

Braking and Accelerating of the Adolescent Brain

B. J. Casey, Rebecca M. Jones, and Leah H. Somerville

Sackler Institute for Developmental Psychobiology

Adolescence is a developmental period often characterized as a time of impulsive and risky choices leading to increased incidence of unintentional injuries and violence, alcohol and drug abuse, unintended pregnancy, and sexually transmitted diseases. Traditional neurobiological and cognitive explanations for such suboptimal choices and actions have failed to account for nonlinear changes in behavior observed during adolescence, relative to childhood and adulthood. This review provides a biologically plausible conceptualization of the mechanisms underlying these nonlinear changes in behavior, as an imbalance between a heightened sensitivity to motivational cues and immature cognitive control. Recent human imaging and animal studies provide a biological basis for this view, suggesting differential development of subcortical limbic systems relative to top-down control systems during adolescence relative to childhood and adulthood. This work emphasizes the importance of examining transitions into and out of adolescence and highlights emerging avenues of future research on adolescent brain development.

Adolescence is characterized as a time when we act more impulsively, fail to consider long-term consequences, and engage in riskier behavior than we do as adults (Gardner & Steinberg, 2005; Scott, 1992; Steinberg et al., 2008). This propensity to take risks is reflected in higher incidences of accidents, suicides, unsafe sexual practices, and criminal activity (Scott, 1992). Juveniles 15 years of age and younger act more impulsively than do older adolescents, but even 16- and 17-year-old youth fail to exhibit adult levels of self-control (Feld, 2008).

In the past decade, a number of cognitive and neurobiological hypotheses have been postulated for why adolescents engage in impulsive and risky acts. Traditional accounts of adolescence suggest that it is a period of development associated with progressively greater efficiency of cognitive control capacities. This efficiency in cognitive control is described as dependent on maturation of the prefrontal cortex as evidenced by imaging (Galvan et al., 2006; Gogtay et al., 2004; Hare et al., 2008; Sowell et al., 2003) and postmortem studies (Bourgeois, Goldman-Rakic, & Rakic, 1994; Huttenlocher, 1979; Rakic, 1994) showing continued structural and functional development of this region well into young adulthood.

The general pattern of improved cognitive control with maturation of the prefrontal cortex (Crone & van der Molen, 2007) suggests a linear increase in development from childhood to adulthood. If cognitive control and an immature prefrontal cortex were the basis for suboptimal choice behavior alone, then children should look remarkably similar or presumably worse than adolescents, given their less developed prefrontal cortex and cognitive abilities (Casey, Getz, & Galvan, 2008). Yet suboptimal choices and actions observed during adolescence represent an inflection in development (Windle et al., 2008) that is unique from either childhood or adulthood, as evidenced by the National Center for Health Statistics on adolescent behavior and mortality (Eaton et al., 2008).

This review addresses the primary question of how the brain is changing during adolescence in ways that may explain inflections in risky behavior. We outline a testable neurobiological model that emphasizes the dynamic interplay between subcortical and cortical brain regions and speculate on the emergence of these systems from an evolutionary perspective. We provide evidence from behavioral and human brain imaging studies to support this model in the framework of actions in motivational contexts (Cauffman et al., 2010; Figner, Mackinlay, Wilkening, & Weber, 2009; Galvan, Hare, Voss, Glover, & Casey, 2007; Galvan et al., 2006) and address why some teenagers may be at greater risk than others for making suboptimal decisions leading to poorer long-term outcomes (Galvan et al., 2007; Hare et al., 2008).

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Requests for reprints should be sent to B. J. Casey, Sackler Institute for Developmental Psychobiology, Weill Cornell Medical College, 1300 York Avenue, Box 140, New York, NY 10065. E-mail: bjc2002@med.cornell.edu

NEUROBIOLOGICAL MODEL OF ADOLESCENCE

An accurate conceptualization of cognitive and neurobiological changes during adolescence must treat adolescence as a transitional developmental period (Spear, 2000), rather than a single snapshot in time. In other words, to understand this developmental period, characterizing transitions into and out of adolescence is necessary for distinguishing distinct attributes of this period of development (Casey, Galvan, & Hare, 2005; Casey, Tottenham, Liston, & Durston, 2005). Establishing developmental trajectories for cognitive processes is essential in characterizing these transitions and constraining interpretations about changes in behavior during this period.

We have developed a testable neurobiological model of adolescent development within this framework that builds on rodent models (Brenhouse, Sonntag, & Andersen, 2008; Laviola, Adriani, Terranova, & Gerra, 1999; Spear, 2000) and recent imaging studies of adolescence (Ernst et al., 2005; Galvan et al., 2006, 2007; Hare et al., 2008; Somerville, Hare, & Casey, in press; Van Leijenhorst, Moor, et al., 2010; Van Leijenhorst, Zanolie, et al., 2010). Figure 1 depicts this model. This characterization of adolescence goes beyond exclusive association of risky behavior to the immaturity of the prefrontal cortex. Rather, the proposed neurobiological model illustrates how subcortical and cortical top-down control regions must be considered together. The cartoon illustrates different developmental trajectories for these systems, with subcortical systems such as the ventral striatum developing earlier than prefrontal

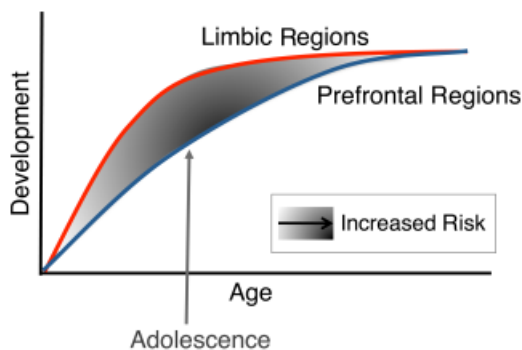


FIGURE 1 Neurobiological model depicting later development of top-down prefrontal regions relative to subcortical regions involved in desire and fear. This imbalance in development of these systems is proposed to be at the core of risky choice behavior in adolescents in contrast to the popular view of adolescent behavior being due to the protracted development of the prefrontal cortex alone (From Somerville, Jones, & Casey, 2010).

control regions. According to this model, the individual is biased more by functionally mature subcortical regions during adolescence (i.e., imbalance of subcortical relative to prefrontal cortical control), compared with children, for whom these systems (i.e., subcortical and prefrontal) are both still developing, and compared with adults, for whom these systems are fully mature.

This perspective provides a basis for nonlinear shifts in risky behavior across development due to earlier maturation of subcortical systems relative to less mature top-down prefrontal control systems. With development and experience, the functional connectivity between these regions provides a mechanism for top-down control of this circuitry (Hare et al., 2008). Further, the model reconciles the contradiction of health statistics of risky behavior during adolescence with the astute observation by Reyna and Farley (2006) that adolescents are quite capable of rational decisions and understand risks of behaviors in which they engage. However, in emotionally salient situations, subcortical systems will win out (accelerator) over control systems (brakes) given their maturity relative to the prefrontal control system.

This model is consistent with models of adolescent development (Ernst, Pine, & Hardin, 2006; Ernst, Romeo, & Andersen, 2009; Geier & Luna, 2009; Nelson, Leibenluft, McClure, & Pine, 2005; Steinberg, 2008; Steinberg et al., 2009) that suggest differential development of subcortical and cortical regions. For example, the triadic model proposed by Ernst et al. (2006) describes motivated behavior as having three distinct neural circuits (approach, avoidance, and regulatory). The approach system relates to reward behaviors and is largely controlled by the ventral striatum. The avoidance system relates to avoidance behaviors and is mostly controlled by the amygdala. Lastly, the regulatory system balances the approach and avoidance systems and is largely controlled by the prefrontal cortex. Accordingly, increased risk taking behavior during adolescence is due to greater influence of the approach system and a weaker influence of the regulatory system.

Our model differs from others in that it is based on empirical evidence for brain changes not only in the transition from adolescence to adulthood, but also the transition into adolescence from childhood. Further, we do not suggest that the striatum and amygdala are specific to approach and avoidant behavior given recent studies showing valence independence of these structures (Levita et al., 2009), but rather that they are systems important in detecting motivationally and emotionally relevant cues in the environment that can bias behavior. This sensitivity

to appetitive and emotive cues during adolescence has been described across species (see Spear, 2009) and is reviewed here.

COMPARATIVE AND EVOLUTIONARY PERSPECTIVES ON ADOLESCENCE

A question that emerges from the imbalance model of adolescent brain development is why the brain might be programmed to develop in this way. This question may be addressed by taking a step backward and considering the definition of adolescence as the transitional period between childhood and adulthood. Puberty marks the onset of adolescence with the beginnings of sexual maturation (Graber & Brooks-Gunn, 1998) and can be defined by biological markers. Adolescence can be described as a progressive transition into adulthood with a nebulous ontogenetic time course (Spear, 2000, p. 419). A complete discussion of the effect of pubertal hormones on brain and behavior is beyond the scope of this paper (see Forbes & Dahl, 2010, and Romeo, 2003, for detailed reviews on the subject).

Evolutionarily speaking, adolescence is a period of gaining independence from the protection of the family, which simultaneously may put the individual in harms way (Kelley, Schochet, & Landry, 2004). Independence-seeking behaviors are observed across mammalian species, with increases in peer-directed social interactions and intensification in novelty seeking which impact adolescents' propensity for risky behavior (Brown, 2004; Chassin et al., 2004; Collins & Laursen, 2004; Laviola et al., 1999). This risky behavior may be defined as the product of a biologically driven imbalance between increased novelty and sensation seeking in conjunction with immature "self-regulatory competence" (Steinberg, 2004). Speculation would suggest that this developmental pattern is an evolutionary feature in that an individual needs to engage in high-risk behavior to leave a safe and familiar niche in order to find a mate and procreate (Spear, 2000). Thus, risk taking appears to coincide with the time in which hormones drive adolescents to seek out sexual partners. In today's society—when adolescence may extend indefinitely—with children living with parents and having financial dependence and choosing mates later in life, this behavior may be less adaptive. Our neurobiological model suggests this occurs through differential development of subcortical and cortical systems. Empirical behavioral and imaging data are reviewed in support of this view.

ADOLESCENT BEHAVIORAL DEVELOPMENT

A core component of behavioral development is the ability to suppress inappropriate actions in favor of goal-directed ones, especially in the presence of compelling incentives. This ability is typically referred to as cognitive control (Casey, Galvan, et al., 2005; Casey, Giedd, & Thomas, 2000; Casey, Thomas, et al., 2000). We review classic cognitive developmental literature in the context of changes in cortically driven cognitive processes with age and provide behavioral and neuroanatomical evidence for its distinction from risky behaviors.

A number of classic developmental studies have shown that cognitive control develops throughout childhood and adolescence (Case, 1972; Flavell, Beach, & Chinsky, 1966; Keating & Bobbitt, 1978; Pascual-Leone, 1970). Several theorists have argued that this development is due to increases in processing speed and efficiency (e.g., Bjorklund, 1985, 1987; Case, 1972), but others have suggested "inhibitory" processes are the key factor (Harnishfeger & Bjorklund, 1993). According to this account, suboptimal choices in childhood are due to greater susceptibility to interference from competing sources that must be suppressed (e.g., Brainerd & Reyna, 1993; Casey, Thomas, Davidson, Kunz, & Franzen, 2002; Dempster, 1993; Diamond, 1985; Munakata & Yerys, 2001). Thus, optimal decision making requires the control of impulses (Mischel, Shoda, & Rodriguez, 1989), and this ability matures in a linear fashion across childhood and adolescence (Eigsti et al., 2006).

In contrast, risk taking or reward seeking behaviors seem to peak during adolescence and then decline in adulthood (Eaton et al., 2008; Windle et al., 2008) and are associated with puberty maturation (Dahl, 2004; Martin et al., 2001). A recent study by Steinberg et al. (2008) delineated the construct of impulse/cognitive control from sensation seeking behaviors, defined as the desire to seek out novel experiences and taking risks in order to achieve them. They tested individuals between the ages of 10 and 30 and showed that differences in sensation seeking with age followed a curvilinear pattern, with peaks in sensation seeking increasing between 10 and 15 years and declining or remaining stable thereafter. In contrast, age differences in impulsivity followed a linear pattern, with decreasing impulsivity with age.

These findings suggest distinct developmental trajectories for the two constructs. Specifically, impulsivity diminishes with age across childhood and adolescence (Casey, Galvan, et al., 2005; Casey, Thomas, et al., 2002; Galvan et al., 2007), although there are differences in the degree to which a given individual

is impulsive or not, regardless of age (Eigsti et al., 2006). In contrast to impulse/cognitive control, sensation seeking/risk taking appears to show a curvilinear pattern, with an increase during adolescence relative to childhood and adulthood (Cauffman et al., 2010; Figner et al., 2009; Galvan et al., 2007). As will be reviewed in the following sections, these findings suggest a distinct neural system for the construct of risky behavior, separate from the neural system for impulse control, with earlier development of risk taking behavior relative to protracted development of impulse control (Galvan et al., 2007; Steinberg et al., 2008).

ADOLESCENT BRAIN DEVELOPMENT

Recent investigations of adolescent brain development have been based on advances in neuroimaging methodologies that can be easily used with developing human populations. These methods rely on magnetic resonance imaging (MRI) methods and include structural MRI, which is used to measure the size and shape of structures; functional MRI (fMRI), which is used to measure patterns of brain activity; and diffusion tensor imaging (DTI), which is used to index connectivity of white matter fiber tracts. Evidence for our developmental model of competition between cortical and subcortical regions is supported by immature structural and functional connectivity as measured by DTI and fMRI, respectively.

MRI Studies of Human Brain Development

Several studies have used structural MRI to map the anatomical course of normal brain development (see review, Casey, Tottenham, et al., 2005). Although total brain size is approximately 90% of its adult size by age 6, the gray and white matter subcomponents of the brain continue to undergo dynamic changes throughout adolescence. Data from recent longitudinal MRI studies indicate that gray matter volume has an inverted U-shape pattern, with greater regional variation than white matter (Giedd, 2004; Gogtay et al., 2004; Sowell, Thompson, & Toga, 2004; Sowell et al., 2003). In general, regions subserving primary functions, such as motor and sensory systems, mature earliest; higher-order association areas, which integrate these primary functions, mature later (Gogtay et al., 2004; Sowell et al., 2004). For example, studies using MRI-based measures show that cortical gray matter loss occurs earliest in the primary sensorimotor areas and latest in the dorsolateral prefrontal and lateral temporal cortices (Gogtay et al.,

2004). This pattern is consistent with nonhuman primate and human postmortem studies showing that the prefrontal cortex is one of the last brain regions to mature (Bourgeois et al., 1994; Huttenlocher, 1979) while subcortical and sensorimotor regions develop sooner. In contrast to gray matter, white matter volume increases in a roughly linear pattern, increasing throughout development well into adulthood (Gogtay et al., 2004). These changes presumably reflect ongoing myelination of axons by oligodendrocytes-enhancing neuronal conduction and communication of relevant connections.

Although less attention has been given to subcortical regions when examining structural changes, some of the largest changes in the brain across development are seen in portions of the basal ganglia such as the striatum (Sowell, Thompson, Holmes, Jernigan, & Toga, 1999), especially in males (Giedd et al., 1996). These developmental changes in structural volume within basal ganglia and prefrontal regions suggest that cortical connections are becoming more refined consistent with neural developmental processes (e.g., dendritic arborization, cell death, synaptic pruning, myelination) that are occurring during childhood and adolescence (Huttenlocher, 1979). These processes allow for fine-tuning and strengthening of connections between prefrontal and subcortical regions with learning that may coincide with greater cognitive control (e.g., signaling of prefrontal control regions to adjust behavior; Casey, Amso, & Davidson, 2006; Casey & Durston, 2006).

It is unclear exactly how structural changes relate to behavior changes. A few studies have shown indirect associations between MRI-based volumetric change and cognitive function using neuropsychological measures (e.g., Casey, Castellanos, et al., 1997; Sowell et al., 2003). Specifically, associations have been reported between MRI-based prefrontal cortical and basal ganglia regional volumes and measures of cognitive control (i.e., ability to override an inappropriate choice/action in favor of another; Casey, Castellanos, et al., 1997; Casey, Trainor, et al., 1997). These findings suggest that cognitive changes are reflected in structural changes in the brain and underscore the importance of subcortical (striatum) as well as cortical (e.g., prefrontal cortex) development.

DTI Studies of Human Brain Development

The MRI-based morphometry studies reviewed suggest that cortical connections are being fine-tuned with the elimination of an overabundance of synapses and strengthening of relevant connections

with development and experience. Recent advances in MRI technology like DTI provide a tool for examining the developmental modulation of specific white matter tracts and their relation to behavior. In one study, development of cognitive control was positively correlated with prefrontal–parietal fiber tracts (Nagy, Westerberg, & Klingberg, 2004) consistent with functional neuroimaging studies showing differential recruitment of these regions in children relative to adults (Klingberg, Forssberg, & Westerberg, 2002).

Using a similar approach, Liston et al. (2006) examined the strength of white matter tracts in frontostriatal circuits, which continue to develop across childhood into adulthood. The frontostriatal fiber tracts were defined by connecting two regions of interest in the striatum and ventral prefrontal cortex identified in an fMRI study using the same task (Durstun, Thomas, Worden, Yang, & Casey, 2002; Epstein et al., 2007). Across these developmental DTI studies, fiber tract measures across the entire brain were correlated with development. However, there was specificity in which particular fiber tracts were associated with cognitive control (Casey et al., 2007; Liston et al., 2006) or cognitive ability (Nagy et al., 2004). Specifically, frontostriatal connection strength positively predicted impulse control capacity, as measured by performance on a go/nogo task (Casey et al., 2007; Liston et al., 2006). These findings underscore the importance of examining not only regional structural changes, but also circuitry-related changes when making claims about age-dependent maturation of neural substrates of cognitive development.

fMRI Studies of Behavioral and Brain Development

Although structural changes as measured by MRI and DTI have been associated with behavioral changes during development, a more direct approach for examining structure–function associations is to measure changes in the brain and behavior simultaneously, as with fMRI. The ability to measure functional changes in the developing brain with MRI has significant potential for the field of developmental science. In the context of the current article, fMRI provides a means for constraining interpretations of adolescent decision making. As stated previously, the development of the prefrontal cortex is believed to play an important role in the maturation of higher cognitive abilities such as decision making and goal-oriented choice behavior (Casey, Tottenham, & Fossella, 2002; Casey, Trainor, et al., 1997).

Many paradigms have been used, together with fMRI, to assess the neurobiological basis of these abilities. These paradigms include go/nogo (participants must respond to one stimulus but suppress responses to a second stimulus), flanker (participants choose the directionality of a target surrounded by symbols that are either compatible or incompatible with the target), stop signal (participants respond as fast as possible to a stimulus but must suppress this response when they receive a stop signal such as an auditory tone), and antisaccade tasks (participants must inhibit reflexive eye movements to gaze in the opposite direction of a target; Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002; Casey, Giedd, et al., 2000; Casey, Trainor, et al., 1997; Durstun et al., 2003; Luna et al., 2001). Collectively, these studies show that children recruit distinct but often larger, more diffuse prefrontal regions when performing these tasks than do adults. The pattern of activity within brain regions central to task performance (i.e., that correlate with cognitive performance) become more focal or fine-tuned with age while regions not correlated with task performance diminish in activity with age. This pattern has been observed across both cross-sectional (Brown et al., 2005) and longitudinal studies (Durstun et al., 2006) and across a variety of paradigms.

Although neuroimaging studies cannot definitively characterize the mechanism of such developmental changes (e.g., dendritic arborization, synaptic pruning) the findings reflect development within, and refinement of, projections to and from activated brain regions with maturation. Further, the findings suggest that these neuroanatomical changes occur over a protracted period of time (Brown et al., 2005; Bunge et al., 2002; Casey, Thomas, et al., 2002; Casey, Trainor, et al., 1997; Crone, Donohue, Honomichl, Wendelken, & Bunge, 2006; Luna et al., 2001; Moses et al., 2002; Schlaggar et al., 2002; Tamm, Menon, & Reiss, 2002; Thomas et al., 2004; Turkeltaub, Gareau, Flowers, Zeffiro, & Eden, 2003).

How can this methodology inform us about whether adolescent decisions are indeed impulsive or are risky? Impulse control as measured by tasks such as the go/nogo task show a linear pattern of development across childhood and adolescence as described above. However, recent neuroimaging studies have begun to examine reward-related processing relevant to risk taking in adolescents (Bjork et al., 2004; Ernst et al., 2005; Galvan et al., 2005; May et al., 2004; Van Leijenhorst, Moor, et al., 2010). These studies have focused primarily on the region of the ventral striatum, a region implicated in learning and predicting reward outcomes.

SENSITIVITY TO APPETITIVE CUES IN ADOLESCENCE

Our neurobiological model suggests that the combination of heightened responsiveness to motivational cues and immaturity in behavioral control may bias adolescents to seek immediate rather than long-term gains. Tracking subcortical (e.g., ventral striatum) and cortical (e.g., prefrontal) development across childhood through adulthood provides constraints on whether changes reported in adolescence are specific to this period of development or reflect maturation that is steadily occurring in a somewhat linear pattern from childhood to adulthood.

Several groups have shown that adolescents show heightened activation of the ventral striatum in anticipation and/or receipt of rewards compared with adults (Ernst et al., 2005; Galvan et al., 2006; Geier, Terwilliger, Teslovich, Velanova, & Luna, 2009; Van Leijenhorst, Zanolie, et al., 2010), coupled with less activation in the prefrontal cortex relative to adults. In one of the first studies to examine this response across the full range of childhood to adulthood, Galvan and her colleagues examined behavioral and neural responses to reward manipulations in 6–29-year olds. They focused on brain circuitry implicated in reward-related learning and behavior in animal studies (Hikosaka & Watanabe, 2000; Pecina, Cagniard, Berridge, Aldridge, & Zhuang, 2003; Schultz, 2006), adult human imaging studies (e.g., Knutson, Adams, Fong, & Hommer, 2001; O'Doherty, Kringelbach, Rolls, Hornak, & Andrews, 2001; Zald et al., 2004), and in studies of addiction (Hyman & Malenka, 2001; Volkow & Li, 2004). Based on rodent models (Laviola et al., 1999; Spear, 2000) and previous imaging work (Ernst et al., 2005), they hypothesized that relative to children and adults, adolescents would show exaggerated activation of the ventral striatum in concert with less mature recruitment of top-down prefrontal control regions. Their results supported this hypothesis showing that the spatial extent of brain activity in adolescents in the ventral striatum to reward was similar to that observed in adults, whereas the extent of activity in prefrontal regions was more similar to children. The extent of activity between these two regions was associated with elevated magnitude of activity in the ventral striatum in adolescents relative to children and adults assumed to result from the imbalance in corticosubcortical development (see Figure 2). Recent work showing delayed functional connectivity between prefrontal and subcortical regions in adolescence relative to adults provides a mechanism for the lack of top-down control of regions related to processing motivational cues (Hare et al., 2008).

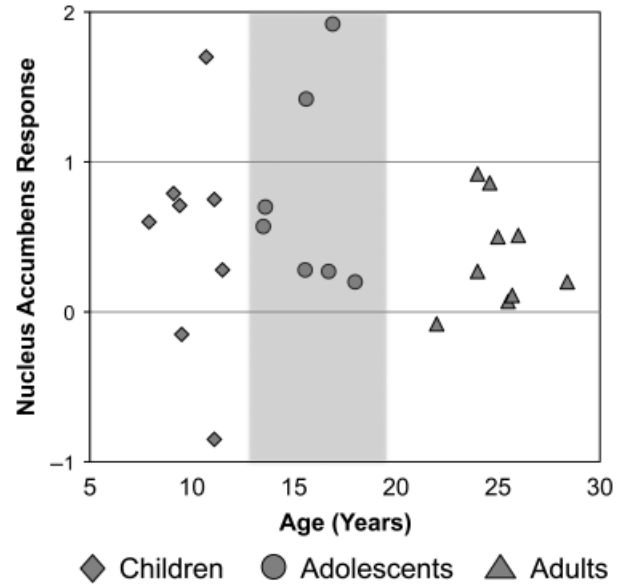


FIGURE 2 Activity in the ventral striatum to anticipated reward as a function of age, for each individual subject, showing enhanced activity between roughly 13 to 18 years (Adapted from Galvan et al., 2006, 2007).

These findings are consistent in part with rodent models (Laviola, Macri, Morley-Fletcher, & Adriani, 2003) and previous imaging studies (Ernst et al., 2005; Van Leijenhorst, Moor, et al., 2010) showing enhanced ventral striatal activity to rewards and anticipation of rewards during adolescence. Relative to children and adults, adolescents showed an exaggerated ventral striatal response to reward. However, both children and adolescents showed a less mature response in prefrontal control regions than adults. These findings suggest that different developmental trajectories for these regions may underlie the enhancement in ventral striatal activity, relative to children or adults, which may in turn relate to the increased risky decisions observed during this period of development (Figner et al., 2009). It is relevant to note that while several laboratories (Ernst et al., 2005; Galvan et al., 2006; Geier et al., 2009; Somerville et al., in press; Van Leijenhorst, Moor, et al., 2010) have shown this heightened response in the ventral striatum in adolescents, one laboratory has failed to observe this response (Bjork et al., 2004; Bjork, Smith, Chen, & Hommer, 2010). Future studies will be needed to clarify the specific conditions under which this pattern of brain activity is or is not observed.

Differential recruitment of prefrontal and subcortical regions have been reported across a number of developmental fMRI studies (Casey, Thomas, et al., 2002; Geier et al., 2009; Luna et al., 2001; Monk

et al., 2003; Thomas et al., 2004; Van Leijenhorst, Zanolie, et al., 2010). Typically these findings have been interpreted in terms of immature prefrontal regions rather than an imbalance between prefrontal and subcortical regional development. Given evidence of prefrontal regions in guiding appropriate actions in different contexts (Miller & Cohen, 2001), immature prefrontal activity might hinder appropriate estimation of future outcomes and appraisal of risky choices, and might thus be less influential on reward valuation than the ventral striatum. This pattern is consistent with previous research showing elevated subcortical, relative to cortical, activity when decisions are biased by immediate over long-term gains (McClure, Laibson, Loewenstein, & Cohen, 2004). During adolescence, relative to childhood or adulthood, immature prefrontal cortex engagement may not provide sufficient top-down control of robustly activated reward processing regions (e.g., ventral striatum), resulting in less influence of prefrontal systems relative to the ventral striatum in reward valuation.

While differential recruitment of cortical and subcortical regions has been robustly reported across development, only a few studies have addressed how cognitive control and reward systems interact. A recent study by Geier et al. (2009) examined this interaction using a version of an antisaccade task during fMRI in adolescents and adults. Their findings showed that on trials for which money was at stake, performance was enhanced, with the greatest enhancement (faster and more accurate responses) observed in adolescents. This performance was paralleled by exaggerated activation in the ventral striatum in adolescents following a cue that the next trial would be rewarded while they were preparing for and subsequently executing the antisaccade. Adolescents also showed elevated prefrontal activity in regions important for controlling eye movements. These findings suggest a reward-related up-regulation in these control regions.

The Geier study provides an example of how appetitive cues can facilitate cognitive performance in adolescents, but high-risk behavior in adolescence in everyday life suggests that appetitive cues may impair cognitive decisions. To test this hypothesis, Somerville et al. (in press) tested children, adolescents, and adults while they performed a go/nogo task on which they had to suppress a response to an appetitive social cue. She showed that adolescents had greater difficulty resisting appetitive social cues compared with children and adults, as evidenced by more false alarms to these cues than neutral ones. This behavioral performance was paralleled by en-

hanced activity in the ventral striatum. In contrast, activation in the prefrontal cortex was associated with overall accuracy and showed a linear decrease in activity with improvement in performance and age. A functional connectivity analysis identified the dorsal striatum as a key convergence point for cortical and subcortical signals. Collectively, these studies suggest that differences in adolescent behavior from adults depend on the context of the behavior. In appetitively charged situations, subcortical systems involved in detection of appetitive cues will win out (accelerator) over cortical control systems (brakes), given differential regional development. However, in situations in which appetitive or emotive cues are not present, cortical control systems are not compromised, leading to more optimal performance in adolescents.

ADOLESCENCE AND INDIVIDUAL DIFFERENCES

Individuals vary in their ability to control impulses and in risk taking, a phenomenon that has been recognized in psychology for some time (Bentlin, Slovic, & Severson, 1993). Therefore, some adolescents will be more likely to engage in risky behaviors, and be more prone to poorer outcomes. Thus, examining individual variability may help to identify potential biobehavioral markers to identify individuals who might be at greater risk for poor outcomes during adolescence.

A classic example of individual differences reported in these abilities in the social, cognitive, and developmental psychology literature is that of delay of gratification (Mischel et al., 1989). Delay of gratification is typically assessed in 3–4-year-old children. The child is asked whether they would prefer a small reward (one marshmallow) now or a large reward (two marshmallows) later. The child is then told that the experimenter will leave the room in order to prepare for upcoming activities and the experimenter explains to the child that if she remains in her seat and does not eat a marshmallow during that time, then she will receive the large reward of both marshmallows. If the child does not or cannot wait, she should ring a bell to summon the experimenter and thereby receive the smaller reward. Once it is clear the child understands the task, she is seated at the table with the two rewards and the bell. Distractions in the room are minimized, with no toys, books, or pictures. The experimenter returns after 15 minutes or after the child has rung the bell, eaten the rewards, or shown any signs of distress. Using this paradigm, Mischel showed that children typi-

cally behave in one of two ways on this task: (1) they ring the bell almost immediately in order to have the marshmallow, which means they only get one; (2) they wait and optimize their gains, and receive both marshmallows. This observation suggests that some individuals are better than others in their ability to control impulses in the face of highly salient incentives, and this bias can be detected in early childhood (Mischel et al., 1989) and appears to remain throughout adolescence and young adulthood (Eigsti et al., 2006).

What might explain individual differences in optimal choice behavior? Some theorists have postulated that dopaminergic mesolimbic circuitry, implicated in reward processing, underlies risky behavior (Blum et al., 2000). Developmental studies provide neurochemical evidence that indicates that the balance in the adolescent brain between cortical and subcortical dopamine systems begins to shift toward greater cortical dopamine levels during adolescence (Brenhouse et al., 2008; Spear, 2000). Similarly, there is a delayed time course of dopaminergic innervation of the nonhuman primate prefrontal cortex through adolescence into adulthood, suggesting that functional maturity is not reached until adulthood (Rosenberg & Lewis, 1995). Individual differences in this circuitry, such as allelic variants in dopamine-related genes, resulting in too little or too much dopamine in subcortical regions, might relate to the propensity of some to engage in risky behavior more than others (O'Doherty, 2004).

The ventral striatum has been shown to increase in activity immediately before people make risky choices on monetary-risk paradigms (Kuhnen & Knutson, 2005; Matthews, Simmons, Lane, & Paulus, 2004; Montague & Berns, 2002) and, as described previously, adolescents show exaggerated striatal activity to rewarding outcomes relative to children or adults (Ernst et al., 2005; Galvan et al., 2006). Collectively, these data suggest that adolescents may be more prone to risky choices as a group (Figner et al., 2009; Gardner & Steinberg, 2005), but some adolescents will be more prone than others to engage in risky behaviors, putting them at potentially greater risk for negative outcomes.

To explore individual differences in risk taking behavior, Galvan et al. (2007) examined the association between activity in reward-related neural circuitry in response to a large monetary reward with personality trait measures of risk taking and impulsivity in adolescence. fMRI and anonymous self-report rating scales of risky behavior, risk perception, and impulsivity were acquired in individuals between the ages of 7 and 29 years. There was a positive association between ventral striatal activity and the likelihood of engaging in risky behavior across development. This activity varied as a function of

individuals' ratings of anticipated positive or negative consequences of such behavior. The individuals who perceived risky behaviors as leading to dire consequences activated the ventral striatum less to reward. This negative association was driven by the child participants, whereas a positive association was seen in the adults who rated the consequences of such behavior as positive.

In addition to linking risk taking to reward circuitry, Galvan et al. (2007) showed no association between activity of this circuitry and ratings of impulsivity. Instead she showed that impulsivity was negatively correlated with age. This finding is consistent with a recent report by Steinberg (2008) showing differential development of sensation seeking and impulsivity, with sensation seeking increasing during adolescence relative to childhood and adulthood, but impulsivity following a linear pattern of decreasing with age. These findings suggest that during adolescence, some individuals may be more prone to engage in risky behaviors due to developmental changes in concert with variability in a given individual's predisposition to engage in risky behavior rather than to simple changes in impulsivity. Further, these individual and developmental differences may help explain vulnerability in some individuals to risk taking associated with substance use and, ultimately, addiction.

CONCLUSION

Human imaging studies show structural and functional changes in corticosubcortical circuitry (for review, see Casey, Tottenham, et al., 2005; Giedd et al., 1996, 1999; Jernigan et al., 1991; Sowell et al., 1999) that parallel increases in cognitive control and self-regulation (Casey, Trainor, et al., 1997; Luna & Sweeney, 2004; Luna et al., 2001; Rubia et al., 2000; Steinberg, 2004; Steinberg et al., 2008). These changes show a shift in activation of prefrontal regions from diffuse to more focal recruitment over time (Brown et al., 2005; Bunge et al., 2002; Casey, Trainor, et al., 1997; Durston & Casey, 2006; Moses et al., 2002) and elevated recruitment of subcortical regions during adolescence (Casey, Thomas, et al., 2002; Durston & Casey, 2006; Luna et al., 2001). Although neuroimaging studies cannot definitively characterize the mechanism of such developmental changes, these changes in volume and structure may reflect development within, and refinement of, projections to and from these brain regions during maturation suggestive of fine-tuning of the system with development (Hare et al., 2008; Liston et al., 2006).

Taken together, the findings synthesized here indicate that increased risk taking behavior in adolescence is associated with different developmental trajectories of subcortical motivational and cortical control regions. However, this is not to say that adolescents are incapable of making rational decisions. Rather, in emotionally charged situations, the more mature limbic system may win over the prefrontal control system in guiding actions.

Although adolescence has been distinguished as a period characterized by reward seeking and risk taking behaviors (Gardner & Steinberg, 2005; Spear, 2000) individual differences in neural responses to reward predispose some adolescents to take more risks than others, putting them at greater risk for poor outcomes such as addiction, substance abuse, and mortality. These findings provide crucial groundwork by synthesizing the various findings related to impulsivity and risk taking in adolescence and in understanding individual differences and developmental markers for propensities for suboptimal choices leading to negative consequences.

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