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# Biological, Developmental, and Neurobehavioral Factors Relevant to Adolescent Driving Risks

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**Abstract:** This article reviews emerging knowledge about key aspects of neurobehavioral development, with an emphasis on the development of self-regulation over behavior and emotions and its relevance to driving risks among youth. It begins with a brief overview of recent advances in understanding adolescent brain maturation and presents a heuristic model focusing on **brain–behavior–social-context interactions** during adolescent development. The article considers the relatively slow neurobehavioral maturation of cognitive control and emphasizes the importance of affective influences on decision making. It points to several questions about programs and policies that may help to protect high-risk youth during this important maturational period. The heuristic model is then used to examine a specific neuroregulatory system during adolescence—the regulation of sleep and arousal. This focus on sleep illustrates key points about brain–behavior–social-context interactions by looking at both biological and social influences on sleep in teens. Moreover, sleep has direct relevance to understanding a specific dimension of driving risk in youth. Sleep deprivation is rampant among adolescents, and the consequences of insufficient sleep (sleepiness, lapses in attention, susceptibility to aggression, and negative synergy with alcohol) appear to contribute significantly to driving risks in teens.  
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## Introduction

Learning to operate a car in a safe and responsible manner consistently requires not only the acquisition of specific knowledge and skills needed for driving but also mature functioning of a broader set of self-regulatory capacities that promote reliable self-control over behavior and emotions across a variety of situations and social contexts. Even a transient lapse in attention or an impulsive action triggered by a strong emotion can lead to deadly consequences in an automobile. These factors are particularly salient in adolescence because youth are still developing important aspects of self-regulatory capacities at the same time that they are learning how to drive. In addition, it appears that adolescents are especially vulnerable to affective influences in some social situations and contexts that make them more prone to risk taking, novelty seeking, sensation seeking, and strong emotional influences on decision making. Moreover, the underlying neural systems that support and influence these emerging abilities in self-control are still maturing throughout the teen years.

The primary focus of this article is to briefly review emerging knowledge about adolescent brain development, focusing particularly on the interplay between cognitive and emotional systems in ways that may provide insights relevant to understanding at least some aspects of the increased driving risks among youth. Clearly, this is a complex area with, at best, limited scientific understanding to date. The reasons why adolescents have difficulty controlling their emotions and behavior are complicated. Important factors include not only the biological dimensions of development but also the wide array of social influences that trigger and influence the underlying neurobehavioral systems of interest. The goals of the articles in this supplement are to present a conceptual framework that, it is hoped, will provide a useful framework for understanding, and to focus on a few areas of advancing knowledge where emerging research on neurobehavioral development may provide untapped opportunities for developing new approaches to effective driving safety efforts to prevent teen crashes.

## A Neurobehavioral Model: Puberty, Brain Maturation, and the Development of Self-Control over Behavior and Emotion in Adolescence

Emerging evidence indicates that adolescence is a period of malleability, or developmental plasticity, in neural systems that underpin behavior, emotions, deci-

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sion making, and self-regulatory capacities. Patterns of neural connection among systems of emotion, motivation, and cognitive processes related to the pursuit of long-term goals appear to undergo a natural reorganization and a set of maturational refinements during adolescence. At the same time, adolescents face new social challenges that require learning how to control their emotions and behaviors across increasingly complex social contexts and experiences, with diminishing amounts of adult monitoring and supervision. This situation creates an increasing set of demands for reliable self-control and responsible decision making across a wide range of circumstances and social contexts.

On the one hand, the increased demands for self-control can promote development. Adolescents need some challenging experiences and freedom from adult control in order to develop the skills and maturity to be able to function as an adult. On the other hand, these situations create a great deal of risk. The process of navigating complex social challenges—including many emotionally charged situations—with relatively immature capacities for self-control creates vulnerabilities for youth. Indeed, morbidity and mortality rates increase across the adolescent years.<sup>1</sup> Moreover, the primary causes of death and disability are rooted in the difficulties teenagers have controlling behavior and emotion—difficulties that are reflected in high rates of unintentional injuries, suicide, depression, alcohol and substance use, eating disorders, and health consequences related to risky sexual behavior.<sup>1</sup>

To understand these risks from a developmental neurobehavioral perspective, it is valuable to consider not only the cognitive control systems that underpin these important self-control capacities during adolescence, but also the changes in affective systems underlying motivation and emotion that are activated in association with the onset of puberty. In the narrowest sense, these pubertal changes contribute to the development of increasingly charged feelings in the realm of sexual and romantic motivations. More broadly, however, pubertal brain changes appear to influence a wide range of emotional processes and motivational tendencies in ways that interact with cognitive control systems, as well as in ways that may provide insights into aspects of risk taking, sensation seeking, and some types of reckless decisions in adolescence relevant to driving.

### **Pubertal Changes in Affective Systems: The Neurobehavioral Underpinnings of Increased Risk Taking, Sensation Seeking, and Novelty Seeking**

Broadly speaking, adolescence represents a transition from “child” status (requiring parent/adult monitoring of behavior) to “adult” status (with expectations for autonomous self-control of behavior in a socially responsible manner). The capacities for competent self-

control of behavior and emotions encompass a set of slow, gradual processes that continue to develop through the late teenage years and into the twenties. In contrast, the emergence of pubertal influences on emotion and motivation usually occurs in early adolescence—with the most tumultuous developments of puberty typically occurring by age 12 in girls and by age 13 in boys.

The onset of pubertal maturation heralds an interval of dramatic changes: rapid physical growth, the onset of sexual maturation, the activation of new drives and motivations, and a wide array of affective changes and challenges that include increased self-consciousness, social anxieties, and the ignition of romantic and sexual interests. At the same time, youth in modern society face increased academic pressures that exacerbate the task of balancing a natural desire for immediate gratification with an increasing understanding of the importance of long-term goals and consequences. Such dramatic changes create challenges in the integration of cognitive and emotional processes in ways that place demands on the functional neural circuits that are critical for mediating arousal, orientation, attention, and affect (e.g., limbic regions) as well as for regulating and integrating these drives in the generation of long-term, goal-directed behaviors (e.g., regions of prefrontal cortex). (See Nelson et al.<sup>2</sup> and Blakemore<sup>3</sup> for more in-depth discussions of these issues within a social–neuroscience framework.)

Although most measures of cognitive development seem to correlate more closely with age and experience rather than with the timing of pubertal maturation, there is evidence for a specific link between pubertal maturation and developmental changes in various aspects of arousal, motivation, and emotion. For example, evidence indicates that pubertal development directly influences the development of romantic interest and sexual motivation.<sup>4,5</sup> Evidence also shows that risk-taking, sensation-seeking, and novelty-seeking tendencies are correlated more strongly with puberty than age.<sup>6,7</sup> Martin et al.,<sup>7</sup> for example, examined sensation-seeking and risk behaviors in a large group of young adolescents, aged 11–14 years. The researchers found no significant correlation between age and sensation seeking, but they did find a significant positive correlation between sensation seeking and pubertal stage among both boys and girls. Other relevant data include evidence, such as increased parent–adolescent conflict, that suggest developmental changes in emotional intensity and reactivity are more closely linked to pubertal maturation than age.<sup>8</sup>

As discussed in greater detail in the final section of this paper, another example of pubertal effects on subcortical regulatory systems is evident in the developmental changes in sleep, arousal, and circadian regulation, which also appear to be linked directly to pubertal maturation.<sup>9,10</sup>

It is important to acknowledge that the field is at an early point in understanding many of these complex changes in adolescence. In particular, there is a need for more studies designed to disentangle the effects of age and puberty amidst the rapid and complex changes of adolescence. Preliminary evidence from some of these studies provides support for a strong link between pubertal maturation and developmental changes in affective systems. For example, recent evidence shows increased emotional modulation of the startle reflex,<sup>11</sup> emotional influences on pupil reactivity,<sup>12</sup> and increased cortisol and cardiovascular responses to social stress as a function of pubertal maturation.<sup>13,14</sup>

It is also important to note that a wide variety of research from animal studies shows a natural increase in exploratory and reward-seeking behavior at puberty.<sup>15,16</sup> This makes sense from an evolutionary perspective because animals often take on new challenges as they become reproductively mature—in many cases needing to leave the safety of their parents and venture out as adults. However, it is not the case that animals simply start taking more risks at puberty; rather, it appears that a complex set of changes in affective influences on behavior may also reflect the need to navigate new dangers and challenges. For example, a recent study reports increased anxiety in mice triggered by the pubertal rise in the sex hormone allopregnanolone acting on GABA receptors (GABA, gamma-aminobutyric acid, is the primary inhibitory neurotransmitter in the brain) in the CA1 region of the hippocampus.<sup>17</sup> On one hand, there is strong evidence for affective and motivational changes at puberty that may contribute to some increased types of risks and vulnerabilities. On the other hand, we should not oversimplify these changes. In fact, there is evidence that fear reactivity (as measured by fear-potentiated startle responses) actually **increases** at puberty.<sup>11</sup> Thus, if fear increases at a time when many youth show increased boldness, this raises important questions about other factors—such as social influences—contributing to the increases in risky behavior that emerge in adolescence.

Relevant to these issues, evidence from both animal and human studies supports a link between increasing levels of reproductive hormones and sensitivity to social status.<sup>18,19</sup> This is a provocative idea to consider in relation to human adolescence. For example, from an anthropologic perspective, some types of risk taking in adolescence can be viewed as an **adaptive** willingness to demonstrate bravery in order to acquire more social status.<sup>20</sup> Consider, for example, an adolescent growing up in a hunter-gatherer society who must make his first successful kill of a dangerous animal with a spear to attain adult status in his society—in this case, a willingness to act boldly despite fear and relative lack of skills and knowledge can be a risky, but necessary, step to succeed. Indeed, in many situations, it seems that adolescents do not become more fearless after puberty,

but rather they may become more highly motivated to act boldly despite their fears, perhaps as a way to master their fears (and at times, to transform these fears into “thrills”), particularly when they perceive that acting in a brave or even reckless way might bring them increased recognition by peers or more social status.

The relevance of these factors in pragmatic terms for adolescent risk taking (and the influence of peer and social context) are illustrated by the study of Gardner and Steinberg,<sup>21</sup> who examined risk preferences and a behavioral risk-taking task in three age groups—adolescents (13–16), youth (18–22), and adults ( $\geq 24$ )—randomly assigned to testing alone or with two same-aged peers. Analyses indicated that participants took more risks, focused more on the benefits than the costs of risky behavior, and made riskier decisions when in peer groups than alone and, most importantly, that these peer effects on risk taking and risky decision making were stronger among adolescents and youth than adults. These findings support the idea that adolescents may be more prone to peer and status-sensitive influences on risky decision making and that peer influences and other social-context variables may play an important role in explaining risky behavior during adolescence.<sup>21</sup>

If additional empirical research supports the idea that an important dimension of adolescent risk taking is driven by an increased motivation to impress peers with one’s boldness, this understanding could have important implications. For example, it would suggest intervention strategies that target the social influences which confer feelings of admiration and status and that treat these influences as crucial elements among the affective factors that increase adolescent tendencies to exhibit risky behavior. This understanding may also be relevant to findings that indicate that the number of peers in the car (particularly male peers) correlates with some aspects of risky driving behavior.<sup>22</sup>

### **Gradual Emergence of Cognitive Self-Control in the Adolescent Brain**

In contrast to the relatively early and rapid changes in affective systems that appear to be linked to pubertal maturation, another set of cognitive skills and, more broadly, competence in self-control of behavior, seem to develop gradually across adolescence and continue to mature long after puberty is over. The underlying neural systems that support these capacities undergo maturational changes throughout adolescence. Brain imaging studies show that cortical development continues well into early adulthood, including structural changes in gray and white matter, particularly in cortical regions in frontal and parietal areas of the brain.<sup>23–26</sup> Moreover, an array of **functional** brain changes have been documented throughout adolescent development. These

include evidence of maturational changes in conflict monitoring and/or error processing in studies using event-related potentials (ERP)<sup>27,28</sup> and in functional magnetic resonance imaging (fMRI) studies of decision making in adolescents.<sup>29–32</sup>

A few of these studies appear to be particularly relevant to the focus of this article and will be discussed in more detail. The first set—a pair of behavioral and fMRI studies by Luna and colleagues<sup>33,34</sup> examining the development of cognitive control of eye movement—indicates a prolonged maturation that extends across adolescence. These studies focus on an ability to control eye movements voluntarily, including the ability to suppress an automatic tendency to look at a flashing light and, instead, look to a specific point away from the light (antisaccade task). The studies have found that, whereas the basic speed and accuracy of eye movement are mature by aged 8 years, the more complex ability to voluntarily suppress automatic responses continued to improve throughout the teenage years. Moreover, even at an age when they begin to perform the task at or near adult levels (by about 15 or 16 years), fMRI data show that adolescents are using different brain regions to perform the task.<sup>33</sup> This finding is consistent with the idea that the neural circuitry underlying the cognitive/voluntary suppression of a prepotent response is not mature until late adolescence or early adulthood. Related studies<sup>35</sup> examined the ability to direct gaze voluntarily to a remembered location (occulomotor delayed-response task) and again found that both the performance data and the fMRI data showed maturational changes throughout adolescence. Taken together, these studies indicate that cognitive control as measured in a basic level of behavior (ability to control eye movements voluntarily) continues to show developmental refinements through the teenage years. These findings suggest that adolescents (compared with adults) show a greater vulnerability to errors in gaze control (a fundamental aspect of attention when driving), and they suggest greater adolescent vulnerability to errors in the general capacity for self-control of behavior.

A second relevant line of investigation focuses on evoked-potential studies that indicate late maturational changes in the neurocognitive development of action monitoring across adolescence.<sup>27,28</sup> In brief, these studies focus on error-related negativity (ERN), a sharp negative response-locked ERP that appears to be generated in the anterior cingulate cortex (ACC) and that reflects fast automatic neural processes involved in error or action monitoring. ERN is usually followed by the P<sub>E</sub> (error positivity, a late positive deflection), a component thought to reflect error awareness. Components of these monitoring processes continue to show maturational changes that extend into late adolescence. This line of investigation appears relevant to understanding some aspects of decision-making processes in adolescence—especially the capacity of the

brain to incorporate fast monitoring processes that may facilitate learning and adjust action according to errors and/or conflict. These processes could be essential elements in some driving situations that require fast but precise reactions.

A third area of research, and perhaps most relevant to the focus of this article, is a set of fMRI studies that examine decision-making tasks in adolescents.<sup>29–32,36,37</sup> In general, these studies show that, during decision-making tasks, adolescents share with adults many similarities in neurocircuitry activation but also have some intriguing differences. Most notably, Ernst et al.<sup>30</sup> found greater response in the left nucleus accumbens (associated with reward processing) in adolescents' responses and relatively more activation of the left amygdala (associated with fear and avoidance) in adults. Galvan and colleagues<sup>37</sup> also reported enhanced nucleus accumbens response to rewards in adolescents compared with adults, as well as reduced activation in areas of the frontal cortex (specifically, lateral orbitofrontal cortex) in adolescents compared with adults. Most recently, Eshel et al.<sup>32</sup> examined risk taking in monetary decision making and also found in adolescents a reduced activation in regions of the orbitofrontal cortex (and ventrolateral prefrontal cortex and dorsal ACC), compared with adults, when making risky decisions. Moreover, reduced activity in these frontal brain regions was correlated with greater risk-taking tendencies in adolescents.

These findings suggest that adolescents engage relatively fewer prefrontal regulatory processes than adults when making decisions—in ways that may make adolescents more prone to risk taking in certain situations. More generally, engaging less prefrontal cognitive control may permit a relatively greater influence from affective systems that influence decision making and behavior which, in turn, increases adolescent vulnerability to some social and peer contexts that activate strong feelings. Finally, this model highlights the importance of considering individual differences, since the specific emotions that are activated and impinge on decision making are likely to vary a great deal across individuals and their social contexts. That is, adolescents do not simply take more risks, they appear to be more vulnerable to a wide range of emotional influences, depending on the specific context.

Taken together, these studies highlight the unique contributions of a developmental neurobehavioral perspective and, in particular, the need to understand the complex interplay between cognitive and affective systems in the maturation of self-control. Emotions, motivations, affective influences on decision making, and the social and peer contexts that activate strong feelings appear to play a crucial role in at least some aspects of risk-taking behavior. Clearly, additional research and further advances in understanding these important issues will help to inform early intervention strategies to

decrease the youth morbidity and mortality that are direct consequences of risky and reckless behavior in adolescence.

The final section of this paper will focus in greater depth on one specific regulatory system within this larger heuristic model—the development of sleep/arousal regulation in adolescence. The three reasons for this focus are to (1) illustrate key features of the model regarding interactions between biological and social influences during adolescent development that lead to sleep problems; (2) highlight how the resulting high rates of sleep deprivation among teens have direct relevance to driving risks; and (3) provide insights into targeting interventions to decrease these risks.

### **The Development of Sleep/Arousal Regulation in Adolescence and the Impact of Sleep Deprivation on Driving in Youth**

There is growing evidence that many youth in the U.S. obtain insufficient sleep—particularly on school nights.<sup>38–40</sup> A recent large study of sleep habits found that 45% of adolescents report insufficient sleep on school nights, and 28% complain they often feel “irritable and cranky” as a result of getting too little sleep.<sup>41</sup> Moreover, concern is growing about the consequences of sleep deprivation among teenagers. These consequences—including sleepiness and negative effects on attention, reaction time, judgment, and emotion regulation—have relevance to driving safety. Before considering the direct links between sleep and driving, it is worthwhile to consider the causes of sleep deprivation in adolescence.

The high rates of sleep problems in adolescence can be best understood within a developmental perspective that considers interactions among biological, behavioral, and social changes. Specifically, three sets of normal developmental changes in adolescence contribute to increased vulnerability to sleep problems: (1) nighttime sleep becomes lighter (less deep stage-4 sleep) and more prone to external disruptions<sup>42–44</sup>; (2) daytime sleepiness increases during puberty, probably reflecting an increased need for sleep during this period of rapid physical growth, cognitive development, and emotional changes<sup>9,45</sup>; and (3) biological changes in the circadian system at puberty shift sleep timing preferences in the direction of delayed-sleep phase,<sup>10,46</sup> that is, a developmental shift in the tendency to prefer later bedtimes and later rising times.

These biological changes interact with a range of behavioral and social factors that promote significant delays in bedtimes. Key social and behavioral factors include: less parental control over bedtime, social interactions with peers, homework, sports, hobbies, part-time employment, and the use of electronic media at night—including TV, movies, video games, Internet, recorded music, cell phones, and text messaging. These

social influences are synergistic with biologic tendencies toward phase delay, and together they can spiral quickly into a pattern of extremely delayed bedtimes in adolescents. Yet school requires a fixed early wake-up time. These forces converge to constrain time available for sleep on school nights, resulting in very high numbers of youth obtaining insufficient sleep.<sup>9,38,41</sup>

A second dimension of the problem focuses on the adaptation to sleep deprivation. Most “catch-up” sleep occurs on weekends and holidays on an extremely phase-delayed schedule. The human circadian system adapts more easily to phase delays than to phase advances, as endogenous rhythms of body temperature and neuroendocrine function are able to reset quickly to later bed and wake times. However, the circadian system has more difficulty accommodating to phase advances (earlier sleep schedules). This difficulty creates an effect that is a bit like “jet lag” on Monday morning, when students try to adjust to a sudden phase advance in which they need to get up for school at a time that is often 3–4 hours (or more) earlier than their biological clocks “expect” to wake up.

Thus, this epidemic is creating not only large numbers of youth struggling with the burdens of sleep deprivation but also the consequences of repeated circadian shifts.<sup>47</sup>

### **Adverse Consequences of Sleep and Circadian Disturbances**

The consequences of insufficient and poorly timed sleep among youth are the focus of increasing concern among public health and education professionals. The negative effects include several overlapping domains of impairment: falling asleep, lapses in attention, fatigue, and decreased motivation, as well as a broader set of cognitive, emotional, and physical health effects (including obesity). Most relevant to the focus of this article is the impact on risks for unintentional injuries.

### **Sleep Loss Increases the Risk for Unintentional Injuries**

The single largest source of mortality in adolescence is deaths due to unintentional injuries—particularly fatal automobile crashes. Compelling evidence shows that sleep deprivation (e.g., 18–24 hours of continuous wakefulness) creates impairments in attention, reaction time, and judgment at levels that are comparable to being legally intoxicated with alcohol.<sup>48</sup> Moreover, youth appear to be particularly vulnerable to sleepiness and nighttime crashes.<sup>49,50</sup> There is growing evidence that the majority of drowsy-driving-related crashes are caused by drivers who are aged <25 years.<sup>51</sup> Previous data showed that while half of all teen crashes take place at night, only 20% of teen driving occurs at night.<sup>52</sup> More recent data (2001–2002 National House-

hold Travel Survey) reported similar findings, which showed that 15% of the mileage of drivers aged 16–19 years was at night (9 PM–6 AM) yet 37% of fatal crashes among teens occurred at night. Australian data show that crash rates adjusted for miles driven are two and a half times higher during hours of darkness,<sup>53</sup> with 60% of young-driver deaths occurring at night.<sup>54</sup>

### **Sleep Restriction Interacts Synergistically with the Effects of Alcohol**

Studies show that even low doses of alcohol (less than 40 mg/100 ml) can impair performance among those suffering moderate levels of sleep deprivation.<sup>55,56</sup> This negative synergy between alcohol and sleep deprivation is striking when considering the sleep patterns of adolescents. During the school week, teens tend to build up a sleep debt (because of late bedtimes and early school start times) and then on the weekends go out to late-night social events (sometimes experimenting with alcohol or other substances) from which they often drive home in a severely sleep-deprived state.

### **Sleep Deprivation Can Increase Aggression**

Growing evidence indicates that problems with sleep can create and/or exacerbate emotional difficulties, including clinical problems with aggression, anger, and impulse control.<sup>57</sup> Both human and animal data show increased aggression and impulsivity following experimental sleep loss. Rats, for example, show increases in aggression and defensive fighting after sleep deprivation. One recent study found that animals who were easy to handle at baseline became irritable and aggressive following modest amounts of sleep deprivation, with evidence of related changes in synaptic plasticity associated with these behavioral changes.<sup>58</sup> Clinical studies of children and adolescents also have revealed associations between sleep deprivation and irritability/aggression and difficulties with self-regulation in youth.<sup>45,59,60</sup> Most relevant is a recent study by Haynes and colleagues<sup>57</sup> that examined behavioral and emotional changes in adolescents with substance-related difficulties undergoing a behavioral sleep treatment. This study reported that improvements in sleep time were associated with significant decreases in the reporting of aggressive thoughts and actions.

Thus, sleep deprivation in adolescents may contribute to driving risks in at least four ways: (1) lapses in attention/falling asleep while driving leading to crashes; (2) impaired judgment and decision making leading to impulsive and risky behavior; (3) a negative synergy of alcohol and sleep deprivation; and (4) increased reactive aggression that could increase risk of impulsive or reckless actions in response to anger. Consider the following sequence: the teenager who gradually accumulates a growing sleep debt during the school week as

described above, who then goes out to a late-night party on Friday, and drives home under the combined influence of sleep deprivation and alcohol. It is difficult to imagine a more dangerous combination of driving risks.

### **Conclusion: Implications for Prevention**

In summary, the specific consideration of sleep regulation provides not only an illustration of brain–behavior–social-context interactions leading to a negative spiral of effects, but also a specific and pragmatic target for intervention. That is, it highlights the importance of policy changes that lead to improving sleep habits and patterns (and better education about the risks of sleep deprivation) in adolescents.

More generally, however, it also highlights the potential value of current and future translational developmental research into risk taking, decision making, and the maturation of reliable self-control (including a neurobehavioral perspective on adolescent brain development). These lines of investigation are providing unique contributions to our understanding of the interactions between biological and social factors leading to risk taking, in ways that can inform other leverage points for early intervention. If additional research indicates that affective and/or social influences are at least as important as cognitive development in responsible decision making, this could have important implications about how to intervene. For example, if sensitivity to social status—not fearlessness—underpins a crucial dimension of risk taking in adolescents, this could provide traction for developing interventions that link adolescent-relevant indicators of social status to patterns of behavior associated with safer driving. Advancing knowledge in these areas (including both affective neuroscience and the development of cognitive control) and integrating these with work in other fields provides a promising approach to discovering new leverage points for intervention and improving the lives—and driving safety—of youth.

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