the visual cortex by seven years of age, in the temporal cortex—where language is processed—by twelve years of age, and in the prefrontal cortex, which plays a primary role in high-level cognition, by sixteen years of age.[17] Magnetic Resonance Imaging ("MRI") studies, which measure the thickness of the gray matter, indicate that association areas across the brain (where high level integration of data occurs), as well as limbic areas (like the basal ganglia, which supports motivated behavior), continue to be immature in adolescence in frontal regions but also in the other lobes.[18] This reduction in gray matter is the

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15. Verne S. Caviness et al., *The Developing Human Brain: A Morphometric Profile*, *in* Developmental Neuroimaging: Mapping The Development of Brain and Behavior 3–14 (R.W. Thatcher et al. eds., 1996); Jay N. Giedd et al., *Quantitative Magnetic Resonance Imaging of Human Brain Development: Ages 4–18*, 6 Cerebral Cortex 551, 551–60 (1996).

16. Joseph Rauschecker & Peter Marler, *What Signals Are Responsible for Synaptic Changes in Visual Cortical Plasticity? in* Imprinting and Cortical Plasticity 193–200 (J.P. Rauschecker & P. Marler eds., 1987).

17. Peter R. Huttenlocher, *Morphometric Study of Human Cerebral Cortex Development*, 28 Neuropsychologia 517, 517–27 (1990); Peter R. Huttenlocher & Arun S. Dabholkar, *Regional Differences in Synaptogenesis in Human Cerebral Cortex*, 387 J. Comp. Neurology 167, 167–78 (1997).

18. Nitin Gogtay et al., *Dynamic Mapping of Human Cortical Development During Childhood Through Early Adulthood*, 101 Proc. Nat'l Acad. Sci. U.S. 8174, 8174–79 (2004); Elizabeth R. Sowell

result of synaptic pruning as well as other maturational changes, including an increase in white matter. These findings indicate that neural processes, which are important for the complex processing necessary for voluntary guided behavior, are still immature in adolescence.

B. Myelination

Myelination is the process of insulating nerve tracts, which significantly increases the speed of neuronal transmission.[19] The increase in the speed of neuronal transmission allows for distant regions to integrate function in an optimal manner, supporting the top-down control of behavior needed for effective information processing.[20] Overall, myelination increases through adolescence.[21] Original histological studies indicate that the visual cortex in the occipital lobe myelinates by the first decade of life while frontal, parietal, and temporal regions continue to myelinate into the teenage years.[22] Given that the changes in white matter are a gradual enhancement of established connections, these results also support the notion that basic processes supporting executive control are in place early in development and that the nature of the protracted progressions through adolescence is a strengthening of existing processes speeding information processing. Diffusion Tensor Imaging, an MRI technique to measure white matter connectivity, has been used as an indirect measure of developmental changes in myelination.[23] During adolescence, major white matter tracts that provide connections across cortical regions and, importantly, between frontal and subcortical regions that form the circuitry for top-down control of behavior, are still maturing

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et al., *In Vivo Evidence for Post-Adolescent Brain Maturation in Frontal and Striatal Regions*, 2 Nature Neurosci. 859, 859–61 (1999); Arthur W. Toga et al., *Mapping Brain Maturation*, 29 Trends Neurosci. 148, 148–59 (2006).

19. Alexander Drobyshevsky et al., *Developmental Changes in Diffusion Anisotropy Coincide with Immature Oligodendrocyte Progression and Maturation of Compound Action Potential*, 25 J. Neurosci. 5988, 5988–97 (2005).

20. Patricia S. Goldman-Rakic, *Topography of Cognition: Parallel Distributed Networks in Primate Association Cortex*, 11 Ann. Rev. Neurosci. 137, 137–56 (1988).

21. Jeffrey R. Wozniak & Kelvin O. Lim, *Advances in White Matter Imaging: A Review of In Vivo Magnetic Resonance Methodologies and Their Applicability to the Study of Development and Aging*, 30 Neurosci. & Biobehavioral Revs. 762, 762–74 (2006).

22. Paul Yakovlev & Andre-Roch Lecours, *The Myelogenetic Cycles of Regional Maturation of the Brain*, *in* Regional Development of the Brain in Early Life 3–70 (Alexandre Minkowski ed., 1967).

23. T. Klingberg et al., *Myelination and Organization of the Frontal White Matter in Children: A Diffusion Tensor MRI Study*, 10 Neuroreport 2817, 2817–21 (1999); Pratik Mukherjee & Robert C. McKinstry, *Diffusion Tensor Imaging and Tractography of Human Brain Development*, 16 Neuroimaging Clinics N. Am. 19, 19–43 (2006).

in parallel with pubertal changes.[24] These improvements in white matter integrity have also been found to correlate with cognitive performance.[25] These results provide evidence that immaturities in the structure of brain connections may contribute to the limitations in adolescence of the ability to effectively exert executive control of behavior.

Taken together, synaptic pruning and myelination indicate that adolescence is marked by refinements across the brain that support integration of information and thereby foster higher-order cognitive processes.[26] Although the establishment of widely distributed processing is nearing adult levels in adolescence, continued increases in myelination through this period indicate persistent limitations in connectivity. The circuitry available in adolescence thus allows for approximations of adult behavior control but with remaining immaturities that limit both efficient higher computations afforded by synaptic pruning and the establishment of widely distributed circuitry. These enhancements in regional circuitry and connectivity support a more effective manner in which executive cortical systems can affect basic subcortical response systems that facilitate mature executive control of behavior.

C. Dopamine

In addition to continued refinements in brain structure, there are important differences in the availability of key neurotransmitters, the neurochemicals used for neuronal communication. Dopamine is a neurotransmitter that acts on synapses in the frontal cortex and the ventral striatum, a nucleus in the limbic system of the brain that plays a crucial role in motivated behavior. Dopamine levels peak during adolescence across species in frontal and striatal regions and subsequently decrease into adulthood.[27] Dopamine is involved in reward-

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24. M.R. Asato et al., *White Matter Development in Adolescence: A DTI Study*, 20 Cerebral Cortex 2122, 2122–31 (2010); Vincent J. Schmithorst et al., *Developmental Differences in White Matter Architecture Between Boys and Girls*, 29 Hum. Brain Mapping 696, 696–710 (2008).

25. Conor Liston et al., *Frontostriatal Microstructure Modulates Efficient Recruitment of Cognitive Control*, 16 Cerebral Cortex 553, 553–60 (2005); Zoltan Nagy et al., *Maturation of White Matter Is Associated with the Development of Cognitive Functions During Childhood*, 16 J. Cognitive Neurosci. 1227, 1227–33 (2004).

26. Goldman-Rakic, *supra* note 20, at 137–56.

27. Patricia S. Goldman-Rakic & Roger M. Brown, *Postnatal Development of Monoamine Content and Synthesis in the Cerebral Cortex of Rhesus Monkeys*, 4 Developmental Brain Res. 339, 339–49 (1982); James E. McCutcheon et al., *Individual Differences in Dopamine Cell Neuroadaptations Following Cocaine Self-Administration*, 66 Biological Psychiatry 801, 801–03 (2009); David R. Rosenberg & David A. Lewis, *Postnatal Maturation of the Dopaminergic Innervation of Monkey Prefrontal and Motor Cortices: A Tyrosine Hydroxylase Immunohistochemical Analysis*, 358 J. Comp. Neurology 383, 383–400 (1995).

seeking behaviors but also, and importantly, in learning.[28] As such, the adolescent period is particularly amenable to behaviors driven by rewards and is believed to contribute to known peaks in risk-taking behavior at this time.[29] However, this may also be the time of a peak ability to learn and be rehabilitated.

III. Functional Maturation of the Adolescent Brain

Functional Magnetic Resonance Imaging ("fMRI") is a non-invasive technique that provides an indirect measure of neuronal activity by measuring regional changes in blood oxygen levels that result from increased metabolism in areas of neuronal activity. Studies using fMRI have been able to provide insight as to how brain immaturities and limitations in processes underlying decisionmaking in adolescence may be associated. Developmental fMRI studies of executive function as well as socioemotional development have been able to identify specific immaturities during the adolescent period.

The fMRI studies in adults indicate that executive function, including response inhibition and working memory, recruits a widely distributed circuitry of brain regions in which the prefrontal cortex plays a primary role. The prefrontal cortex ("PFC") is unique in its cellular architecture as well as its distributed connectivity with the rest of the brain, making it especially well-suited to support volitional planned responses. It is the PFC's wide reciprocal interactions within the frontal cortex and other cortical and subcortical regions, including sensory and limbic structures, that allow it to receive information, integrate it, and subsequently control behavior. As synaptic pruning reaches adult levels by sixteen years of age in prefrontal cortex, its core architecture is already on line by adolescence. The continued myelination of tracts that provide connections to and from PFC into adulthood enhances its ability to establish networks needed for reliable controlled action.[30]

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28. Wolfram Schultz, *Reward Signaling by Dopamine Neurons*, 7 Neuroscientist 293, 293–302 (2001).

29. R. Andrew Chambers et al., *Developmental Neurocircuitry of Motivation in Adolescence: A Critical Period of Addiction Vulnerability*, 160 Am. J. Psychiatry 1041, 1041–52 (2003); L.P. Spear, *The Adolescent Brain and Age-Related Behavioral Manifestations*, 24 Neurosci. & Behav. Revs. 417, 417–63 (2000); Dustin Wahlstrom et al., *Developmental Changes in Dopamine Neurotransmission in Adolescence: Behavioral Implications and Issues in Assessment*, 72 Brain Cognition 146, 146–59 (2010); Dustin Wahlstrom et al., *Neurobehavioral Evidence for Changes in Dopamine System Activity During Adolescence*, 34 Neurosci. & Biobehavioral Rev. 631, 631–48 (2010).

30. Harry T. Chugani et al., *Positron Emission Tomography Study of Human Brain Functional Development*, 22 Annals Neurology 487, 487–97 (1987); Pernille Olesen et al., *Combined Analysis of DTI and fMRI Data Reveals a Joint Maturation of White and Grey Matter in a Fronto-Parietal Network*, 18 Cognitive Brain Res. 48, 48–57 (2003); Robert W. Thatcher, *Maturation of the Human Frontal Lobes: Physiological Evidence for Staging*, 7 Developmental Neuropsychol. 397, 397–419 (1991).

The fMRI studies, using similar response inhibition and working memory tasks used in behavioral studies, described in Part I, have found evidence of differences in how PFC is recruited in adolescence, reflecting unique immaturities. Some studies find decreased recruitment of PFC from adolescence to adulthood,[31] suggesting that adolescents require greater effort to exert voluntary control. That is, while adolescents can utilize the same regions as adults to accomplish voluntary control, they need to exert a greater effort to do so. As such, adolescents may look like adults who are doing a much more difficult task, which can lead to committing more errors. Other studies using different methods have found evidence for age-related increases in PFC engagement,[32] suggesting that late maturation of PFC may allow it to participate in cognitive control in unique ways in adulthood that are not yet available in adolescence. More specifically, studies have found fMRI evidence of limitations during adolescence in the ability to monitor performance and detect errors of cognitive control.[33] Additionally, adolescents do not recruit the extensive set of regions, including prefrontal areas that support the ability to maintain an executive mode of operation—which in turn supports the ability to flexibly exert executive function in a controlled manner for sustained period of time.[34] When looking at how PFC interacts with other regions, studies indicate that from adolescence to adulthood there is a significant increase in the number and strength of connections that allow the PFC to influence other brain regions.[35] Studies have found that there is

31. Beatriz Luna et al., *Maturation of Widely Distributed Brain Function Subserves Cognitive Development*, 13 NEUROIMAGE 786, 786–93 (2000); K. Suzanne Scherf et al., *Brain Basis of Developmental Change in Visuospatial Working Memory*, 18 J. COGNITIVE NEUROSCI. 1045, 1045–58 (2006); Leanne Tamm et al., *Maturation of Brain Function Associated with Response Inhibition*, 41 J. AM. ACAD. CHILD & ADOLESCENT PSYCHIATRY 1231, 1231–38 (2002).

32. Nancy E. Adleman et al., *A Developmental fMRI Study of the Stroop Color-Word Task*, 16 NEUROIMAGE 61, 61–75 (2002); Silvia A. Bunge et al., *Immature Frontal Lobe Contributions to Cognitive Control in Children: Evidence from fMRI*, 33 NEURON 301, 301–11 (2002); Kristina T. Ciesielski et al., *Developmental Neural Networks in Children Performing a Categorical N-Back Task*, 33 NEUROIMAGE 980, 980–90 (2006); Rachel Marsh et al., *A Developmental fMRI Study of Self-Regulatory Control in Tourette's Syndrome*, 27 HUM. BRAIN MAPPING 848, 848–63 (2007); Katya Rubia et al., *Functional Frontalisation with Age: Mapping Neurodevelopmental Trajectories with fMRI*, 24 NEUROSCI. & BIOBEHAVIORAL REVS. 13, 13–19 (2000); Katya Rubia et al., *Linear Age-Correlated Functional Development of Right Inferior Fronto-Striato-Cerebellar Networks During Response Inhibition and Anterior Cingulate During Error-Related Processes*, 28 HUM. BRAIN MAPPING 1163, 1163–77 (2007) [hereinafter Rubia et al., *Linear*]; Tamm et al., *supra* note 31, at 1231–38.

33. Rubia et al., *Linear*, *supra* note 32, at 1163–77; Katerina Velanova et al., *Maturational Changes in Anterior Cingulate and Frontoparietal Recruitment Support the Development of Error Processing and Inhibitory Control*, 18 CEREBRAL CORTEX 2505, 2505–22 (2008).

34. Velanova et al., *supra* note 7, at 12558–67.

35. Kai Hwang et al., *Strengthening of Top-Down Frontal Cognitive Control Networks Underlying the Development of Inhibitory Control: A Functional Magnetic Resonance Imaging Effective Connectivity Study*, 30 J. NEUROSCI. 15535, 15535–45 (2010); Michael C. Stevens et al., *Functional*

an association between the integrity of white matter connections and the time it takes to inhibit a response.[36] Studies investigating developmental differences in core, functional network connections when not engaged in a task also indicate that the functional brain connections associated with cognitive processes continue to strengthen and rearrange through adolescence and support the integration of widely distributed brain circuitries.[37] Together, these studies suggest that the brain systems that support voluntary planned responses are available in adolescence but are still sluggish, rendering them unreliable primarily due to immaturities in the ability to effectively integrate function throughout the brain in a timely fashion.

An executive system that is vulnerable to error can be more easily influenced by motivational factors. As described above, there is a tendency for the adolescent brain to be driven by rewards to a greater degree than at other times of the lifespan. The reward system has been well-delineated, identifying regions such as the ventral striatum, situated deep in the brain, as underlying the processing of reward information through its connections to frontal and other brain regions that can affect behavior. Increased activity in the striatum has been found to be associated with increased propensity for risk-taking in adults.[38] fMRI studies have found that when presented with a reward, the adolescent brain shows hyperactivity of striatal regions that support reward processing.[39] This increased activity has been associated with increased propensity for sensation seeking in adolescence.[40] These fMRI studies have also found that in parallel to reward-related enhancements in the ventral striatum, there is increased activity in brain regions that support the response that will gain the reward.[41] Hyperactivity of the reward

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Neural Networks Underlying Response Inhibition in Adolescents and Adults, 181 BEHAV. BRAIN RES. 181, 12–22 (2007).

36. Liston et al., *supra* note 25, at 553–60.

37. Damien A. Fair et al., *Development of Distinct Control Networks Through Segregation and Integration*, 104 PROC. NAT'L ACAD. SCI. U.S. 13507, 13507–12 (2007).

38. George I. Christopoulos et al., *Neural Correlates of Value, Risk, and Risk Aversion Contributing to Decision Making Under Risk*, 29 J. NEUROSCI. 12574, 12574–83 (2009).

39. Monique Ernst et al., *Triadic Model of the Neurobiology of Motivated Behavior in Adolescence*, 36 PSYCHOL. MED. 299, 299–312 (2006); Adriana Galvan et al., *Risk-Taking and the Adolescent Brain: Who is at Risk?*, 10 DEVELOPMENTAL SCI. F8, F8–14 (2007); Linda Van Leijenhorst et al., *What Motivates the Adolescent? Brain Regions Mediating Reward Sensitivity Across Adolescence*, 20 CEREBRAL CORTEX 61, 61–69 (2010).

40. Linda Van Leijenhorst et al., *Adolescent Risky Decision-Making: Neurocognitive Development of Reward and Control Regions*, 51 NEUROIMAGE 345, 345–55 (2010).

41. Charles Geier et al., *Immaturities in Reward Processing and Its Influence on Inhibitory Control in Adolescence*, 20 CEREBRAL CORTEX 1613, 1613–29 (2009); Aarthi Padmanabhan, *Developmental Changes in Brain Function Underlying the Influence of Reward Processing on Inhibitory Control*, 1 DEVELOPMENTAL COGNITIVE NEUROSCI. 517, 517–29 (2011); Marieke van der Schaaf et al., *Distinct Linear and Non-Linear Trajectories of Reward and Punishment Reversal*

system in adolescence, paired with increased preparation to respond to obtain the reward, could underlie a system that is prone to impulsive sensation seeking.[42] In this context, adolescents have limitations in delayed gratification—that is, choosing rewards that require waiting when given an option for immediate rewards—because of immaturities in engaging networks that integrate cortical and subcortical regions including prefrontal and striatal regions.[43]

In addition to increased reward reactivity, the priority of what is found to be rewarding in adolescence is also unique, including novelty seeking[44] and social interactions.[45] The most unique aspect of adolescence is the dramatic change in hormones that accompany puberty as the body reaches reproductive maturity. The timing and exposure to gonadal hormones on the brain[46] exerts unique effects on brain and behavior processes during adolescence.[47] These pubertal changes have been associated with significant changes in socioemotional processes that can potentially affect an executive system that is immature and vulnerable to error. fMRI studies show that adolescents display increased reactivity to emotional stimuli—typically emotional faces—that engage striatum, as well as prefrontal regions that underlie executive processing of emotions and other cortical regions involved in processing emotional stimuli.[48] These emotional cues undermine impulse control and have been associated with weaker connectivity between prefrontal regions and amygdala.[49]

Learning During Development: Relevance for Dopamine's Role in Adolescent Decision Making, 1 DEVELOPMENTAL COGNITIVE NEUROSCI. 578, 578–90 (2011).

42. Charles Geier & Beatriz Luna, *The Maturation of Incentive Processing and Cognitive Control*, 93 PHARMACOLOGY BIOCHEMISTRY & BEHAV. 212, 212–21 (2009).

43. Anastasia Christakou et al., *Maturation of Limbic Corticostriatal Activation and Connectivity Associated with Developmental Changes in Temporal Discounting*, 54 NEUROIMAGE 1344, 1344–54 (2011).

44. Susan E. Rivers et al., *Risk Taking Under the Influence: A Fuzzy-Trace Theory of Emotion in Adolescence*, 28 DEVELOPMENTAL REV. 28, 107–44 (2008).

45. Sarah-Jayne Blakemore et al., *The Role of Puberty in the Developing Adolescent Brain*, 31 HUM. BRAIN MAPPING 926, 926–33 (2010).

46. Bruce S. McEwen, *Estrogen*[']*s Effects on the Brain: Multiple Sites and Molecular Mechanisms*, 91 J. APPLIED PSYCHOL. 2785, 2785–801 (2001).

47. Spear, *supra* note 29, at 417–63.

48. Eric E. Nelson et al., *Developmental Differences in Neuronal Engagement During Implicit Encoding of Emotional Faces: An Event-Related fMRI Study*, 44 J. CHILD PSYCHOL. & PSYCHIATRY 1015, 1015–24 (2003); Sarah Ordaz & Beatriz Luna, *Sex Differences in Physiological Reactivity to Acute Psychosocial Stress in Adolescence*, 37 PSYCHONEUROENDOCRINOLOGY (forthcoming 2012); Jennifer H. Pfeifer et al., *Entering Adolescence: Resistance to Peer Influence, Risky Behavior, and Neural Changes in Emotion Reactivity*, 69 NEURON 1029, 1029–36 (2011); Leah H. Somerville et al., *A Time of Change: Behavioral and Neural Correlates of Adolescent Sensitivity to Appetitive and Aversive Environmental Cues*, 72 BRAIN & COGNITION 124, 124–33 (2009); Deborah A. Yurgelun-Todd & William D.S. Killgore, *Fear-Related Activity in the Prefrontal Cortex Increases with Age During Adolescence: A Preliminary fMRI Study*, 406 NEUROSCI. LETTERS 194, 194–99 (2006).

49. Somerville et al., *supra* note 48, at 124–33.

Additionally, adolescence is a period of increased socialization, when bonding with peers and romantic relationships take on increasing importance over established family relationships. Social processing is one of the most complex information processes that the human brain engages in and is supported by the integration of brain networks, including the frontal and posterior specialized regions that support mentalizing and related emotional arousal.[50] The ability to integrate brain circuits into networks to support social processing continues through adolescence.[51] fMRI studies show that adolescents have a harder time assessing the intentions of others[52] and also engaging executive control regions to process rejection.[53] A recent study showed that when adolescents performed a simulated driving task in the presence of peers, they demonstrated greater risk-taking than adults and that risk-taking was modulated by increased activation of reward circuitry.[54] Taken together, these studies suggest that in adolescence socioemotional stimuli result in greater reactivity of systems that support impulsive behavior interacting with an already immature executive system that undermines the ability to effectively engage in controlled decisionmaking.

Despite the fact that the adolescent brain is referred to as an "immature" brain, it is important to note that it should not be viewed as a damaged or limited version of an adult brain. There is growing consensus in understanding the unique dynamics of the adolescent brain, especially its proneness to sensation seeking, impulsivity, and capacity to be adaptive.[55] During puberty, across societies and species there is an increase in behaviors that seek novelty and independence from the "nest" in searching for sexual partners and establishing a network of peers. It is these behaviors that encourage the acquisition of skills that support independence and long-term survival as an independent adult.

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50. James K. Rilling & Allen G. Sanfey, *The Neuroscience of Social Decision-Making*, 62 Ann. Rev. Psychol. 23, 23–48 (2011).

51. Sarah-Jayne Blakemore, *The Social Brain in Adolescence*, 9 Nature Revs. Neurosci. 267, 267–77 (2008); Mark H. Johnson et al., *Mapping Functional Brain Development: Building a Social Brain Through Interactive Specialization*, 45 Developmental Psychol. 151, 151–59 (2009).

52. Berna Güroğlu et al., *Fairness Considerations: Increasing Understanding of Intentionality During Adolescence*, 104 J. Experimental Child Psychol. 398, 398–409 (2009).

53. Bregtje Gunther Moor et al., *Do You Like Me? Neural Correlates of Social Evaluation and Developmental Trajectories*, 5 Soc. Neurosci. 461, 461–82 (2010).

54. Jason Chein et al., *Peers Increase Adolescent Risk Taking by Enhancing Activity in the Brain's Reward Circuitry*, 14 Developmental Sci. F1, F1–10 (2011).

55. B.J. Casey et al., *Adolescence: What Do Transmission, Transition, and Translation Have to Do with It*, 67 Neuron 749, 749–60 (2010).

IV. Relevance of Neuroscience Findings to Juvenile Law

Neuroscientific evidence of limitations in exerting executive control and increased socioemotional reactivity can be seen as providing substantiation for what has already been known intuitively and supported by psychological studies. What neuroscience adds is knowledge of the biological mechanisms for how these behaviors occur. Understanding that there are concrete biological underpinnings to adolescent behavior better informs culpability. Hence, beyond neuroimaging studies generating attractive brain images, the studies provide evidence about biological mechanisms underlying our intuitions about adolescent behavior.

It is also of great importance that neuroscience informs the law in a responsible manner and that it does not overextend claims. At this point, neuroimaging data can only inform us about adolescents as a special population and cannot inform us regarding an individual's guilt or future trajectory. Using predictive models, neuroimaging studies have at best shown the ability to predict brain age in a manner akin to a growth chart at a pediatric office,[56] and even then there is a significant margin of variability. Even if in the future it would be possible to attain neuroimaging evidence regarding an individual's guilt or antisocial or psychopathic tendencies, these would only be indirect associations that point to a vulnerability, not to what may transcend at the individual level as they mature into adulthood. It would be highly irresponsible to make such claims since there is no possibility to establish causal links with complex behavior such as crime using neuroimaging data. Still, group level data can and should inform culpability and sentencing as circumstantial evidence is considered.

Immaturities in the adolescent brain can inform culpability at the time of the criminal act, indicating that an adolescent may have acted in an impulsive, impassioned manner that may not have occurred had the individual had full maturity and the availability of optimal executive control. This is an important piece of information that needs to be considered, but it should not be the primary piece of evidence, given that it does not speak to moral issues and therefore does not exonerate all responsibility. There is great variability in risk-taking behavior, with the majority of adolescents not committing crimes, and we have a responsibility to acknowledge dangerous acts and prevent them from reoccurring in the future.

The evidence for protracted maturation of brain systems that support executive behaviors indicates that the vulnerability to impulsive risk-taking behaviors in adolescence is transitional. As such, the propensity for

56. Nico U.F. Dosenbach et al., *Prediction of Individual Brain Maturity Using fMRI*, 329 Sci. 1358, 1358–61 (2010).

impulsive acts or irresponsibility in adolescent is a mode of behavior that can be outgrown. Additionally, how an individual will develop, particularly with respect to responsible behavior in adulthood as brain resources increase, cannot be determined with certainty in adolescence. Lifelong sentencing that is based solely on a characterization of the individual at the time of adolescence—such as in life without parole—undermines the possibility that an adolescent may change with development into adulthood. There is the possibility that criminal behavior in adolescence is a marker for psychopathy that will persist into adulthood, but until assessments for psychopathic characteristics that can predict future behavior become well established and reliable, there is a risk for false positives that could incorrectly identify an individual as a life criminal.

A less discussed feature of adolescence is that the processes that underlie increased reward processing also underlie enhanced learning. Namely, the neurotransmitter dopamine not only supports reward processing, but it does so in the context of learning contextual associations. On one hand, adolescence is a time when bad habits become established, including substance abuse[57] and potentially criminal behavior. On the other hand, this is potentially a period when rehabilitation could have a more effective impact on behavior than during adulthood. Optimal rehabilitation programs could benefit from neuroscience and psychological evidence for effective learning. The increased potential for rehabilitation in adolescence could also inform sentencing.

Finally, it has been suggested that the brain system immaturities which, in the adolescent period, undermine responsible behavior with respect to criminal acts, also undermine adolescents' ability to make other responsible decisions, such as choosing to have an abortion. Both decisions require the ability to exert executive control. Criminal acts that are impulsive in nature are distinct from decisions such as whether to have an abortion, where the procedures often require days or weeks of assessments and discussions with clinicians. Adolescents are at a disadvantage with regard to their vulnerability to act in an impulsive manner, especially in emotional contexts. However, adolescents do have the ability to engage executive functions in a manner that allows them to make decisions that approximate adult levels, but it is less efficient and slower. A situation that encourages deliberation, especially with guidance from a mature responsible adult, can support the ability to access executive circuitry needed for responsible decisionmaking. Some juvenile crimes are well planned, such as in cases of school shootings, where they are no longer impulsive in nature. Even in these cases it could

57. Kimberly Nixon & Justin A. McClain, *Adolescence as a Critical Window for Developing an Alcohol Use Disorder: Current Findings in Neuroscience*, 23 CURRENT OPINION PSYCHIATRY 227, 227–32 (2010).

be argued that, while the crimes were planned, immaturities in executive control and temporal discounting, which undermine the ability to consider long-term consequences, may have undermined the ability to understand the nature of their planned act. For example, juvenile school shooters often have no plan after the crime.

Conclusion

Neuroimaging studies provide evidence for immaturities in adolescent brain systems that specifically undermine the ability to make planned executive responses and enhance reward and socioemotional reactivity. These immaturities, though adaptive in encouraging the acquisition of independent skills needed for a successful adulthood, make adolescents vulnerable to impulsive risk-taking, including criminal behavior. This, however, is a transitional period that most individuals will "grow out" of as brain maturity enables more efficient access to brain systems that encourage responsible behavior. Neuroscience evidence is relevant and of great importance when assessing culpability and sentencing, but it is not primary in the moral and ethical issues most relevant to the law. Importantly, neuroimaging evidence only provides correlational, not causal, evidence regarding underlying behavior and can only speak to the group rather than the individual level. The evidence regarding adolescents as a group, however, is compelling in indicating that neurobiological immaturities can undermine responsible behavior. Importantly, the same immaturities that lead to sensation seeking and risk-taking behavior also support learning, suggesting that adolescents are more amenable to rehabilitation.

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