Nos. 10-9646, 10-9647

In the
Supreme Court of the United States

EVAN MILLER,

Petitioner,

v.

STATE OF ALABAMA,

Respondent.

(Additional Caption on the Reverse)

On Writ of Certiorari to the Alabama Court of Criminal Appeals

BRIEF FOR THE AMERICAN MEDICAL ASSOCIATION AND THE AMERICAN ACADEMY OF CHILD AND ADOLESCENT PSYCHIATRY AS *AMICI CURIAE* IN SUPPORT OF NEITHER PARTY

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January 13, 2012

KUNTRELL JACKSON,

Petitioner,

v.

RAY HOBBS, DIRECTOR,
ARKANSAS DEPARTMENT OF CORRECTION,

Respondent.

On Writ of Certiorari to the Supreme Court of Arkansas

QUESTION PRESENTED

Whether the Eighth Amendment's ban on cruel and unusual punishment prohibits the imprisonment of a juvenile for life without the possibility of parole as punishment for the juvenile's commission of a homicide offense.

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INTERESTS OF AMICI CURIAE*

The American Medical Association. The American Medical Association (AMA) is the largest professional association of physicians, residents and medical students in the United States. Additionally, through state and specialty medical societies and other physician groups seated in its House of Delegates, substantially all U.S. physicians, residents and medical students are represented in the AMA's policy making process. Founded in 1847, the objects of the AMA are to promote the science and art of medicine and the betterment of public health.

The American Academy of Child and Adolescent Psychiatry. Founded in 1953, the American Academy of Child and Adolescent Psychiatry (AACAP) is comprised of over 7,500 child and adolescent psychiatrists and other interested physicians. Consistent with the focus of the juvenile court system on rehabilitation rather than retribution and multiple international treaties, including the UN Convention of Rights of the Child, the AACAP has adopted a policy statement strongly opposing the imposition of a sentence of life without

* The parties have consented to the filing of this brief. Pursuant to Rule 37.3(a), letters consenting to the filing of this brief are on file with the Clerk of the Court. No counsel for a party authored this brief in whole or in part, and no counsel or party made a monetary contribution intended to fund the preparation or submission of this brief. No person other than *amici curiae,* their members, or their counsel made a monetary contribution to its preparation or submission.

the possibility of parole for crimes committed as juveniles. AACAP Policy Statement, June 2009, *available at* http://www.aacap.org/cs/root/policy_statements/life_without_parole_for_juvenile_offenders.

Each of the above-referenced *amici* is committed to the advancement of science. While not taking a formal position on whether sentencing a juvenile to a term of imprisonment of life without the possibility of parole violates the protections provided by the Eighth Amendment of the U.S. Constitution, *amici* submit this brief to describe the scientific findings of medical, psychiatric, and psychological research relevant to this issue.

SUMMARY OF ARGUMENT

The adolescent's mind works differently from ours. Parents know it. This Court has said it. Legislatures all over the world have presumed it for decades or more. And scientific evidence has continued to shed more light on how and why adolescent behavior differs from adult behavior.

The differences in behavior have been documented by scientists along several dimensions. Scientists have found that adolescents as a group, even at later stages of adolescence, are more likely than adults to engage in risky, impulsive, and sensation-seeking behavior. This is, in part, because they overvalue short-term benefits and rewards, and are less capable of controlling their impulses making them susceptible to acting in a reflexive rather than a planned voluntary manner. Adolescents are also more emotionally volatile and susceptible to stress and peer influences. In short, the average adolescent cannot be expected to act with the same control or foresight as a mature adult.

Behavioral scientists have observed these differences for some time, but only recently have studies provided an understanding of the neurobiological underpinnings for why adolescents act the way they do. For example, brain imaging studies reveal that adolescents generally exhibit greater neural reactivity than adults or children in areas of the brain that promote risky and reward-based behavior. These studies also demonstrate that the brain continues to mature, both structurally and functionally, throughout adolescence in regions of the brain responsible for controlling thoughts, actions, and emotions. Together, these studies indicate that the adolescent period poses vulnerabilities to risk taking behavior but, importantly, that this is a temporary stage.

While science cannot gauge moral culpability, scientists can shed light on some of the measurable attributes that the law has long treated as highly relevant to culpability and the appropriateness of punishment. This brief focuses on what science can tell us about the neurological, physiological, psychological, emotional, and behavioral development of adolescents from the perspective of researchers and medical professionals.

ARGUMENT

THE STRUCTURAL AND FUNCTIONAL IMMATURITIES OF THE ADOLESCENT BRAIN PROVIDE A BIOLOGICAL BASIS FOR THE BEHAVIORAL IMMATURITIES EXHIBITED BY ADOLESCENTS.

Although adolescents[1] can, and on occasion do, exhibit adult levels of judgment and control, their ability to do so is limited and unreliable compared to that of adults. Adolescents, as a group, value risks and rewards differently from adults, which, coupled with limitations in controlling their impulses and recognizing and regulating emotional responses, makes them vulnerable to impulsive acts. *See* Point A, *infra.*

Moreover, recent advances in brain-imaging technology confirm that the very regions of the brain that are associated with voluntary behavior control and regulation of emotional response and impulsivity are structurally immature during adolescence. Studies have also revealed that these structural immaturities are consistent with age-related differences in both brain function and behavior. *See* Point B, *infra*.

These findings have led to an "explosion of scientific papers and popular articles" about the

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[1] There is a continuum of differences in brain maturation and cognitive abilities between the youngest and oldest of adolescents. All of the scientific conclusions recounted in this brief, however, are applicable to adolescents as a class—ranging from ages 12 to 17.

immaturities of the adolescent brain and how these immaturities explain the risky and impulsive behavior exhibited by teens.[2]

A. Adolescents Are Less Able Than Adults to Voluntarily Control Their Behavior.

Numerous studies of adolescent behavior over the last two decades confirm the stereotype that adolescents, as a group, are prone to making impulsive or reactive judgments. "Relative to individuals at other ages, . . . adolescents . . . exhibit a disproportionate amount of reckless behavior, sensation seeking and risk taking."[3] Sensation-seeking peaks during adolescence across cultures and species, and is believed to be an adaptive and normal part of development that promotes learning and independence.[4]

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[2] David Dobbs, *Beautiful Brains*, 220:4 NAT'L GEOGRAPHIC 36, 48 (Oct. 2011).

[3] Linda Patia Spear, *The Adolescent Brain and Age-Related Behavioral Manifestations*, 24 NEUROSCI. & BIOBEHAV. REVS. 417, 421 n. 1 (2000); *see also* Lawrence Steinberg et al., *Age Differences in Sensation Seeking and Impulsivity as Indexed by Behavior and Self-Report: Evidence of a Dual Systems Model*, 44:6 DEVELOPMENTAL PSYCHOL. 1774 (2008); B.J. Casey et al., *The Adolescent Brain*, 28 DEVELOPMENTAL REV. 62, 62-77 (2008); *see generally* Sarah Durston & B.J. Casey, *What Have We Learned About Cognitive Development from Neuroimaging?*, 44 NEUROPSYCHOLOGIA 2149 (2006); Luciana Hooper et al., *Adolescents' Performance on the Iowa Gambling Task: Implications for the Development of Decision-Making and Ventromedial Prefrontal Cortex,* 40:6 DEVELOPMENTAL PSYCHOL. 1148 (2004).

[4] Beatriz Luna, *The Maturation of Cognitive Control and the Adolescent Brain*, *in* FROM ATTENTION TO GOAL-DIRECTED BEHAVIOR 250 (Francisco Aboitiz and Diego Cosmelli eds.,

Nevertheless, sensation-seeking behavior can result in actions that compromise survival (referred to as "risk-taking" behaviors) and involve sub-optimal decision-making. Risk-taking of all sorts — whether drunk driving, unprotected sex, experimentation with drugs, or even criminal activity — is so pervasive that "it is statistically aberrant to refrain from such [risk-taking] behavior during adolescence."[5] The difference between adolescent and adult behavior, however, is not a function of adolescents' inability to distinguish right from wrong or in their intellectual abilities *per se*, but rather from psychosocial limitations in their ability to consistently and reliably control their behavior.[6]

Specifically, adolescents are less able, on average, than adults to self-regulate, or "cognitively" control, their behavior.[7] Cognitive control refers to the

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Springer Berlin Heidelberg 2009) (explaining that "these behaviors may be necessary to develop the social skills needed to gain independence in adulthood").

[5] Spear (2000), *supra* note 3, at 421; *see also* Casey (2008), *supra* note 3, at 65 ("[R]isk-taking appears to increase during adolescence relative to childhood and adulthood….")

[6] Elizabeth Cauffman & Lawrence Steinberg, *(Im)Maturity of Judgment in Adolescences: Why Adolescents May Be Less Culpable Than Adults*, 18 BEHAV. SCI. & L. 741, 742 (2000); *see also* William Gardner, *A Life-Span Rational-Choice Theory of Risk Taking*, *in* ADOLESCENT AND ADULT RISK TAKING: THE EIGHTH TEXAS TECH SYMPOSIUM ON INTERFACES IN PSYCHOLOGY 66, 67 (N. Bell & R. Bell eds., 1993).

[7] *See* Deborah Yurgelun-Todd, *Emotional and Cognitive Changes During Adolescence*, 17 CURRENT OPINION IN NEUROBIOLOGY 251, 253 (2007); *see also* R. K. Lenroot & Jay N. Giedd, *Brain Development in Children and Adolescents:*

ability to voluntarily exert goal-directed behavior while controlling compelling but goal-inappropriate responses.[8] Scientists have identified various interrelated immaturities in adolescents' self-regulatory abilities that contribute to their limitation in controlling their impulses and their greater tendency to engage in risky or reckless behavior. To name just a few, adolescents (1) tend to be more strongly motivated by the possibility of reward than adults; (2) have greater difficulty controlling their impulses; and (3) have greater difficulty recognizing and regulating emotional responses. We take a closer look at each of these factors below.

Reward Sensitivity. One of the main reasons adolescents are more likely to engage in risky behavior than adults is that adolescents tend to experience heightened levels of sensitivity to rewards, especially to immediate rewards.[9]

Insights from Anatomical Magnetic Resonance Imaging, 30 NEUROSCI. & BEHAV. REVS. 718, 723 (2006); Luna (2009), *supra* note 4, at 249, 51; *see also* Lawrence Steinberg et al., *Age Differences in Future Orientation and Delay Discounting*, 80 CHILD DEV. 28, 40-41 (2009) [hereinafter Steinberg, *Future Orientation*] ("[C]hanges in impulse control and planning are mediated by a 'cognitive control' network . . . which matures more gradually and over a longer period of time, into early adulthood.").

[8] *See* Luna (2009), *supra* note 4, at 251.

[9] *See* Laurence Steinberg, *Adolescent Development and Juvenile Justice*, 16:3 ANN. REV. CLINICAL PSYCHOL. 47, 57 (2009) [hereinafter Steinberg, *Adolescent Development*]; *see also* C.F. Geier, et al., *Immaturities in Reward Processing and Its Influence on Inhibitory Control in Adolescence*, 20:7 CEREBRAL CORTEX 1613, 1624-26 (2010).

Placing a higher value on the potential reward leads to lower risk-reward ratios for adolescents, relative to adults, and thus a higher likelihood of engaging in the risky behavior.[10] In other words, adolescent behavioral research suggests that adolescents take more risks because they overvalue the potential reward, not because they are less able to appreciate the risks, as was once believed.[11] "[A]dolescents' greater involvement in risk taking, compared to adults', does not appear to stem from youthful ignorance, irrationality, delusions of invulnerability, or misperceptions of risk."[12] Rather, it appears that adolescents and adults perceive *risks* similarly[13], but they evaluate potential *rewards* differently, especially when the risky behavior is weighed against the cost.[14]

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[10] *See* Steinberg, *Adolescent Development*, *supra* note 9, at 57-58.

[11] *Id.* at 58.

[12] Elizabeth Cauffman & Elizabeth Shulman, *Age Differences in Affective Decision Making as Indexed by Performance on the Iowa Gambling Task*, 46:1 DEVELOPMENTAL PSYCHOL. 193, 194 (2010); *see also* Steinberg, *Adolescent Development*, *supra* note 9, at 57.

[13] Valerie Reyna & Charles Brainerd, *Dual Processes in Decision Making and Developmental Neuroscience: A Fuzzy-Trace Model*, 31 DEVELOPMENTAL REV. 180, 193 (2011).

[14] *See* Susan L. Andersen, *Trajectories of Brain Development: Point of Vulnerability or Window of Opportunity?* 27 NEUROSCI. AND BIOBEHAV. REVS 3, 3-18 (2003); Fulton Crews, Jun He & Clyde Hodge, *Adolescent Cortical Development: A Critical Period of Vulnerability for Addiction*, 86 PHARMACOLOGY BIOCHEMISTRY AND BEHAV. 189 (2007); Spear (2000), *supra* note 3; Cauffman & Shulman, *supra* note 12, at 206; Steinberg

Furthermore, studies have shown that adolescents are more likely to take risks when they are in the presence of peers. "[O]ne of the hallmarks of adolescent risk taking is that it is much more likely than that of adults to occur in the presence of peers, as evidenced in studies of reckless driving, substance abuse, and crime."[15] More recent studies have also shown that this increased risk taking in the presence of peers is associated with greater neural activity in the areas of the brain associated with reward processing.[16] In fact, adolescents appear to place unique reward value on the presence of peers. With adolescents, "awareness of peers selectively amplifies activity in the [] brain's incentive processing system, which in turn influences subsequent decisions about risk."[17] Adults, on the other hand, "showed no differences in the

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(2008), *supra* note 3, at 1776 (linking lack of impulse control to sensation seeking behaviors).

[15] Albert Chein, et al., *Peers Increase Adolescent Risk Taking by Enhancing Activity in the Brain's Reward Circuitry*, 14:2 DEVELOPMENTAL SCI. F1, F1 (2011) (internal citations omitted); Linda Patia Spear, *Rewards, Aversions and Affect in Adolescence: Emerging Convergences Across Laboratory Animal and Human Data*, 1 DEVELOPMENTAL COGNITIVE NEUROSCI. 390, 400 (2011).

[16] *See* Chein, *supra* note 15, at F7. These areas include the ventral striatum and orbitofrontal cortex. *Id.* at F1, F7 ("Specifically, relative to adults, adolescents demonstrated significantly greater activation of VS and OFC as they rendered decisions about risk, but only when they were aware that friends were watching them.").

[17] *Id.* at F8.

activation of these regions as a function of social context."[18]

Impulse Control. "A cornerstone of cognitive development is the ability to suppress inappropriate thoughts and actions in favor of goal-directed ones, especially in the presence of compelling incentives."[19] Impulse control means allowing a goal-directed response to override a more compelling/reflexive, yet goal-inappropriate response.[20] The ability to control one's impulsive reactions to an event or problem is necessary to achieve adult levels of problem solving ability, logical reasoning, and the consistent exercise of good judgment.[21]

Adolescents have observable limitations in their ability to control their impulses. The relative inability of adolescents to control impulsive behavior is well-documented by studies on developmental changes in impulsivity and self-management over the course of adolescence.[22] "A number of classic developmental studies have shown that this ability develops throughout

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[18] *Id*. at F7.

[19] *See* Casey (2008), *supra* note 3, at 64.

[20] *See* Luna, *supra* note 4, at 251.

[21] *See id.*

[22] *See* Steinberg, *Adolescent Development*, *supra* note 9, at 58; *see also* Laurence Steinberg & Kathryn C. Monahan, *Age Differences in Resistance to Peer Influence*, 43 DEVELOPMENTAL PSYCHOL. 1531, 1538 (2007); Steinberg (2008), *supra* note 3, at 1772-74.

childhood and adolescence."[23] Capacity for self-direction has been shown to increase gradually throughout adolescence and into young adulthood.[24] Likewise, impulsivity tends to decline linearly from childhood to adulthood.[25] These findings indicate that adolescents have not yet attained adult levels of impulse control. In other words, adolescents are less able than adults to consistently reflect before they act.

Emotional Regulation. All individuals regulate their emotional responses to events. They increase or decrease their emotional reactions to stimuli in accordance with their behavioral goals.[26] The ability to regulate one's emotions efficiently is crucial for mental and physical health as well as for appropriate social interactions, and impairment of this capability is associated with affective disorders and a variety of other maladaptive psychological conditions.[27] This ability, however, continues to develop through adolescence into adulthood.[28] As a result,

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[23] *See* Casey (2008), *supra* note 3, at 64.

[24] *See* Steinberg, *Future Orientation*, *supra* note 7, at 28-29, 38-40.

[25] Steinberg (2008), *supra* note 3, at 1776; *see* Steinberg, *Adolescent Development*, *supra* note 9, at 57.

[26] *See* Sang Hee Kim & Stephan Hamann, *Neural Correlates of Positive and Negative Emotion Regulation*, 19:5 J. COGNITIVE NEUROSCI. 776 (2007); Kelly Anne Barnes et al., *Developmental Differences in Cognitive Control of Socio-Affective Processing*, 32:3 DEVELOPMENTAL NEUROPSYCHOL. 787 (2007).

[27] *Id.* at 776.

[28] *See* Casey (2008), *supra* note 3, at 65.

similar to their ability to control impulses, adolescents have less ability to regulate their emotional responses to stimuli than adults.[29]

This relative limitation is important for understanding adolescents' ability to voluntarily control their behavior. Indeed, many situations, particularly those involving social interactions, arouse adolescents' emotional system and impact their ability to make informed decisions about their actions. Peer pressure, for example, can arouse emotions of fear, rejection, or desire to impress friends that can undermine the reliability of adolescent behavioral control systems and result in actions taken without full consideration or appreciation of the consequences.[30]

Each of these attributes continues to develop throughout adolescence and early adulthood, and is critical to the ability to effectively and consistently control one's behavior.[31] The developmental immaturities that adolescents

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[29] Isabelle M. Rosso et al., *Cognitive and Emotional Components of Frontal Lobe Functioning in Childhood and Adolescence*, 1021 ANNALS N.Y. ACAD. SCI. 355, 360-61 (2004); *see also, e.g.,* Todd A. Hare et al., *Biological Substrates of Emotional Reactivity and Regulation in Adolescence During an Emotional Go-Nogo Task,* 63:10 BIOLOGICAL PSYCHIATRY 927 (2008) (adolescents show exaggerated responses in subcortical brain regions involved in emotional behaviors, which is associated with risk taking and heightened emotional responses to empty threats).

[30] *See* Steinberg (2007), *supra* note 22, at 1536-38 (explaining that "resistance to peer influence increases linearly over the course of adolescence, especially between ages 14 and 18").

[31] *See* Casey (2008), *supra* note 3, at 68.

exhibit with respect to each of these attributes compound to make them particularly prone to engage in risky and sensation-seeking behavior.

Researchers have also found that these limitations are especially pronounced when other factors — such as stress, emotions, and peer pressure — enter the equation. These factors affect everyone's cognitive functioning, but they operate on the adolescent mind differently and with special force.

The interplay among stress, emotion, cognition, and voluntary behavior control in teenagers is particularly complex — and different from adults. Stress affects the ability to effectively regulate behavior as well as the ability to weigh costs and benefits and override impulses with rational thought.[32] Adolescents are more susceptible to stress from daily events than adults, which translates into a further distortion of their already skewed cost-benefit analysis.[33]

Emotion, like stress, also plays an important role in the ability to voluntarily control behavior, influencing decision-making and risk-taking behavior.[34] Because of their greater stress,

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[32] *See* Spear (2000), *supra* note 3, at 423; Lita Furby & Ruth Beyth-Maron, *Risk Taking in Adolescence: A Decision-Making Perspective,* 12 DEVELOPMENTAL REV. 1, 22 (1992).

[33] *See* Spear (2000), *supra* note 3, at 423; Furby, *supra* note 32, at 22.

[34] *See* Laurence Steinberg & Elizabeth S. Scott, *Less Guilty by Reason of Adolescence: Developmental Immaturity, Diminished*

greater influx of gonadal hormones, and their relative inability to consistently regulate their emotional responses, adolescents are more emotionally volatile than adults — and children, for that matter.[35] As a result, adolescents tend to experience emotional states that are more extreme and more variable than those experienced by adults.[36]

In sum, the conclusion of the scientific research is that, for a variety of interrelated reasons, adolescents, as a group, cannot be expected to behave or make decisions in the same way as adults.

B. Recent Studies of the Brain Have Established a Biological Basis for the Observed Immaturities in Adolescent Behavior.

Modern brain research technologies have developed a body of data from the late 1990s to the present that provides a compelling picture of the inner workings of the adolescent brain.[37]

Responsibility, and the Juvenile Death Penalty, 58 AM. PSYCHOL. 1009, 1011-13 (2003).

[35] *See* Spear (2000), *supra* note 3, at 429.

[36] *See id.*; Cauffman (2000), *supra* note 6, at 743-45, 756-57, 59.

[37] *See* Sarah Durston et al., *Anatomical MRI of the Developing Human Brain: What Have We Learned?* 40 J. AM. ACAD. CHILD & ADOLESCENT PSYCHIATRY 1012, 1012 (2001) (reviewing results of MRI studies of brain development in childhood and adolescence); Michael S. Gazzaniga et al., COGNITIVE NEUROSCIENCE: THE BIOLOGY OF THE MIND 20-21, 138 (2d ed. 2002).

Indeed, brain imaging data provides convergent evidence for the ways in which adolescents are still immature.[38] Developmental neuroscience has now gathered extensive evidence that both the structure of the adolescent brain, and the way it functions, are immature compared to the adult brain.

This insight emerges from sophisticated and non-invasive brain imaging techniques performed by high-resolution structural and functional magnetic resonance imaging ("MRI") methods.[39] These imaging techniques are a quantum leap beyond previous methods for assessing brain development. Before the rise of neuroimaging, the understanding of brain development was gleaned

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[38] *See* Nitin Gogtay et al., *Dynamic Mapping of Human Cortical Development During Childhood Through Early Adulthood*, 101 PROC. NAT'L ACAD. SCI. 8174, 8177 (2004).

[39] "MRI measures the response of atoms in different tissues when they are pulsed with radio waves that are under the influence of magnetic fields thousands of times the strength of the Earth's. Each type of tissue responds differently, emitting characteristic signals from the nuclei of its cells. The signals are fed into a computer, the position of those atoms is recorded, and a composite picture of the body area being examined is generated and studied in depth." Florence Antoine, *Cooperative Group Evaluating Diagnostic Imaging Techniques*, 81 J. NAT'L CANCER INST. 1347, 1348 (1989); *see also* Yurgelun-Todd, *supra* note 7, at 251-52 (explaining that "structural MRI and functional MRI (fMRI), have become important modalities for research on brain development as they have been able to provide a more detailed picture of how the brain changes. The application of these methods to the study of children and adolescents provides an extraordinary opportunity to advance our understanding of neurobiological changes and functional abilities associated with the brain.")

largely from post-mortem examinations.[40] Modern imaging techniques, however, have begun to shed light on how a live brain operates, and how a particular brain develops over time.[41]

Technological breakthroughs have not only enabled scientists to confirm some of what was previously known or believed, but have also provided new evidence that has changed the way scientists understand the development of the human brain as it progresses from childhood through adolescence and into adulthood.[42] "[B]rain imaging studies in normal children and adolescents have been helpful in relating the dramatic maturation of cognitive, emotional, and social functions with the brain structures that ultimately underlie them."[43]

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[40] *See* Gazzaniga, *supra* note 37, at 63.

[41] *See generally* Elizabeth R. Sowell et al., *Development of Cortical and Subcortical Brain Structures in Childhood and Adolescence: A Structural MRI Study*, 44 DEVELOPMENTAL MED. & CHILD NEUROLOGY 4 (2002); Elizabeth R. Sowell et al., *Mapping Continued Brain Growth and Gray Matter Density Reduction in Dorsal Frontal Cortex: Inverse Relationships During Postadolescent Brain Maturation*, 21 J. NEUROSCI. 8819 (2001).

[42] *See* Elizabeth R. Sowell et al., *In Vivo Evidence for Post-Adolescent Brain Maturation in Frontal and Striatal Regions*, 2 NATURE NEUROSCI. 859 (1999); *see also* Jay N. Giedd et al., *Brain Development During Childhood and Adolescence: A Longitudinal MRI Study*, 2 NATURE NEUROSCI. 861 (1999).

[43] Elizabeth R. Sowell et al., *Mapping Cortical Change Across the Human Life Span*, 6 NATURE NEUROSCI. 309 (2003); *see also* Gogtay, *supra* note 38, at 8177.

In this regard, two complementary observations have been especially revealing. First, the parts of the brain that work together to support the control of behavior, including the prefrontal cortex (which comprises roughly the front third of the human brain), continue to mature even through late adolescence.[44] Second, in making behavioral choices, adolescents rely more heavily than adults on systems and areas of the brain that promote risk-taking and sensation-seeking behavior.

1. Adolescent Brains Are Structurally Immature in Areas of the Brain Associated with Enhanced Abilities of Executive Behavior Control.

When it comes to "response inhibition, emotional regulation, planning and organization," the so-called executive functions, a crucial part of the brain is the prefrontal cortex.[45] The prefrontal cortex is a core region that through its ability to integrate information across the brain supports

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[44] *See* Casey (2008), *supra* note 3, at 68.

[45] Sowell (1999), *supra* note 42, at 860; *see* Eveline A. Crone et al., *Neurocognitive Development of Relational Reasoning*, 12:1 DEVELOPMENTAL SCI. 55, 56 (2009) (explaining that "[n]europsychological and neuroimaging studies have shown that prefrontal cortex is strongly implicated in relational reasoning."); *see also* Gazzaniga, *supra* note 37, at 75; Rosso, *supra* note 29, at 360-61 (finding a correlation between frontal lobe development in adolescents, response inhibition and social anxiety levels); *see generally,* Silvia A. Bunge et al., *Immature Frontal Lobe Contributions to Cognitive Control in Children: Evidence from fMRI*, 33 NEURON 301 (2002).

planning of voluntary goal-directed responses and can exert control over more impulsive brain systems. As such, it is associated with a variety of cognitive abilities,[46] including those associated with voluntary behavior control and inhibition[47] such as risk assessment,[48] evaluation of reward and punishment,[49] and impulse control.[50] More generally, other functions associated with the prefrontal cortex include decision-making,[51] the

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[46] *See* B.J. Casey et al., *Structural and Functional Brain Development and Its Relation to Cognitive Development*, 54 BIOLOGICAL PSYCHOL. 241, 244 (2000).

[47] *See* R. Dias et al., *Dissociable Forms of Inhibitory Control Within Prefrontal Cortex with an Analog of the Wisconsin Card Sort Test: Restriction to Novel Situations and Independence from "On-Line" Processing*, 17 J. NEUROSCI. 9285 (1997); Durston, *supra* note 37, at 1016; *see also* Yurgelun-Todd, *supra* note 7, at 253.

[48] *See* Facundo Manes et al., *Decision-Making Processes Following Damage to the Prefrontal Cortex*, 125 BRAIN 624 (2002).

[49] *See* J. O'Doherty et al., *Abstract Reward and Punishment Representations in the Human Orbitofrontal Cortex*, 4 NATURE NEUROSCI. 95 (2001); Robert D. Rogers et al., *Choosing Between Small, Likely Rewards and Large, Unlikely Rewards Activates Inferior and Orbital Prefrontal Cortex*, 20 J. NEUROSCI. 9029 (1999).

[50] *See* Antoine Bechara et al., *Characterization of the Decision-Making Deficit of Patients with Ventromedial Prefrontal Cortex Lesions*, 123 BRAIN 2189, 2198-99 (2000).

[51] *See* Samantha B. Wright et al., *Neural Correlates of Fluid Reasoning in Children and Adults*, 1:8 FRONTIERS HUMAN NEUROSCI. 7 (2008) (finding that important changes in the prefrontal cortex during adolescence lead to the development of logical reasoning abilities); *see also* Antoine Bechara et al., *Dissociation of Working Memory from Decision Making Within the Human Prefrontal Cortex*, 18 J. NEUROSCI. 428 (1998).

ability to judge and evaluate future consequences,[52] recognizing deception,[53] responses to positive and negative feedback,[54] working memory,[55] and making moral judgments.[56]

The brain's frontal lobes are still structurally immature well into late adolescence,[57] and the prefrontal cortex is "one of the last brain regions to mature."[58] This, in turn, means that "response inhibition, emotional regulation, planning and

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[52] *See* Bechara (2000), *supra* note 50.

[53] *See* D. D. Langleben et al., *Brain Activity During Simulated Deception: An Event-Related Functional Magnetic Resonance Study*, 15 NEUROIMAGE 727 (2002).

[54] *See* R. Elliott et al., *Differential Neural Response to Positive and Negative Feedback in Planning and Guessing Tasks*, 35 NEUROPSYCHOLOGIA 1395 (1997).

[55] *See* Luna, *supra* note 4, at 264.

[56] *See* Jorge Moll et al., *Frontopolar and Anterior Temporal Cortex Activation in a Moral Judgment Task: Preliminary Functional MRI Results in Normal Subjects*, 59 ARQ NEUROPSIQUIATR 657 (2001); Steve W. Anderson et al., *Impairment of Social and Moral Behavior Related to Early Damage in Human Prefrontal Cortex*, 2 NATURE NEUROSCI. 1032 (1999).

[57] *See* Gogtay, *supra* note 38, at 8174 (subjects of study aged 4 to 21 years); Giedd (1999), *supra* note 42, at 861 (subjects of study aged 4.2 to 21.6 years); Sowell (1999), *supra* note 42, at 860-61 (subjects of study aged 12 to 16 and 23 to 30 years); *see also* Sowell (2001), *supra* note 41, at 8826 (noting pronounced brain maturational processes continuing into post-adolescence; subjects of study aged 7 to 30 years); Sowell (2003), *supra* note 43, at 309 (subjects of study aged 7 to 87 years).

[58] Casey (2000), *supra* note 46, at 243; *see also* Gogtay, *supra* note 38, at 8175.

organization . . . continue to develop between adolescence and young adulthood."[59]

The adolescent brain, in particular the frontal lobes and specifically the prefrontal cortex, is immature in at least two distinct ways that directly affect an adolescent's ability to cognitively control behavior. First, the gray matter where neuronal brain cells reside continues to mature, supporting complex neural processing needed for generating cognitive plans. Second, the integrity of white matter neuronal connections, which supports the fast connectivity needed to executively control impulsive responses, is still improving. Maturation of processes in the gray and white matter of the brain support the complex information processing that underlies executive voluntary control of behavior, which underlies decreased risk taking in adulthood. When fully mature, the ability to effectively process complex information and quickly affect behavior supports the adult's ability to make better-informed executive decisions.[60]

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[59] Sowell (1999), *supra* note 42, at 860; *see also* Kenneth E. Towbin & John E. Schowalter, *Adolescent Development*, *in* PSYCHIATRY 145, 151-52 (Allan Tasman ed., 2d ed. 2003).

This paper recognizes the link between "improvement during adolescence in specific cognitive skills such as organizing information, conceptualization, perspective taking, and social perception, to structural changes in frontal cortical and sub-cortical structures." *Id.* at 152.

[60] *See* Steven Petersen et al., *Functional Brain Networks Develop from a "Local to Distributed" Organization*, 5:5 PLOS COMPUTATIONAL BIOLOGY 1, 8 (2009) (increased connectivity

Pruning. The gray matter of the brain is where brain cell "neurons" reside and includes the top layer of the brain and also the nuclei within the brain.[61] As the brain matures, gray matter *thins*[62] through processes called synaptic pruning, which is the programmed elimination of unused and cumbersome neuronal connections believed to support the ability for the brain to adapt to its environment. Just as the pruning of a rose bush strengthens the remaining branches, the pruning of excess connections leads to greater efficiency and strengthening of the ability for complex information processing that support consistent exercise of good judgment.[63] Maturational improvements in the gray matter continue to take

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"promote[s] interactions between brain regions . . . allowing for a more effective 'solution' to any particular set of processing demands").

[61] *See* Gazzaniga, *supra* note 37, at 64-65; *see* Eric R. Kandel et al., PRINCIPLES OF NEURAL SCIENCE 9 (James H. Schwartz & Thomas M. Jessel, eds., McGraw-Hill 2000).

[62] *See* Durston, *supra* note 37, at 1014; Jay N. Giedd et al., *Anatomical Brain Magnetic Resonance Imaging of Typically Developing Children and Adolescents*, 48:5 J. AM. ACAD. CHILD ADOLESCENT PSYCHIATRY 465, 469 (2009); Gogtay, *supra* note 38, at 8174 (10 year study of gray matter loss showed continued gray matter loss until adulthood).

[63] *See* Robert F. McGivern et al., *Cognitive Efficiency on a Match to Sample Task Decreases at the Onset of Puberty in Children*, 50 BRAIN & COGNITION 73 (2002) (subjects of study aged 10 to 22 years); Casey, *supra* note 46, at 241 ("findings are consistent with the view that increasing cognitive capacity during childhood coincides with a gradual loss rather than formation of new synapses . . ."); *see also* Daniel J. Siegel, THE DEVELOPING MIND: TOWARD A NEUROBIOLOGY OF INTERPERSONAL EXPERIENCE 13-14 (Guilford Press 1999).

place through adolescence and into adulthood.[64] Thus, changes in gray matter, including pruning, enhance the ability to process complex information quickly allowing the brain to make executive plans supporting voluntary control of behavior.

Scientists have known about pruning for decades,[65] but modern brain imaging technology has provided important insights into the process.[66] Until MRI technology emerged, the common wisdom was that the volume of gray matter spurted only once, shortly after birth, and then declined gradually over time. Brain scans have revealed a more complicated reality: In particular regions of the brain, gray matter blossoms once again later in childhood.[67] Gray matter volumes

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[64] *See* Gogtay, *supra* note 38, at 8175.

[65] *See generally* Peter R. Huttenlocher, *Synaptic Density in Human Frontal Cortex: Developmental Changes and Effects of Aging*, 163 BRAIN RES. 195 (1979).

[66] *See*, *e.g.*, Sowell (2002), *supra* note 41, at 4.

[67] *See* McGivern, *supra* note 63, at 85; *see also* David N. Kennedy et al., *Basic Principles of MRI and Morphometry Studies of Human Brain Development*, 5 DEVELOPMENTAL SCI. 268, 274 (2002).

> Studies showed . . . nonlinear changes in cortical gray matter, summarized as a preadolescent increase followed by a postadolescent decrease. Further localization of these changes indicated that the frontal and parietal lobe peaked at about age 12, the temporal lobe at about age 16, and the occipital lobe continued its increase through age 20, although the confidence intervals on these observations are large.

peak during the ages from 10-20 years,[68] and the prefrontal cortex is one of the places where gray matter increases — before adolescence — and then gets pruned over time, beyond adolescence.[69] The prefrontal cortex is also one of the last regions where pruning is complete and this region continues to thin past adolescence.[70] This means that one of the last areas of the brain to reach full maturity, as measured by pruning, is the region most closely associated with risk assessment, impulse control, emotional regulation, decision-making, and planning — in other words, the ability to reliably and voluntarily control behavior.[71]

Myelination. Another important measure of brain maturity is myelination.[72] Myelination is

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Giedd (1999), *supra* note 42, at 861.

[68] *See* Giedd (1999), *supra* note 42, at 861; McGivern, *supra* note 63, at 85; Yurgelun-Todd, *supra* note 7, at 252, 55.

[69] *See* Jay N. Giedd, *The Teen Brain: Insights from Neuroimaging*, 42 J. ADOLESCENT HEALTH 335, 339 (2008).

[70] A study by the National Academy of Sciences measured gray matter density in individuals longitudinally from childhood to early adulthood and concluded that "the [gray matter] maturation ultimately involves the dorsolateral prefrontal cortex, which loses [gray matter] only at the end of adolescence." Gogtay, *supra* note 38, at 8175.

[71] *See id*. at 8177 (explaining that "[l]ater to mature were areas involved in executive function"); *see also* Michael C. Stevens et al., *Functional Neural Networks Underlying Response Inhibition in Adolescents and Adults,* 181 BEHAV. BRAIN RESEARCH 12 (2007).

[72] *See* Elkhonon Goldberg, THE EXECUTIVE BRAIN: FRONTAL LOBES & THE CIVILIZED MIND 144 (Oxford Univ. Press, 2001);

the process by which the brain's axonal connections become progressively insulated with a fatty white matter called myelin. Myelin surrounds the axons, which are neural fibers that use electrical impulses to carry information across long distances, and insulates the pathway, speeding the neural signal along the pathway.[73] "The presence of myelin makes communication between different parts of the brain faster and more reliable."[74] Myelination of "white matter"[75] continues through adolescence and into adulthood.[76]

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see also Sowell (2001), *supra* note 41, at 8819; Sowell (2003), *supra* note 43, at 311; Yurgelun-Todd, *supra* note 7, at 253.

[73] *See* Zoltan Nagy, Helena Westerberg & Torkel Klingberg, *Maturation of White Matter is Associated with the Development of Cognitive Functions During Childhood*, 16:7 J. COGNITIVE NEUROSCI. 1227, 1231-32 (2004) (explaining that "the physiological effects of increases in axon thickness and myelination are similar in that they both increase conduction speed."); Gazzaniga, *supra* note 36, at 31, 48-49.

[74] Goldberg, *supra* note 72, at 144.

[75] White matter is the tissue that composes the pathways between brain regions and that permits communication and interaction within the brain and between the brain and the body. *See* Gazzaniga, *supra* note 37, at 70, 72. For example, the corpus callosum, a critical white matter structure, bridges the two halves of the frontal lobes, permitting and regulating communication between the two halves of the brain. *See* Tomas Paus et al., *Structural Maturation of Neural Pathways in Children and Adolescents: In Vivo Study*, 283 SCIENCE 1908 (1999).

[76] M. R. Asato et al., *White Matter Development in Adolescence: A DTI Study*, 20:9 CEREBRAL CORTEX 2122, 2125 (2010) ("In agreement with other studies, we found evidence for continuing maturation of white matter throughout distributed brain

The integrity of the white matter, including myelination, matures at different rates across the brain.[77] Brain imaging data, supported by data gathered through the original histological (autopsy) techniques,[78] provides credible evidence that the connections from the prefrontal cortex are still developing well into adolescence and beyond, and are among the last pathways of the brain to mature.[79] In other words, maturation of prefrontal connectivity associated with voluntary behavior control (*i.e.*, risk assessment, impulse control, and emotional regulation) is not complete until late adolescence or beyond. Myelination also increases the efficiency of information processing and supports the integration of the widely

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regions from childhood into adulthood.") (internal citations omitted); *see* Nagy, Westerberg & Klingberg, *supra* note 73, *at* 1231-32; Durston, *supra* note 37, at 1014; Sowell (1999), *supra* note 42, at 860; Adolf Pfefferbaum et al., *A Quantitative Magnetic Resonance Imaging Study of Changes in Brain Morphology from Infancy to Late Adulthood*, 51 ARCHIVES OF NEUROLOGY 874, 885 (1994) (after age 20 white matter volume did not fluctuate until about age 70; subjects of study aged 3 months to 70 years).

[77] *See* Sowell (2003), *supra* note 43, at 311; Sowell (2002), *supra* note 41, at 4; Towbin & Schowalter, *supra* note 59, at 151.

[78] *See* Paus, *supra* note 75, at 1908.

[79] *See* Gogtay, *supra* note 38 *at* 8177 (noting that different parts of the brain undergo myelination and pruning at different rates, and finding that the higher-order cortices mature later than lower-order cortices."); *see also* Sowell (1999), *supra* note 42, at 859; K. Rubia et al., *Functional Frontalisation with Age: Mapping Neurodevelopmental Trajectories with fMRI,* 24 NEUROSCI. & BIOBEHAV. REVS. 13 (2000) (subjects of study aged 12 to 19 and 22 to 40 years).

distributed circuitry needed for complex behavior.[80] These structural changes are believed to underlie the functional integration (discussed below) of frontal regions with the rest of the brain.[81] The functional improvement of the connections between the various regions of the brain is believed to result from myelination that occurs during adolescence and is necessary for improved abilities of reliable self-control and better decision-making.[82] Efficient connectivity is needed for cognitive regions to interact with regions processing emotion, rewards, and social information in a timely and effective manner in order to control responses for optimal decision making. For example, recent research on the neural underpinnings of resistance to peer influence in adolescence indicates that improvements in this capacity may be linked to the development of greater connectivity between brain regions, and likely facilitates the better coordination of affect and cognition.[83] More generally, however, the development of improved self-regulatory abilities during and after adolescence is positively correlated with white matter maturation.[84]

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[80] *See* Luna (2009), *supra* note 4, at 257.

[81] *See id.; see also* Giedd (2009), *supra* note 62, at 467.

[82] *See* Steinberg, *Adolescent Development*, *supra* note 9, at 56; Beatriz Luna & John A. Sweeney, *The Emergence of Collaborative Brain Function: fMRI Studies of the Development of Response Inhibition*, 1021 ANNALS N.Y. ACAD. SCI. 296, 296-309 (2004); Damien A. Fair et al., *Development of Distinct Control Networks Through Segregation and Integration*, 104 PROC. NAT'L ACAD. SCI. U.S. 13507 (2007).

[83] *See* Steinberg, *Adolescent Development*, *supra* note 9, at 56.

[84] *See* Nagy, Westerberg & Klingberg, *supra* note 73, at 1231-32.

Top-Down Connectivity. Recent studies have shown that "development of top-down effective connectivity from cognitive control regions is critical in supporting active inhibitory control."[85] Top-down connectivity refers to the ability for executive regions, such as in the prefrontal cortex, to exert executive control on response regions.[86] fMRI has shown that the strength and number of top down functional connections continues to increase into adulthood. In addition, the organization of functional brain connections forming networks continues to optimize into adulthood.[87] These results are supported by studies measuring the integrity of structural white matter pathways, which show protracted development of the connections between the prefrontal cortex and subcortical regions of the brain areas that support cognitive control.[88] The protracted development of top-down connectivity therefore "may reflect a period of particular vulnerability to both the peak in risk-taking behavior during adolescence and the emergence and exacerbation of psychopathology, which is associated

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[85] 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*, 30:46 J. NEUROSCI. 15535, 15543 (2010).

[86] *Id*. at 15542.

[87] *Id*.; Nico Dosenbach et al., *Prediction of Individual Brain Maturity Using fMRI*, 329 SCIENCE 1358, 1360-61 (2010) (brain continues to mature until 22 years of age, with region of brain most highly correlated to brain maturity was pre-frontal cortex).

[88] Asato, *supra* note 76 at 2128; Petersen, *supra* note 60, at 8.

with abnormalities in reward processing and cognitive control."[89]

2. Adolescent Brains Tend to Be More Active Than Adult Brains in Regions Associated With Risky, Impulsive, and Sensation-Seeking Behavior and Less Active in Regions Associated with the Ability to Voluntarily Control Behavior.

The brain is a complex network of interrelated parts. Each part is associated with different functions and works in conjunction with other parts to form systems. In general, the two neurobiological systems that inform our understanding of adolescent behavior, as discussed above in Point A, are (1) the motivational system, which includes the limbic and paralimbic regions of the brain; and (2) the cognitive control system, which is primarily comprised of the prefrontal cortex and its connections to the rest of the brain.[90] The differences between adolescent and adult behavior correlate with their respective and disparate reliance on each of these systems and their related brain structures.[91]

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[89] Asato, *supra* note 76, at 2128; *see* Spear (2011), *supra* note 15, at 391 (top-down control gradually gains a "competitive edge" over "'bottom-up' systems that express exaggerated reactivity to motivational stimuli").

[90] *See* Steinberg, *Adolescent Development*, *supra* note 9, at 54.

[91] Stephanie Burnett et al., *Development During Adolescence of the Neural Processing of Social Emotion,* 21:9 J. COGNITIVE

The structural immaturities of the adolescent brain discussed above represent only one dimension of the immaturity of the adolescent brain. Developmental neuroimaging studies demonstrate that the regions of the brain associated with voluntary behavior control mature structurally at the same time as specific changes in how the brain functions.[92] These findings reveal that adolescents and adults exhibit different patterns of brain activity during decision-making tasks and provide insight into the neural underpinnings of the risky, impulsive, and sensation-seeking behavior of adolescents.[93]

Studies show that the motivational system, which underlies risky and reward-based behavior, develops earlier than the cognitive control system, which regulates such behavior. Furthermore, during adolescence, the motivational system

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NEUROSCI. 173 (2009); S. J. Blakemore, *Adolescent Development of the Neural Circuitry for Thinking About Intentions*, 2:2 SOC. COGNITIVE & AFFECTIVE NEUROSCI. 130 (2007).

[92] Amy L. Krain et al., *An fMRI Examination of Developmental Differences in the Neural Correlates of Uncertainty and Decision Making,* 47:10 J. CHILD PSYCHOL. & PSYCHIATRY 1023, 1024 (2006); *see also* Liston C. Watts et al., *Frontostriatal Microstructure Predicts Individual Differences in Cognitive Control,* 16:4 CEREBRAL CORTEX 553 (2006); B.J. Casey et al., *Contribution of Frontostriatal Fiber Tracts to Cognitive Control in Parent–Child Dyads with ADHD,* 164:11 AM. J. PSYCHIATRY 1729 (2007).

[93] Krain, *supra* note 92; *see also* Adriana Galvan et al., *Earlier Development of the Accumbens Relative to Orbitofrontal Cortex Might Underlie Risk-Taking Behavior in Adolescents*, 26:25 J. NEUROSCI. 6885 (2006*); see* Hare, *supra* note 29.

continues to develop more quickly than the cognitive control system.[94] The result is that adolescents experience increasing motivation for risky and reward-seeking behavior without a corresponding increase in the ability to self-regulate behavior.

The earlier development of the motivational system is evident in a number of areas of the brain. Among these are the amygdala and the nucleus accumbens which, in conjunction with specific neurochemical imbalances in the adolescent brain (see below), contribute to the relative dominance of the adolescent motivational system.

Amygdala. The amygdala is associated with aggressive and impulsive behavior.[95] The

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[94] *See* Steinberg, Adolescent Development, *supra* note 9, at 54; *see also* Monique Ernst et al., *Neurobiology of the Development of Motivated Behaviors in Adolescence: A Window into a Neural Systems Model*, 93 PHARMACOLOGY, BIOCHEMISTRY & BEHAV. 199 (2009).

[95] *See generally* Jan Gläscher & Ralph Adolphs, *Processing of the Arousal of Subliminal and Supraliminal Emotional Stimuli by the Human Amygdala*, 23 J. NEUROSCI. 10274 (2003); Ralph Adolphs, *Neural Systems for Recognizing Emotion*, 12 CURRENT OPINION IN NEUROBIO. 169 (2002); Gazzaniga, *supra* note 37, at 553-72; K. Luan Phan et al., *Functional Neuroanatomy of Emotion: A Meta-Analysis of Emotion Activation Studies in PET and fMRI*, 16 NEUROIMAGE 331, 336 (2002); Goldberg, *supra* note 72, at 31; Kevin S. LaBar et al., *Human Amygdala Activation During Conditioned Fear Acquisition and Extinction: A Mixed-Trial fMRI Study*, 20 NEURON 937 (1998); Richard D. Lane et al., *Neuroanatomical Correlates of Pleasant and Unpleasant Emotion*, 35 NEUROPSYCHOLOGIA 1437, 1441 (1997); Hans C. Breiter et al., *Response and Habituation of the*

amygdala is "a neural system that evolved to detect danger and produce rapid protective responses without conscious participation."[96] It dictates instinctive gut reactions, including fight or flight responses.[97] The amygdala is also a key component of circuitry involved in assessing salience, or the importance of environmental stimuli to survival, and is generally associated with processing emotional responses to a perceived danger.[98]

The prefrontal cortex — the primary region associated with self-regulation and the cognitive control system — modulates function in the amygdala[99] to which it is strongly connected.[100] A

Human Amygdala During Visual Processing of Facial Expression, 17 NEURON 875 (1996); Steinberg, *Future Orientation*, *supra* note 7, at 40.

[96] Abigail A. Baird et al., *Functional Magnetic Resonance Imaging of Facial Affect Recognition in Children and Adolescents*, 38 J. AM. ACAD. CHILD & ADOLESCENT PSYCHIATRY 1, 1 (1999) (study found that adolescents 12-17 years old showed significant amygdala activation in response to a task that required the judgment of fearful facial affect); *see also* William D.S. Killgore & Deborah Yurgelun-Todd, *Activation of the Amygdala and Anterior Cingulate During Nonconscious Processing of Sad Versus Happy Faces*, 21 NEUROIMAGE 1215 (2004); Phan, *supra* note 95, at 336.

[97] *See* Goldberg, *supra* note 76, at 31; Phan, *supra* note 95, at 336.

[98] *See* Giedd (2008), *supra* note 69, at 338.

[99] *See* Mario Beauregard et al., *Neural Correlates of Conscious Self-Regulation of Emotion*, 21 J. NEUROSCI. 165RC (2001); Ahmad Hariri et al., *Modulating Emotional Responses: Effects of a Neocortical Network on the Limbic System*, 11 NEUROREPORT 43 (2000).

still-maturing prefrontal cortex exerts less control over the amygdala and has less influence over behavior and emotions than a fully mature prefrontal cortex.[101]

Nucleus Accumbens. The nucleus accumbens, a brain region rich in dopamine, is associated with reward processing. Its primary function is to process responses to a potential reward.[102] Studies show that when making decisions, "relative to children and adults, adolescents show exaggerated activation of the accumbens, in concert with less mature recruitment of top-down prefrontal control."[103] This exaggerated activity is consistent with the tendency of adolescents to overvalue rewards in risk-reward assessment and provides a

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[100] Ralph Adolphs, *The Human Amygdala and Emotion*, 5 NEUROSCIENTIST 125, 125-26 (1999); *see also* Joseph LeDoux, THE EMOTIONAL BRAIN: THE MYSTERIOUS UNDERPINNINGS OF EMOTIONAL LIFE 303 (1996).

[101] *See* Neir Eshel et al., *Neural Substrates of Choice in Adults and Adolescents: Development of the Ventrolateral Prefrontal and Anterior Cingulate Cortices*, 45 NEUROPSYCHOLOGIA 1270, 1270-71 (2007) (reporting prefrontal brain areas associated with higher-order cognition, emotional regulation, reward values, and behavior control are some of the last to mature and that this lag in maturation may explain why adolescents demonstrate poor decision-making); *see also* Gargi Talukder, *Decision-Making Is Still a Work in Progress for Teenagers*, Report dated July 2000 at http://www.brainconnection.com; *see also* Spear (2000), *supra* note 3, at 440 (reporting Dr. Yurgelun-Todd's research); *see also* Ralph Adolphs et al., *Fear and the Human Amygdala*, 15 J. NEUROSCI. 5879, 5889 (1995).

[102] Galvan, *supra* note 93, at 6890.

[103] *See* Casey, *supra* note 3, at 69.

neurobiological basis for the "increased impulsive and risky behaviors observed during [adolescence]."[104]

The nucleus accumbens, which is found in the ventral striatum, is a "critical node" in the reward related neurocircuitry of the brain, contributing to directing behavior toward appropriate goals by consolidating contextual and goal directed information from other areas of the brain.[105] Developmental studies have shown hyperactivity in the ventral striatum during anticipation of rewards in adolescents, as compared to adults.[106] In parallel with increased reward reactivity in the ventral striatum, these studies have found increased engagement of the regions that support the behavior that leads to the reward. Increased reactivity to rewards paired with increased engagement of response regions can lead to an impulsive reaction in the presence of rewards in adolescence.[107] Such increased reactivity, coupled with other aspects of the developing brain, is

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[104] *See id.* at 69-70.

[105] Spear (2011), *supra* note 15, at 392; *see* Chein, *supra* note 15, at F1 (the ventral striatum is part of the "incentive processing system in the brain").

[106] *See* Geier, *supra* note 9, at 1625; Aarthi Padmanabhan et al., *Developmental Changes in Brain Function Underlying the Influence of Reward Processing on Inhibitory Control*, 1 DEVELOPMENTAL COGNITIVE NEUROSCIENCE 517, 526 (2011), Spear (2011); *supra* note 15, at 394 (adolescents have been reported by a number of groups to show heightened activation of the ventral striatum during *receipt* of rewards relative to younger and/or older individuals").

[107] Geier, *supra* note 9, at 1626; Padmanabhan, *supra* note 106, at 523.

thought to potentially contribute to the high rate of risk taking in adolescence.[108]

Dopamine and Serotonin. Dopamine is a neurotransmitter that underlies pleasure and motivation.[109] Around the time of puberty, adolescents experience "a rapid and dramatic increase in dopaminergic activity within the motivational system."[110] Because dopamine plays a critical role in the brain's reward circuitry this increase in activity is likely to promote reward-seeking behavior.[111] At the same time, adolescents have correspondingly lower levels of serotonin, a neurotransmitter known to support inhibitory control.[112] This imbalance between lower levels of serotonin and higher levels of dopamine

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[108] Padmanabhan, *supra* note 106, at 527; Chein, *supra* note 15, at F1 ("Many research groups . . . have posited that adolescents' relatively greater propensity toward risky behavior" is based in part on the "*incentive processing* system involving the ventral striatum") (emphasis in original).

[109] *See* Andersen, *supra* note 14, at 3-18; Crews, He & Hodge, *supra* note 14, at 189-99; Spear (2000), *supra* note 3, at 417-63.

[110] Steinberg, *Adolescent Development*, *supra* note 9, at 54.

[111] *Id.* at 258; *see* Luna, *supra* note 4, at 258. Moreover, "[t]here is evidence that changes in the density and distribution of receptors for dopamine . . . within regions critical to incentive processing take place around the time of puberty, and that these changes coincide with a dramatic elevation in the salience of peer interactions." Chein *supra* note 15, at F8.

[112] *See* Luna, *supra* note 4, at 258; R. Andrew Chambers, Jane R. Taylor & Marc N. Potenza, *Developmental Neurocircuitry of Motivation in Adolescence: A Critical Period of Addiction Vulnerability*, 160 AM. J. PSYCHIATRY 1041 (2003).

during adolescence is believed to underlie risky and impulsive decision making by adolescents.

In addition to motivation, dopamine also plays a crucial role in reinforcement learning. Thus, the adolescent period does not only include heightened motivation but also a greater capacity for learning[113] having implications for enhanced amenability for rehabilitation in the adolescent period compared to adulthood.

In sum, adolescent behavior is characterized by a hyperactive reward-driven system (involving the nucleus accumbens and increased dopamine), a limited harm-avoidant system (involving the amygdala), and an immature cognitive control system (involving the prefrontal cortex and decreased serotonin).[114] As a result, adolescent behavior is more likely to be impulsive and motivated by the possibility of reward, with less self-regulation and effective risk assessment. In other words, the adolescent brain is biologically biased to engage in exploring new environments and experiences which can involve taking risks.

Adolescence is a time of great physiological and psychological development. It is also a time marked by impulsive, risky, and sensation-

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[113] Dustin Wahlstrom et al., *Neurobehavioral Evidence for Changes in Dopamine System Activity During Adolescence*, 34 NEUROSCIENCE BIOBEHAVIORAL REV. 631, 643 (2010).

[114] Monique Ernst et al., *Triadic Model of the Neurobiology of Motivated Behavior in Adolescence*, 36 PSYCHOL. MED. 299, 300-302 (2006).

seeking behavior. Scientific research has shed light on the biological mechanisms that help to explain this behavior. And each time this Court has examined the constitutional limitations of imposing severe penalties on juvenile offenders, the scientific research on the development of the adolescent brain has grown. This research establishes that "the brain systems that are crucial for exerting cognitive control over behavior and processing rewards are still immature during adolescence."[115] "These immaturities result in a system that is able to exert cognitive control, but in an inconsistent manner with limited flexibility and motivational control."[116] In other words, "the basic elements are established, but refinements are needed to support the necessary efficiency in circuit processing to establish reliable executive control."[117] As one researcher put it, the process of adolescent development is akin to "starting the engines without a skilled driver behind the wheel."[118]

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[115] *See* Luna, *supra* note 4, at 258; *see also* Ryan L. Muetzel et al., *The Development of Corpus Callosum Microstructure and Associations with Bimanual Task Performance in Healthy Adolescents*, 39:4 NEUROIMAGE 1918 (2008); Elizabeth A. Olson, *White Matter Integrity Predicts Delay Discounting Behavior in Adolescents: A Diffusion Tensor Imaging Study*, 21:7 J. COGNITIVE NEUROSCI. 1406 (2008); Elizabeth A. Olson, *Delay and Probability Discounting Behavior in Healthy Adolescents: Associations with Age, Personality Style, and Other Measures of Executive Function,* 43:7 PERSONALITY AND INDIVIDUAL DIFFERENCES 1886 (2007).

[116] *See* Luna, *supra* note 4, at 258.

[117] *Id.*

[118] Steinberg, *Adolescent Development*, *supra* note 9, at 56.

CONCLUSION

While not formally supporting either party in these cases, the *amici* hope that the Court will consider the scientific evidence presented here in its deliberations about whether, in the present case, the Eighth Amendment (1) requires that these defendants be held to a different standard of culpability from that which applies to adults and (2) prohibits the imposition of a sentence of life without the possibility of parole on an adolescent offender.

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