Developmental Psychology
2008, Vol. 44, No. 6, 1764–1778

0012-1649/08/$12.00 DOI: 10.1037/a0012955

Age Differences in Sensation Seeking and Impulsivity as Indexed by Behavior and Self-Report: Evidence for a Dual Systems Model

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It has been hypothesized that sensation seeking and impulsivity, which are often conflated, in fact develop along different timetables and have different neural underpinnings, and that the difference in their timetables helps account for heightened risk taking during adolescence. In order to test these propositions, the authors examined age differences in sensation seeking and impulsivity in a socioeconomically and ethnically diverse sample of 935 individuals between the ages of 10 and 30, using self-report and behavioral measures of each construct. Consistent with the authors' predictions, age differences in sensation seeking, which are linked to pubertal maturation, follow a curvilinear pattern, with sensation seeking increasing between 10 and 15 and declining or remaining stable thereafter. In contrast, age differences in impulsivity, which are unrelated to puberty, follow a linear pattern, with impulsivity declining steadily from age 10 on. Heightened vulnerability to risk taking in middle adolescence may be due to the combination of relatively higher inclinations to seek excitement and relatively immature capacities for self-control that are typical of this period of development.

Keywords: adolescence, risk taking, sensation seeking, impulsivity

In the past several years, a new perspective on risk taking and decision making during adolescence has emerged, one that is informed by advances in developmental neuroscience (Casey, Getz, & Galvan, 2008; Steinberg, 2008). According to this view, risky behavior in adolescence is the product of the interaction between changes in two distinct neurobiological systems: a socioemotional system, which is localized in limbic and paralimbic areas of the brain, including the amygdala, ventral striatum, orbitofrontal cortex, medial prefrontal cortex, and superior temporal sulcus, and a cognitive control system, which comprises the lateral prefrontal and parietal cortices and those parts of the anterior cingulate cortex to which they are interconnected (Steinberg, 2007). According to this dual systems model, adolescent risk taking is hypothesized to be stimulated by a rapid and dramatic increase in dopaminergic activity within the socioemotional system around the time of puberty, which is presumed to lead to increases in reward seeking. However, this increase in reward seeking precedes the structural maturation of the cognitive control system and its connections to areas of the socioemotional system, a maturational process that is gradual, unfolds over the course of adolescence, and permits more advanced self-regulation and impulse control. The temporal gap between the arousal of the socioemotional system, which is an early adolescent development, and the full maturation of the cognitive control system, which occurs later, creates a period of heightened vulnerability to risk taking during middle adolescence (Steinberg, 2008). As one writer has characterized it, the process may be akin to starting the engines without a skilled driver behind the wheel (Dahl, 2001).

Neurobiological evidence in support of the dual systems model is rapidly accumulating. A growing literature, derived primarily from rodent studies, but with implications for human development, indicates that the remodeling of the dopaminergic system within the socioemotional network involves an initial postnatal rise and then, starting in preadolescence, a subsequent reduction of dopamine receptor density in the striatum and prefrontal cortex; this pattern is more pronounced among males than females (Sisk & Foster, 2004; Sisk & Zehr, 2005; Teicher, Andersen, & Hostetter, 1995). As a result of this remodeling, dopaminergic activity in the prefrontal cortex increases significantly in early adolescence and is

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This research was supported by the John D. and Catherine T. MacArthur Foundation Research Network on Adolescent Development and Juvenile Justice.

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higher during this period than before or after. Because dopamine plays a critical role in the brain's reward circuitry, the increase, reduction, and redistribution of dopamine receptor concentration around puberty, especially in projections from the limbic system to the prefrontal area, is likely to increase reward-seeking behavior and, accordingly, sensation seeking.

There is equally compelling neurobiological evidence for changes in brain structure and function during adolescence and early adulthood that facilitate improvements in self-regulation that permit individuals to modulate their inclinations to seek rewards, although this development is presumed to unfold along a different timetable and be independent of puberty (see Paus, 2005, for a summary). As a consequence of synaptic pruning and the continued myelination of prefrontal brain regions, resulting in improved connectivity among cortical areas and between cortical and subcortical areas, there are improvements over the course of adolescence in many aspects of executive function, such as response inhibition, planning ahead, weighing risks and rewards, and the simultaneous consideration of multiple sources of information. There is also improved coordination of affect and cognition, reflected in improved emotion regulation, which is facilitated by the increased connectivity between regions associated with the socioemotional and cognitive control systems.

Research on adolescent behavioral development has not kept pace with advances in our understanding of brain development, however, and the notion that the developmental course of sensation seeking (thought to increase between preadolescence and middle adolescence and then decline) differs from that of impulse control (thought to increase gradually over adolescence and early adulthood) has not been examined systematically. Thus, while there is good evidence that risk taking is higher during adolescence than during preadolescence or adulthood (as evidenced by age differences in a wide range of risky activity, including criminal behavior, reckless driving, unprotected sex, and binge drinking; Steinberg, 2007), studies of age differences in risk taking itself cannot separate the contribution of age differences in sensation seeking from the contribution of age differences in impulse control. As a consequence, it is not clear whether the increase and then decline in risk taking that occurs at this time is due to changes in sensation seeking, changes in impulse control, or some combination of the two. At least one recent study (Galvan, Hare, Voss, Glover, & Casey, 2007) indicates that individuals' self-reported likelihood of engaging in risky behavior is more strongly connected to reward processing (which is presumably associated with sensation seeking) than to impulsivity, but studies of this issue are sparse. In order to examine whether sensation seeking and impulsivity develop along different timetables, it is necessary to have conceptually and empirically distinct measures of each.

Although impulsivity and sensation seeking may each affect risk taking, they are not the same thing. *Impulsivity* refers to a lack of self-control or deficiencies in response inhibition; it leads to hasty, unplanned behavior. *Sensation seeking*, in contrast, refers to the tendency to seek out novel, varied, and highly stimulating experiences, and the willingness to take risks in order to attain them (Zuckerman, 1979). Not all impulsivity leads to stimulating or even rewarding experiences (e.g., impulsively deciding to end a friendship), and not all sensation seeking is done impulsively (e.g., purchasing advance tickets to ride a roller coaster or sky dive). It is quite possible, therefore, that developmental changes in each follow different trajectories and are mediated by different brain systems.

Efforts to map the differential contributions of sensation seeking and impulsivity to risk taking have been hindered by conceptual and measurement overlap between the two constructs. The multidimensionality of the sensation-seeking construct is reflected in the breadth of the four subscales assessed by Zuckerman's widely used Sensation Seeking Scale (SSS; Zuckerman, Eysenck, & Eysenck, 1978): (a) Thrill and Adventure Seeking, (b) Experience Seeking, (c) Disinhibition, and (d) Boredom Susceptibility. Given that the SSS Disinhibition subscale clearly involves a component of impulsivity, which is typically defined in terms of behavioral disinhibition or undercontrol, research describing individual differences in sensation seeking using total SSS scores likely confounds sensation seeking and impulsivity. Complicating matters further, many self-report measures of impulsivity include items that tap sensation seeking. Indeed, one of four factors extracted from an analysis of scores on a battery of impulsivity-related scales was sensation seeking (Whiteside & Lynam, 2001).

Zuckerman has long postulated that sensation seeking increases between childhood and early adolescence and thereafter steadily declines into adulthood (Zuckerman, 1969). Only the latter half of this proposition has been thoroughly examined, with linear age declines on the SSS reported across culturally diverse samples aged 16 and older (e.g., Ball, Farnill, & Wangeman, 1984; Magaro, Smith, Cionini, & Velicogna, 1979; Zuckerman et al., 1978). This same adolescence-to-adulthood decline has been found using alternative self-report instruments. Employing a measure designed to remove confounds between SSS items and risk-taking behaviors (Arnett's Inventory of Sensation Seeking), Arnett reported lower scores for 41- to 59-year-olds compared to 16- to 28-year-olds; individual Arnett's Inventory of Sensation Seeking scores were also significantly correlated with self-reported risk taking (Arnett, 1994). Additional studies utilizing the Arnett's Inventory of Sensation Seeking (e.g., Roth, Schumacher, & Brahler, 2005) or a conceptually related measure of stimulation seeking (Giambra, Camp, & Grodsky, 1992) also report the post-age 16 decline, but surprisingly few studies have studied the development of sensation seeking from childhood to early adolescence, despite the fact that it is presumed to increase during this period.

One explanation for the scarcity of research using the SSS in childhood and early adolescence is the inappropriateness of the item content for young samples. Using a version of the SSS that was modified to more accurately reflect children's environments (e.g., interest in activities, puzzles, mazes, etc.), Kafry (1982) found that kindergartners, second graders, and fourth graders showed significantly lower levels of sensation seeking than high school and college students. Russo et al. (1991, 1993) further refined and validated a Sensation Seeking Scale for Children and demonstrated modest increases from age 7 to adolescence. Using the Sensation Seeking Scale for Children with a sample of 11- to 14-year-olds, Martin et al. (2002) found no relation between age and sensation seeking but did find a positive correlation between sensation seeking and pubertal status, even after controlling for age. A study using a different, brief version of the SSS found increases in sensation seeking between Grades 7–8 and 9–11 (i.e., between roughly 12 and 14 years of age; Stephenson, Hoyle, Palmgreen, & Slater, 2003). Although each of these studies provides modest evidence for an increase in sensation seeking from childhood to adolescence, Roth and colleagues (2005) pointed out that no single study has yet shown the curvilinear relationship between age and sensation seeking using a single measure across childhood, adolescence, and adulthood.

Dahl (2004) has described sensation seeking as one of a suite of developmental domains that appear to be linked to puberty-specific maturational changes. Interestingly, most of these domains—romantic motivation, sexual interest, emotional intensity, sleep/arousal regulation, appetite, and sensation or reward seeking—have conceptual links to the socioemotional reward system. Consistent with this model, animal studies indicate that increases in reward seeking are coincident with pubertal maturation, although it is not clear whether these increases are caused by increases in pubertal hormones or merely coincident with them (Sisk & Foster, 2004; Spear, 2000); it is plausible that changes in brain systems that subserve reward seeking are biologically programmed to occur simultaneously with reproductive maturation, in order to encourage the sort of risk taking that would facilitate mating (Casey et al., 2008; Steinberg, 2008). Research linking sensation seeking to pubertal maturation among humans is scarce, but at least one study, using the self-report Pubertal Development Scale, has shown that the two are positively correlated (Martin et al., 2002). Sensation seeking is also positively correlated with levels of testosterone and estradiol among both men and women of college age (Zuckerman, Buchsbaum, & Murphy, 1980). Further, girls' retrospective report of early pubertal onset is related to elevated sensation seeking, whereas boys' report of late onset is related to decreased sensation seeking (Martin et al., 2001). Regardless of whether sensation seeking (or reward seeking) is directly or indirectly associated with pubertal maturation, however, there is clear support for the prediction that this behavior increases during the first part of adolescence.

Self-report studies of age differences in impulsivity that span adolescence and adulthood are even rarer than those addressing sensation seeking. Galvan et al. (2007) reported a significant negative correlation between chronological age and impulsivity (using the Connors Impulsivity Scale) in a sample of individuals ranging in age from 7 to 29, suggesting that impulse control continues to develop over the course of adolescence and early adulthood. Leshem and Glicksohn (2007) likewise reported a significant decline in impulsivity from ages 14–16 to 20–22 on both the Eysenck (Eysenck, Pearson, Easting, & Allsop, 1985) and Barratt (Patton et al., 2005) impulsiveness scales. Another study found higher scores on the Barratt Impulsiveness Scale for high school, relative to college, students, although the authors attributed the finding to a filtering effect, whereby highly impulsive and presumably low achieving high school students do not continue on to college (Stanford, Greve, Boudreaux, Mathias, & Brumbelow, 1996). Although these studies all suggest a steady decline in impulsivity from childhood through adolescence and into adulthood, there is a clear need for normative data from a large sample across a broad age range.

Given this scarcity of self-report evidence for distinct developmental trends in sensation seeking and impulsivity, combined with the difficulty of ensuring that self-report items are equally appropriate across age groups, it is important to examine age differences on behavioral measures assumed to index these constructs. Laboratory studies of age differences in impulse control point to the gradual development of cognitive control mechanisms over the course of adolescence and into adulthood, consistent with the developmental trends in self-reported impulsivity described above. Brain imaging studies examining performance on tasks requiring cognitive control (e.g., Stroop, flanker tasks, go/no go, antisaccade) have shown that improved performance on cognitive control tasks between childhood and adulthood is gradual and is accompanied by two different sets of functional changes. Between childhood and adolescence, there appears to be an increase in focal activation of the dorsolateral prefrontal cortex (Adleman et al., 2002; Casey, Giedd, & Thomas, 2000; Durston et al., 2002; Luna et al., 2001; Tamm, Menon, & Reiss, 2002). In contrast, the period between adolescence and adulthood appears to be one of fine tuning (rather than one characterized by an overall increase or decrease in activation) (Brown et al., 2005), presumably facilitated by the more extensive connectivity within and across brain areas (Crone, Donohue, Honomichl, Wendelken, & Bunge, 2006; Luna et al., 2001).

Behavioral and imaging studies of age differences in sensation seeking per se are rare. Studies of a closely related construct, reward seeking, suggest a curvilinear pattern consistent with Zuckerman's model of sensation seeking (Zuckerman et al., 1978), with reward seeking increasing between childhood and adolescence and then declining between adolescence and adulthood (see Casey et al., 2008). Consistent with this model, one recent analysis of age differences in performance on the Iowa Gambling Task found that attentiveness to rewards increases between age 10 and 16 and then declines thereafter; attentiveness to punishment, however, increases gradually and linearly with age (Cauffman et al., 2008). This finding lends support to the argument that heightened risk taking in adolescence, relative to childhood or adulthood, may be due in part to an increase in reward salience during the first part of the adolescent decade.

In the present study, we examine age differences in sensation seeking and impulsivity between the ages of 10 and 30 using both self-report and performance measures of each. To our knowledge, it is the first study to span a wide enough age range to examine the developmental course of each phenomenon from preadolescence through early adulthood, to measure impulsivity and sensation seeking independently within the same sample, and to employ both self-report and performance measures. Consistent with the notion that sensation seeking and impulsivity are distinct phenomena that are subserved by different brain systems and follow different developmental trajectories, we hypothesized that sensation seeking is curvilinearly related to chronological age, increasing during early adolescence but declining thereafter, whereas impulsivity declines gradually over this same age period.

Method

Participants

The present study employed five data collection sites: Denver; Irvine (California), Los Angeles, Philadelphia, and Washington, DC. The sample includes 935 individuals between the ages of 10 and 30 years, recruited to yield an age distribution designed both to facilitate the examination of age differences within the adolescent decade and to compare adolescents of different ages with three specific groups of young adults: (a) individuals of traditional college age (who in some studies of decision making behave in ways similar to adolescents; Gardner & Steinberg, 2005); (b) individuals who are no longer adolescents but who still are at an age during which brain maturation is continuing, presumably in regions that subserve impulse control (Giedd et al., 1999); and (c) individuals who are older than this putatively still-maturing group. Six individuals were dropped because of missing data on one or more key demographic variables. In order to have cells with sufficiently large and comparably sized subsamples for purposes of data analysis, we created age groups as follows: 10–11 years (n = 116), 12–13 years (n = 137), 14–15 years (n = 128), 16–17 years (n = 141), 18–21 years (n = 138), 22–25 years (n = 136), and 26–30 years (n = 123).

The sample was evenly split between males (49%) and females (51%) and was ethnically diverse, with 30% African Americans, 15% Asians, 21% Latino(a)s, 24% Whites, and 10% others. Participants were predominantly working and middle class. Each site contributed an approximately equal number of participants, although site contributions to ethnic groups were disproportionate, reflecting the demographics of each site.

Procedure

Prior to data collection, all site project directors and research assistants met at one location for several days of training to ensure consistent task administration across data collection sites. The project coordinators and research assistants conducted on-site practice protocol administrations prior to enrolling participants.

Participants were recruited via newspaper advertisements and flyers posted at community organizations, Boy's and Girl's clubs, places of worship, community colleges, and local places of business in neighborhoods targeted to have an average household education level of some college according to 2000 U.S. Census data. Individuals who were interested in the study were asked to call the research office listed on the flyer. Members of the research team described the nature of the study to the participant over the telephone and invited those interested to participate. Given this recruitment strategy, it was not possible to know how many participants saw the advertisements, what proportion responded, and whether those who responded are different from those who did not.

Data collection took place either at one of the participating university's offices or at a location in the community where it was possible to administer the test battery in a quiet and private location. Before beginning, participants were provided verbal and written explanations of the study, their confidentiality was assured, and their written consent or assent was obtained. For participants who were under the age of 18, informed consent was obtained from either a parent or guardian.

Participants completed a 2-hr assessment that consisted of a series of computerized tasks, a set of computer-administered self-report measures, a demographic questionnaire, several computerized tests of general intellectual function (e.g., digit span, working memory), and an assessment of IQ. The tasks were administered in individual interviews. Research assistants were present to monitor the participant's progress, reading aloud the instructions as each new task was presented and providing assistance as needed. To keep participants engaged in the assessment, participants were told that they would receive $35 for participating in the study and that they could obtain up to a total of $50 (or, for the participants under 14, an additional prize of approximately $15 in value) based on their performance on the video tasks. In actuality, we paid all participants ages 14–30 the full $50, and all participants ages 10–13 received $35 plus the prize. This strategy was used to increase the motivation to perform well on the tasks but ensure that no participants were penalized for their performance. All procedures were approved by the institutional review board of the university associated with each data collection site.

Measures

Of central interest in the present analyses are our demographic questionnaire, the assessment of IQ, the self-report measures of impulsivity and sensation seeking, a computerized version of the Tower of London task (used as a behavioral measure of impulsivity), and a computerized driving game ("Stoplight"; used as a behavioral measure of sensation seeking).

Demographics. Participants reported their age, sex, ethnicity, and household education. Individuals under 18 reported their parents' education, whereas participants 18 and older reported their own educational attainment (used as a proxy for socioeconomic status [SES]).[1] The age groups did not differ with respect to sex or ethnicity but did differ (modestly) with respect to SES. As such, all subsequent analyses controlled for this variable.

Intelligence. The Wechsler Abbreviated Scale of Intelligence Full-Scale IQ Two-Subtest (Psychological Corporation, 1999) was used to produce an estimate of general intellectual ability based on two (Vocabulary and Matrix Reasoning) out of the four subtests. The Wechsler Abbreviated Scale of Intelligence can be administered in approximately 15 min and is correlated with the Wechsler Intelligence Scale for Children—4th Edition (Wechsler, 2003; r = .81) and the Wechsler Adult Intelligence Scale—3rd Edition (Wechsler, 1997; r = .87). It has been normed for individuals between the ages of 6 to 89 years. Because there were small but significant differences between the age groups in IQ, this variable was controlled in all subsequent analyses.

Pubertal status. We assessed pubertal status for all individuals age 16 and younger using the Pubertal Development Scale (Petersen, Crockett, Richards, & Boxer, 1988), a widely used and well-validated self-report measure. The four-item measure asks about perceived pubertal changes in skin, height, underarm hair, breast growth (for girls), and voice (for boys). Each item has four options (*has not yet started*, *barely started*, *definitely started but not finished*, and *definitely completed*). A composite score averaging these four items is used as an overall measure of pubertal development, with scores ranging from 1 (*prepubertal*) to 4 (*postpubertal*). Scores on the Pubertal Development Scale have been

[1] We recognize that using respondents' current level of educational attainment to index SES among college-enrolled individuals aged 18 and older may misrepresent the actual SES of these individuals' background, because college students who are adults are coded as having attained "some college" when in fact their parents may have attained more or less than this. However, our sample, unlike many samples in studies of young adults, includes both students and nonstudents. There is no consensus, when studying young adults, about how best to characterize their socioeconomic circumstances. Reasonable people may disagree about whether the proper index of these individuals' SES should be based on their own circumstances or on those within which they were raised.

shown to be significantly correlated with Tanner staging derived from physician examination, among both males and females (Schmitz et al., 2004).

Impulsivity. A widely used self-report measure of impulsivity, the Barratt Impulsiveness Scale, Version 11 (Patton, Stanford, & Barratt, 1995), was part of the questionnaire battery; the measure has been shown to have good construct, convergent, and discriminant validity. Based on inspection of the full list of items (the scale has six subscales comprising 34 items) and some exploratory factor analyses, we opted to use only 18 items ($\alpha = .73$) from three 6-item subscales: Motor Impulsivity (e.g., "I act on the spur of the moment"), Inability to Delay Gratification (e.g., "I spend more money than I should"), and Lack of Perseverance (e.g., "It's hard for me to think about two different things at the same time"). Each item is scored on a 4-point scale (*rarely/never*, *occasionally*, *often*, *almost always/always*), with higher scores indicative of greater impulsivity. Subscales were averaged to form a total impulsivity score. The three subscales we elected not to use measure attention (e.g., "I am restless at movies or when I have to listen to people"), cognitive complexity ("I am a great thinker"), and self-control ("I plan for my future"), which the instrument developers describe as assessing "planning and thinking carefully" (Patton et al., 1995, p. 770). We could not replicate the six-factor structure of the scale in our sample—which is not surprising, given that the psychometrics of this version of the scale were derived from data pooled from samples very different from ours in age and circumstances: introductory psychology undergraduates, psychiatric patients, and prisoners. In addition, we concluded that scales measuring attention, cognitive complexity, and planning and thinking carefully were not components of impulsivity as we conceptualized the construct. Although our composite only includes three of the six subscales, the correlation between our measure and one that includes items from all six subscales is .87. The 18-item scale showed excellent fit to the data (NFI = .912, CFI = .952, RMSEA = .033), and reliability of the scale is $\alpha = .73$.

We assessed sensation seeking using a subset of 6 items from the SSS (Zuckerman et al., 1978). Many of the items on the full 19-item Zuckerman scale appear to measure impulsivity, not sensation seeking (e.g., "I often do things on impulse," "I usually think about what I am going to do before doing it"). In view of our interest in distinguishing between impulsivity and sensation seeking, we used only the six Zuckerman items that clearly index thrill or novelty seeking ("I like to have new and exciting experiences and sensations even if they are a little frightening," "I like doing things just for the thrill of it," "I sometimes like to do things that are a little frightening," "I'll try anything once," "I sometimes do 'crazy' things just for fun," and "I like wild and uninhibited parties"). All items were answered as either true (coded 1) or false (coded 0), and item scores were averaged. The resulting 6-item scale showed an excellent fit to the data (NFI = .955, CFI = .967, RMSEA = .053) and good internal consistency ($\alpha = .70$).

Tower of London. We used this task, which is typically used to measure planning and executive function, to generate a behavioral index of impulsivity. In the computerized version of the task employed in the present study (Berg & Byrd, 2002), the participant is presented with pictures of two sets of three colored balls distributed across three rods, one of which can hold three balls, one two balls, and the last only one ball. The first picture shows the starting positioning of the three balls, and the second depicts the goal position. The participant is asked to move the balls in the starting arrangement to match the other arrangement in as few moves as necessary, using the computer cursor to drag and drop each ball. Five sets of four problems are presented, beginning with four that can be solved in three moves and progressing to those that require a minimum of seven moves.

In the administration of the task, the starting and goal positions are displayed, and the participant takes as much (or as little) time as necessary before making each move. Although the task is usually scored with regard to the number of problems correctly solved at each level of difficulty (or correctly solved with the minimum number of moves), in the present analysis, our interest is in the amount of time that elapses (in milliseconds) between the presentation of each problem and the participant's first move. Hasty performance, particularly with respect to first moves on each problem, has been linked to response inhibition difficulties among children, adolescents, and adults (Asato, Sweeney, & Luna, 2006). Thus, in the current study, shorter latencies to first move indicate greater impulsivity.

Working memory. The test battery included a test of resistance to interference in working memory (Thompson-Schill, 2002). In this task, participants saw four probe letters on the screen, followed by a screen displaying a target letter. They were then asked whether the target was among the four probes. We computed an overall accuracy of working memory score by averaging the number of correct responses across all experimental trials. Because Tower of London performance is influenced by working memory as well as inhibitory control (Asato et al., 2006), and because there are gains in working memory during the first part of adolescence (Keating, 2004), this variable was examined as a covariate in analyses examining age differences in impulsivity as indexed by Tower of London performance (so as to ensure that any observed differences were due to impulsivity rather than to memory).

Stoplight. We developed a computerized driving game for this program of research based on a modification of the "Chicken" game used by Gardner and Steinberg (2005). In the Stoplight game, the player is asked to "drive" a car before time runs out to a distant location, where a party is taking place, and is told that most people are able to reach the destination in under 2 min. The participant's vantage point is that of someone behind the wheel, with the road and roadside scenery visible and changing as the car travels down the road. Also shown on the screen is a clock counting down the time; the clock is initially set to 2 mi and 30 s. The participant hears the clock ticking down and "party" music, which grows increasing louder as the car approaches the destination. In order to reach the destination, the driver must pass through eight intersections, each marked by a traffic signal.

Before playing the game, participants see a demonstration that is accompanied by prerecorded audio instructions. They are informed that when they are approaching an intersection, the traffic signal may turn yellow, and that if this happens, they must decide whether to stop the car (by using the space bar) and either wait for the light to cycle from yellow to red to green or attempt to cross through the intersection; participants are told that they cannot control the speed of the car and that the only time the brake works is after the traffic light has turned yellow. Participants are told that if the car is driven through the intersection and the light turns red, there is a chance that it may crash into another vehicle that is driving through at the same time.

The narrator then explains that one of three things may happen depending on the participant's decision (each scenario is illustrated with video simultaneously with the narrated instructions): (a) If the brakes are not applied and the car makes it through the intersection, no time is lost; (b) if the brakes are applied before the light turns red, the car will stop safely, but time will be lost waiting for the light to cycle back to green (approximately 3 s); (c) if the brakes are not applied or are applied too late, and the car crashes into the crossing vehicle (this is accompanied by squealing tires and a loud crash, as well as the image of a shattered windshield), even more time will be lost (approximately 6 s) than had the participant decided to brake. Thus, participants must decide whether to try to drive through the intersection in order to save time and risk losing twice as much time if a crash occurs or to stop and wait (and willingly lose a smaller amount of time).

Unlike the Tower of London, successful performance on the Stoplight game does not require that participants exercise impulse control, plan ahead, or deliberate over their actions. Because the outcome of each intersection in the Stoplight game is unknown to the player, the task involves decision making under conditions of uncertainty, in which one is asked to decide between a low-risk, low-payoff option and a high-risk, high-payoff one. It is akin to many other tasks designed to measure gambling, which has been shown in many studies to be associated with sensation seeking (Horvath & Zuckerman, 1993).

The Stoplight game software was written so that investigators can configure each intersection to suit their research needs. The configuration is determined by the timing of the yellow light, the timing of the red light, the timing of the entrance of the crossing vehicle into the intersection, and the speed with which the crossing vehicle passes through the intersection. All four parameters can be set by the researcher. In the present study, the eight intersections were configured in the following fashion:

1. The latency between the appearance of the yellow light and the appearance of the crossing vehicle is very short (1,300 ms), and virtually all participants (even most of those who brake) experience a crash. This is designed to expose all participants to the potential for crashing.

2. The latency between the appearance of the yellow light and the appearance of the red light is long (3,000 ms), and it is possible to either stop safely or to drive through the intersection safely without crashing. It is not possible to crash. This is designed to expose all participants to a safe outcome.

3. The latency between the appearance of the yellow light and the appearance of the crossing vehicle is shorter than the previous intersection (2,000 ms), but it is possible to stop safely or drive through the intersection safely without crashing. It is not possible to crash.

4. The latency between the appearance of the yellow light and the appearance of the crossing vehicle is shorter than the previous intersection (1,750 ms), but it is possible to stop safely or to drive through the intersection safely. It is not possible to crash.

5. The light remains green and all cars pass through the intersection without crashing. Because the light does not turn yellow, it is not possible to apply the brakes. This is designed to break any established "set" the participant may have established. No data from this intersection are used because by design there is no variation across participants.

6. The latency between the appearance of the yellow light and the appearance of the crossing vehicle is shorter than at Intersection 2 (2,900 ms). It is possible to stop safely, but by design it is not possible to pass through the intersection without crashing.

7. The latency between the appearance of the yellow light and the appearance of the crossing vehicle is slightly shorter than the previous intersection (2,450 ms). It is possible to stop safely, but not possible to drive through the intersection without crashing.

8. The latency between the appearance of the yellow light and the appearance of the red light is slightly shorter than the previous intersection (2,000 ms). It is possible to stop safely, but not possible to pass through the intersection without crashing.

The principal outcome variables extracted from each intersection for which there are data (i.e., all but Intersection 5) are (a) whether the participant stopped safely, (b) the latency to brake (i.e., the amount of time that elapsed between the appearance of the yellow light and the application of the brake for those intersections at which the brake was applied), (c) whether the participant crossed through the intersection successfully, and (d) whether the individual crashed (which can result from either failure to brake or too long a latency to brake). We also constructed an overall measure of (e) risky driving, which combined the measures of failure to brake and latency to brake, by assigning an individual who failed to brake the maximum possible score for latency to brake (i.e., the preprogrammed amount of time between the appearance of the yellow light and the crossing vehicle's entrance into the intersection) at that intersection.

Means and standard deviations for all study outcome variables across the age groups and for the sample as a whole, adjusted for IQ and SES, are presented in Table 1.

Results

Relations Between Individual Differences in Self-Report and Behavioral Indicators of Impulsivity and Sensation Seeking

In order to examine whether the two behavioral tasks did, as proposed, differentially index sensation seeking and impulsivity, we conducted regression analyses in which the two self-report measures were considered as simultaneous predictors of the two behavioral tasks' principal outcome measures (the two self-report measures are correlated at $r = .38$, $p < .001$). As expected, in the regression predicting average time to first move on the Tower of London from self-reported impulsivity and sensation seeking, self-reported impulsivity is a significant

Table 1
Means and Standard Deviations of Study Outcomes

Outcome and age group	*M*	*SD*
Self-reports		
Impulsivity		
10–11	13.31	2.36
12–13	13.24	2.26
14–15	13.21	2.08
16–17	12.91	2.11
18–21	12.86	2.20
22–25	12.67	2.45
26–30	12.17	2.16
Total	12.90	2.26
Sensation seeking		
10–11	0.65	0.23
12–13	0.70	0.24
14–15	0.69	0.27
16–17	0.66	0.27
18–21	0.66	0.32
22–25	0.62	0.34
26–30	0.54	0.31
Total	0.65	0.29
Stoplight outcomes		
Safe stops		
10–11	4.51	1.73
12–13	4.73	1.60
14–15	4.87	1.40
16–17	5.03	1.32
18–21	4.83	1.52
22–25	4.85	1.54
26–30	4.91	1.48
Total	4.83	1.51
Crashes		
10–11	1.73	1.12
12–13	1.61	0.96
14–15	1.60	0.95
16–17	1.53	0.91
18–21	1.54	0.94
22–25	1.55	1.00
26–30	1.50	1.01
Total	1.57	0.98
Intersections crossed successfully		
10–11	0.76	0.95
12–13	0.65	0.89
14–15	0.53	0.71
16–17	0.44	0.71
18–21	0.63	0.80
22–25	0.60	0.80
26–30	0.59	0.74
Total	0.60	0.80
Latency to brake (ms)		
10–11	918.15	388.13
12–13	858.99	367.40
14–15	984.71	367.39
16–17	872.87	382.16
18–21	771.52	311.73
22–25	802.09	351.04
28–30	808.16	299.48
Total	856.56	358.64
Risky Driving Index		
10–11	1250.60	416.21
12–13	1184.94	420.72
14–15	1238.39	363.60
16–17	1122.28	396.00
18–21	1119.56	408.94
22–25	1126.44	412.67
26–30	1132.69	379.82
Total	1163.77	402.30
Tower of London time to first move		
Three-move trials		
10–11	5.98	2.51
12–13	5.29	2.11
14–15	5.31	1.86
16–17	5.14	1.76
18–21	5.30	1.88
22–25	5.99	2.81
26–30	6.56	3.82
Total	5.63	2.50
Four-move trials		
10–11	5.10	1.80
12–13	5.20	1.92
14–15	5.09	1.83
16–17	5.34	2.21
18–21	5.80	3.03
22–25	6.70	4.00
26–30	6.96	3.16
Total	5.75	2.80
Five-move trials		
10–11	4.80	1.86
12–13	5.15	3.22
14–15	5.29	2.18
16–17	6.74	5.42
18–21	7.12	5.11
22–25	7.74	5.14
26–30	9.11	6.11
Total	6.61	4.71
Six-move trials		
10–11	5.36	3.04
12–13	5.87	4.44
14–15	6.44	4.10
16–17	8.67	6.60
18–21	9.32	7.34
22–25	10.72	8.93
26–30	13.12	10.39
Total	8.58	7.36
Seven-move trials		
10–11	5.37	4.07
12–13	6.19	4.39
14–15	6.59	5.17
16–17	8.30	5.77
18–21	9.00	6.95
22–25	10.41	8.72
26–30	11.94	8.82
Total	8.33	6.89

Note. All values adjusted for IQ and socioeconomic status. Subsamples sizes are as follows: 10–11 years (n = 116), 12–13 years (n = 137), 14–15 years (n = 128), 16–17 years (n = 141), 18–21 years (n = 138), 22–25 years (n = 136), and 26–30 years (n = 123).

predictor ($\beta = -.082$), $t = 2.28$, $p < .05$, but self-reported sensation seeking is not ($\beta = .059$), $t = 1.64$, *ns*. In contrast, in the comparable regression analysis predicting risky driving in the Stoplight game, self-reported impulsivity is not a significant predictor ($\beta = .034$), $t = 0.95$, *ns*, but self-reported sensation seeking is ($\beta = .085$), $t = 2.39$, $p < .05$. Consistent with the assertion that the two behavioral tasks index different psychological phenomena, we also find that time to first move on the

Tower of London and risky driving in the Stoplight game are uncorrelated (r = –.04, *ns*).

Age Differences in Self-Reported Impulsivity and Sensation Seeking

In order to test the hypothesis that sensation seeking increases in early adolescence and then declines but that impulsivity shows a gradual decline with age, continuing through late adolescence and into young adulthood, we examined age differences in these self-reports via sets of two hierarchical multiple regression analyses. In the first, age, IQ, and SES were entered on the first step, and the quadratic term for age was entered on the second step. In the second regression, designed to test whether sex or race moderated patterns of age differences, this analysis was repeated with either race (represented by dummy variables for each major ethnic group, with "other" as the omitted reference category) or sex also entered on the first step, the interactions between age and sex or age and race entered on the second step, and the quadratic age term and the interactions between the quadratic age term and either sex or race entered on the third step.

Results of the first set of regression analyses indicate significant linear and curvilinear effects of age on sensation seeking (β = –.115, t = 3.48, $p < .001$, and β = –.437, t = 2.79, $p < .005$, for the linear and quadratic terms, respectively) but only a linear effect of age on impulsivity (β = –.149, t = 4.57, $p < .001$, and β = –.091, t = .59, *ns*, respectively). Figure 1 illustrates these two age patterns. Consistent with our hypothesis, sensation seeking increases during the first half of adolescence and then declines steadily from age 16 on. In contrast, impulsivity declines or remains stable over the entire 20-year period studied. Results of the second set of analyses indicate that although there are significant main effects for sex on sensation seeking (but not impulsivity), with males scoring higher than females ($p < .01$), the pattern of age differences in sensation seeking or impulsivity is not moderated by sex. Similarly, although there are significant ethnic differences in impulsivity (but not in sensation seeking), with White individuals reporting greater impulsivity than Latino individuals ($p < .001$), ethnicity does not moderate the pattern of age differences in either impulsivity or sensation seeking.

In order to further explore these patterns of age differences, we conducted two analyses of covariance (ANCOVAs), with

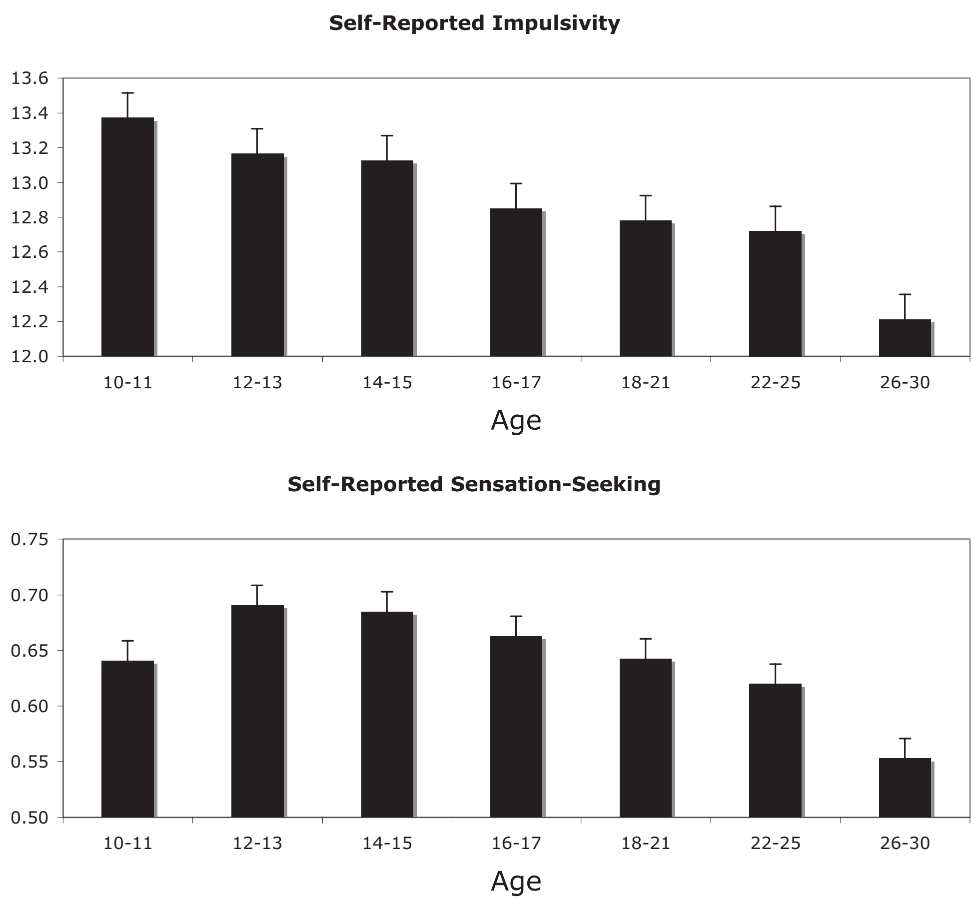

Figure 1. Age differences in self-reported impulsivity and sensation seeking. Impulsivity scores can range from 6 to 24. Sensation-seeking scores can range from 0 to 1. The linear trend for impulsivity is significant at $p < .001$; the linear and quadratic trends for sensation seeking are significant at $p < .001$ and $p < .005$, respectively. Error bars represent the standard errors.

age, sex, and ethnicity as independent variables, IQ and SES as covariates, and either self-reported sensation seeking or impulsivity as the outcome. The ANCOVA examining sensation seeking indicates a near-significant relation between age and sensation seeking, $F(6, 834) = 1.98$, $p = .07$. More importantly, and consistent with the significant quadratic effect found in the regression analysis, Bonferroni-corrected post hoc comparisons indicate that the 12- to 13-year-olds and the 14- to 15-year-olds report significantly greater sensation seeking than the 26- to 30-year-olds but that the oldest (26–30 years) and youngest (10–11 years) groups do not differ. Consistent with the regression analyses, the ANCOVA examining impulsivity indicates there is a significant effect of age on impulsivity, $F(6, 837) = 2.62$, $p < .05$; the main effects for sex and ethnicity are not significant, nor are there significant interactions between these variables and age. Bonferroni-corrected post hoc comparisons indicate that the two youngest groups (10- to 11-year-olds and 12- to 13-year-olds) both are significantly more impulsive than the oldest group (26- to 30-year-olds), consistent with a pattern of linear decline in impulsivity with age.

Pubertal Status, Sensation Seeking, and Impulsivity

In order to test the hypothesis that sensation seeking, but not impulsivity, is related to pubertal status, we conducted two regression analyses in which scores on either the sensation seeking or impulsivity measures were regressed on pubertal status, controlling for IQ and SES on the first step and for chronological age on the second step.[2] Analyses were conducted separately among males and females in light of previous animal research indicating more pronounced remodeling of dopaminergic receptor systems at puberty among males than females. Recall that data on self-reported pubertal maturation were collected only on individuals 16 and younger (231 males and 186 females).

Results of the regression analyses indicate a significant effect of pubertal status on self-reported sensation seeking among males ($\beta = .171$, $t = 2.54$, $p < .05$), even with age controlled ($\beta = .159$, $t = 1.89$, $p = .06$), but no significant effect on sensation seeking among females ($\beta = .100$, $t = 1.33$, *ns*, and $\beta = .085$, $t = .807$, *ns*, with and without age controlled, respectively). In contrast, comparable regression analyses indicate no significant relation between puberty and impulsivity among either males ($\beta = .052$, $t = .778$, *ns*, and $\beta = .113$, $t = 1.34$, *ns*, with and without age controlled, respectively) or females ($\beta = –.093$, $t = 1.25$, *ns*, and $\beta = –.069$, $t = .672$, *ns*). The relations between sensation seeking and pubertal status among males and females are shown in Figure 2. Of particular note is that the postpubertal males' average sensation seeking score (.918) is near the scale maximum (1.0). Although, as noted earlier, there were no sex differences in sensation seeking in the entire sample as a whole, within the subsample limited to individuals 16 and younger (i.e., the sample on whom we gathered information on pubertal status), males reported significantly greater sensation seeking (.713) than females (.654), $F(1, 427) = 4.18$, $p < .05$, with IQ and SES controlled.

Age Differences in Behavioral Impulsivity as Indexed by the Tower of London

We examined participants' time before first move on the Tower of London task using a repeated measures ANCOVA, with age, sex, and ethnicity as the independent variables; IQ and SES as covariates; and individuals' average time (in milliseconds) before making a first move at each level of problem difficulty (three, four, five, six, and seven moves) as a five-level within-subjects factor. Analyses reveal a significant effect of age on average time to first move, with older participants taking more time before moving than younger ones, $F(6, 813) = 17.58$, $p < .001$. More interesting, however, and as Figure 3 illustrates, there is a significant interaction between age and problem difficulty, such that with increasing problem difficulty, older, but not younger, participants wait longer before their first move, $F(24, 3252) = 8.976$, $p < .001$. The effect size for the age difference in time to first move on the seven-move problem is twice as large as it is on the three-move problems (partial $\eta^2 = .08$ vs. .04, respectively). Indeed, as Figure 3 shows, the three youngest groups generally do not wait any longer before their first move in the most difficult (seven-move) problems than in the easiest ones (three moves). These age differences, either in average time before first move or in changes in time to first move as a function of problem difficulty, are not moderated by either sex or race, although we do find a significant main effect of sex, with males on average taking more time before making their first move (7.6 s) than females (6.5 s), $F(1, 813) = 12.33$, $p < .001$. Analyses were repeated with working memory as an additional covariate, and the results were unchanged, suggesting that the observed age and sex differences in time to first move were not due to differences in working memory capacity.

Post hoc pairwise comparisons (with Bonferonni adjustment) reveal a pattern of age differences consistent with the hypothesis that the development of impulse control is gradual but mainly ongoing in late adolescence and early adulthood. Thus, for example, there are no significant differences in average time to first move among the 10- to 11-year-olds, the 12- to 13-year-olds, and the 14- to 15-year-olds (no pairwise comparisons among these groups are significant); the 16- to 17-year-olds and the 18- to 21-year olds wait significantly longer than the three youngest age groups (all pairwise comparisons significant at $p < .05$) but wait significantly less than the 22- to 25-year-olds or the 26- to 30-year-olds (all pairwise comparisons significant at $p < .05$). The 22- to 25-year-olds wait significant longer than all younger age groups (all comparisons significant at $p < .05$) but significantly less than the 26- to 30-year-olds ($p < .05$), who wait longer than any other age group (all comparisons significant at $p < .05$). This pattern of age differences, pointing to significant declines in impulsivity from age 16 on, but not before, and continuing well into the mid-20s, are consistent with observed age differences in self-reported impulsivity presented earlier. The relation between pubertal status and time to first move was not statistically significant, among either males

[2] It is not clear whether analyses examining the link between pubertal status and some other variable, such as sensation seeking or impulsivity, should control for age (see Steinberg, 1987, for a discussion). On the one hand, age and pubertal status are confounded, which suggests that age should be controlled. On the other hand, controlling for age changes the test to a test of the impact of pubertal timing (i.e., early vs. late maturation), since this adjusts pubertal status for age. We report the relations between puberty and sensation seeking and between puberty and impulsivity both with and without controlling for age.

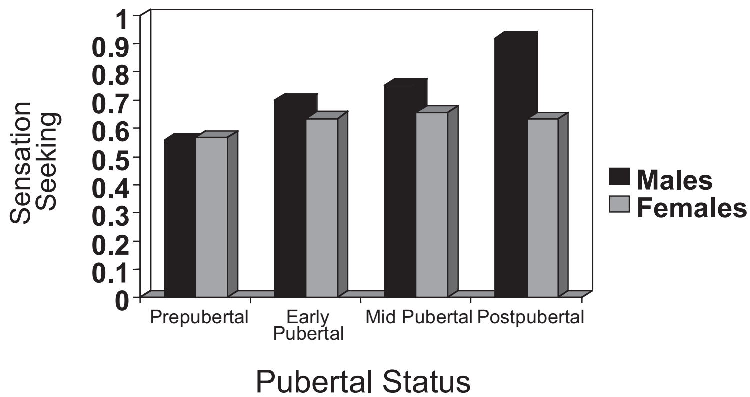

Figure 2. Relation between pubertal status and sensation seeking. Means are adjusted for IQ and socioeconomic status. The relation between pubertal status and sensation seeking is significant among males at $p < .05$ but not females.

or females, which is also consistent with the pattern of findings for self-reported impulsivity.

Age Differences in Sensation Seeking as Indexed by the Stoplight Game

Data for the Stoplight game were first analyzed using a repeated measures ANCOVA, with age, sex, and ethnicity as the independent variables; IQ and SES as covariates; and the number of times individuals stopped safely over the seven intersections for which data were obtained as the within-subjects factor (recall that the light remains green at Intersection 5, and no data are extracted for this intersection). Analyses indicated a significant between-subjects effect of age on safe braking, $F(6, 818) = 2.12$, $p < .05$, as well as a significant within-subjects difference, $F(36, 4908) = 1.50$, $p < .05$; the between-subjects effect was not moderated by sex or ethnicity, nor was there a main effect of sex on safe braking, but there was a significant main effect for ethnicity, with Latino individuals more likely to brake safely than African Americans ($p < .05$).

Comparable between- and within-subjects effects were identified in the analysis of the risky driving variable, which, as de-

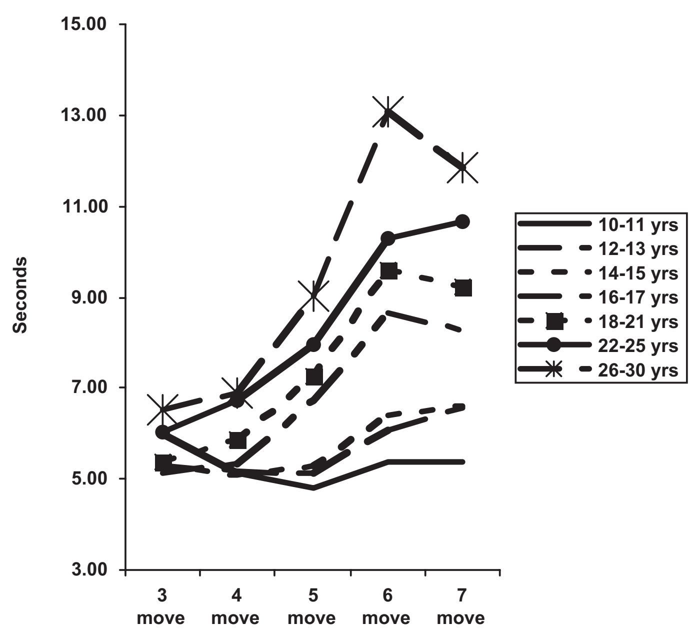

Figure 3. Age differences in time to first move (in seconds) on the Tower of London task as a function of problem difficulty. Means are adjusted for IQ and socioeconomic status. The Age × Problem Difficulty interaction is significant at $p < .001$.

scribed earlier, combines failure to brake at all with failure to brake quickly (for between- and within-subjects effects, respectively, $F[6, 799] = 3.50$, $p < .01$, and $F[36, 4794] = 1.55$, $p < .05$). In both cases, the Age × Intersection interaction is characterized by a quadratic trend, with age differences apparent only during Intersections 3, 4, 6, and 7. This is not surprising because the task was programmed to make it virtually guaranteed that individuals would crash at Intersection 1 and pass through safely at Intersection 2, to make it certain that no braking was necessary at Intersection 5, and to make it extremely likely that individuals would crash at Intersection 8. This age effect was not moderated by sex or ethnicity, nor were there main effects for either of these variables on risky driving.

As Figures 4 and 5 indicate, the youngest participants (10- to 11-year-olds, 12- to 13-year-olds, and 14- to 15-year-olds) more often fail to stop safely, $F(6, 818) = 2.12$, $p < .05$, and take more risks (i.e., either not braking or waiting too long to apply the brakes) than do participants of other ages. Inspection of post hoc pairwise comparisons of age groups indicated that the significant age differences are mainly observed at Intersections 4 and 6 (recall that no data are used from Intersection 5) and most consistently seen in differences between the 10- to 11-year-olds and individuals 16 and older, although there also are significant differences between 14- to 15-year-olds and individuals 16 and older in risky driving at Intersection 4, and between 12- to 13-year-olds and 18- to 21-year-olds in risky driving at Intersection 6.

The higher incidence of risky behavior seen among younger participants results in age differences both in crashes and in successful (albeit risky) crossings. At the three intersections where crashing is possible, but not predetermined or prohibited by the software configuration (Intersections 6, 7, and 8), younger participants crash more frequently than older ones, multivariate $F(18, 2454) = 1.65$, $p < .05$, with a significant univariate effect at Intersection 6, $F(6, 818) = 2.30$, $p < .05$, and a borderline significant one at Intersection 7, $F(6, 818)=1.90$, $p = .08$); there are no age differences at Intersection 8. Similarly, at the three intersections where crossing through without crashing is possible but not predetermined or prohibited (Intersections 2, 3, and 4), younger participants tend to cross through more frequently than older ones, multivariate $F(18, 2454) = 1.58$, $p = .06$, with a significant univariate effect at Intersection 4, $F(6,818 = 2.48$, $p < .05$, and a borderline significant one at Intersection 3, $F(6, 818) = 1.90$, $p = .08$; there are no age differences at Intersection 2. Not surprisingly, age differences in driving outcomes only appear when the task permits individuals to influence their own driving fate.

The relation between pubertal status and performance on the Stoplight game was also examined within the sample of individuals aged 16 and younger, covarying IQ and SES, as in all previous analyses. Although pubertal status is not related to safe stopping, risky driving, or crashing, it is predictive of the number of intersections individuals cross through successfully, both with, $F(3, 384) = 3.34$, $p < .05$, and without, $F(3, 385) = 3.95$, $p < .01$, controlling for age. As Figure 6 indicates, prepubertal individuals are less likely to cross through intersections than are individuals who are in the midst of, or have completed, puberty. Unlike the findings for self-reports of sensation seeking, however, this pattern is the same among both males and females (i.e., the interaction between sex and pubertal status is not significant). The curvilinear pattern depicted in Figure 6 is statistically significant among both males ($\beta = -.787$, $t = 2.10$, $p < .05$) and females ($\beta = -.787$, $t = 2.10$, $p < .05$); in neither case is the linear trend significant. Interestingly, and in contrast to the analyses that include the entire sample, when the sample is restricted to individuals 16 and younger, we see a sex difference in successfully crossing through intersections, with girls more likely to do this than boys, $F(1, 421) = 14.44$, $p < .001$. This does not appear to be due simply to sex differences in how well individuals play the game, because boys stop safely more often than girls, $F(1, 421) = 8.73$, $p < .01$, and because there are no sex differences in actual crashes, $F(1, 421) = 1.90$, *ns*. Rather, it would appear that in contrast to adolescents' self-reports, on this task, girls evince greater sensation seeking than boys.

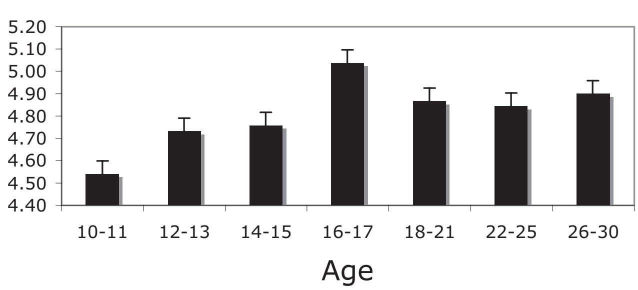

Figure 4. Number of intersections with a safe stop in the Stoplight game as a function of age. A safe stop occurs when no attempt is made to drive through the yellow light, and the brakes are applied in sufficient time to avoid a crash. Means are adjusted for IQ and socioeconomic status. The main effect for age is significant at $p < .01$. Error bars represent the standard errors.

Discussion

According to their own reports, and as reflected in their performance on computer tasks designed to measure sensation seeking and impulsivity, adolescents and adults differ along both dimensions in ways that are theoretically coherent with recent research on adolescent brain development, which points to extensive and dramatic remodeling of reward circuitry early in adolescence but a lengthier period of more gradual maturation of brain systems implicated in self-regulation. Consistent with this neurobiological evidence, in the present study heightened sensation seeking is most clearly and consistently seen among individuals between the ages of 12 and 15. In contrast, we find that gains in impulse control occur throughout adolescence and well into young adulthood.

The observed pattern of age differences on the self-report and performance measures of impulsivity were very similar, with both indicating a linear decline in impulsivity between ages 10 and 30. The self-report and performance measures of sensation seeking, in contrast, did not show entirely consistent results. On the self-report measure of sensation seeking, we find a curvilinear trend similar to what others have hypothesized: increasing sensation seeking during early adolescence, a peak around age 14 or 15, and a steady decline thereafter (see Roth et al., 2005). On the driving game, however, we see heightened sensation seeking during the period from 10 to 15 (with no increase between 10 and 15), a sharp decline in middle adolescence, and no further decline after that. Whether this difference is due to differences between self-report and performance measures of sensation seeking in general or to

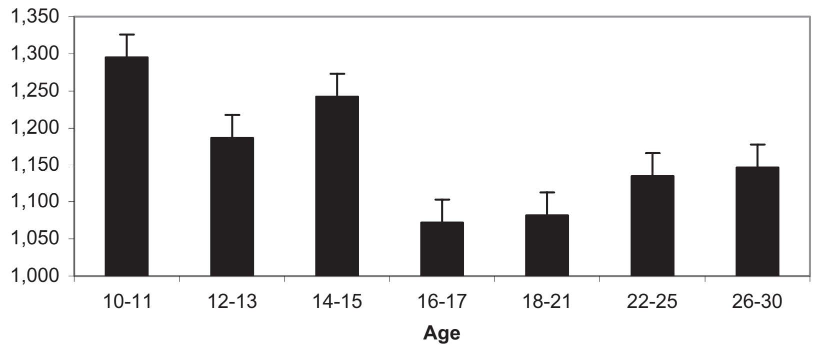

Figure 5. Age differences in risky driving in the Stoplight game. Risky driving index is a composite of failure to brake at yellow light and/or long latency to brake after yellow light appears. Means are adjusted for IQ and socioeconomic status. The main effect for age is significant at $p < .01$. Error bars represent the standard errors.

differences between the specific measures used in this study (i.e., the driving game may be tapping into other aspects of psychological functioning in addition to sensation seeking that develop along a different timetable, or perhaps the onset of actual driving at age 16 contributes to more skillful or cautious performance on the game) is not something that can be determined. One possibility is that the Stoplight game is tapping a combination of sensation seeking (which impels players to take risks) as well as a lack of inhibitory control (which affects players' latency to brake). Although the fact that performance on the Stoplight task is uncorrelated with both the self-report and performance measures of impulsivity but correlated with the self-report measure of sensation seeking suggests that it is more influenced by sensation seeking than inhibitory control, it is important that further studies of the task's discriminant validity be conducted. What does seem clear, however, is that sensation seeking, by either measure, is significantly higher during early adolescence than later. It is also worth noting, as discussed below, that the pattern of findings varies as a function of whether sensation seeking is plotted against chronological age or pubertal status. Further studies using other performance measures of sensation seeking would help clarify this issue.

The contribution of the present research to the literature on psychological development in adolescence and young adulthood stems from its inclusion of a much wider age range than has been examined previously in one sample (from age 10 to 30), its use of both self-report and cognitive/behavioral indicators of sensation seeking and impulsivity, its socioeconomically and ethnically diverse sample, and its independent measurement of two constructs that often have been conflated both conceptually and empirically. The fact that differential patterns of age differences found in self-reports are similar to those found in conceptually linked behavioral tasks (albeit more so for impulsivity than for sensation seeking), and the general absence of variation in these patterns as a function of sex or ethnicity, inspires more confidence in the conclusion that the developmental trajectories of sensation seeking and impulsivity differ. Although one must be cautious about drawing inferences about change over time from cross-sectional research, the current findings provide a foundation from which

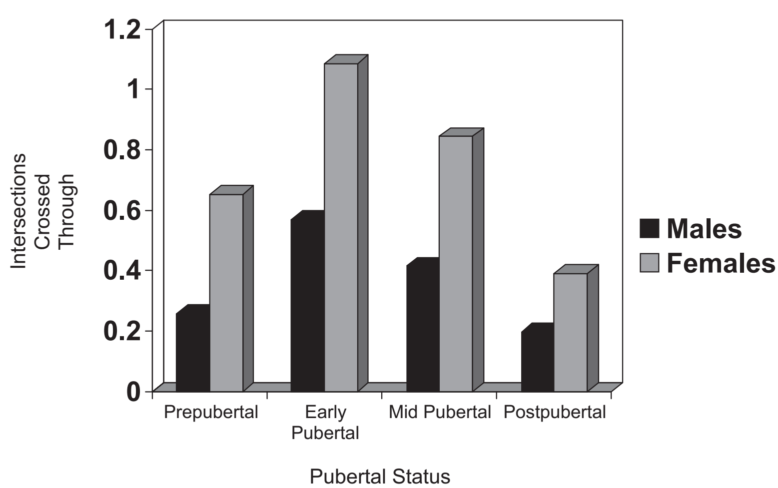

Figure 6. Number of intersections crossed through in the Stoplight game as a function of pubertal status. Means are adjusted for IQ and socioeconomic status. The curvilinear trends for males and females are both significant at $p < .05$ or better.

further longitudinal study, using self-reports, behavioral tasks, and brain imaging, should proceed.

The heightened sensation seeking during early adolescence seen here, as well as evidence (at least from self-reports) that sensation seeking increases between preadolescence and middle adolescence and then declines, calls to mind other studies of sensation seeking (e.g., Stephenson et al., 2003), reward sensitivity (e.g., Galvan et al., 2006), and reward salience (e.g., Cauffman et al., 2008), which show increases in all three during the early adolescent years; these increases are thought to be linked to increases and then declines in prefrontal and paralimbic dopamanergic activity during the period following puberty (Steinberg, 2008). In this study, the link between sensation seeking and puberty was observed among males on the self-report measure, and among both males and females on the driving task. However, whereas the relation between pubertal status and self-reported sensation seeking is linear (and self-reported sensation seeking is higher among boys than girls), the observed relation between puberty and sensation seeking on the driving task is curvilinear, increasing during early puberty and declining thereafter (and sensation seeking in this task is higher among girls than boys), as hypothesized. In the absence of more data on the validity of the Stoplight task, we are reluctant to interpret these differences in patterns of results (as a function of sex, puberty, or the interaction between them). What is important, however, is pubertal status is linked to sensation seeking but is unrelated to impulsivity, regardless of whether it is indexed by self-report or in the Tower of London task. This lends support to our contention that sensation seeking and impulsivity have different biological underpinnings and follow different developmental trajectories.

The absence of age differences in performance on the Stoplight task after middle adolescence is of particular interest in light of findings reported by Gardner and Steinberg (2005), who examined age differences in performance on a similar video driving game. In that study, the researchers found no differences between adolescents (average age = 14), youths (average age = 19), and adults (average age = 37) when individuals were alone but significantly more risky behavior among the adolescents, and, to a lesser extent, youths, when the task was performed with their friends watching. It is therefore important to keep in mind that the absence of differences in sensation seeking on the driving task after age 16 in the present study may be context specific, because all participants were tested in one-on-one sessions. It is the case, however, that Cauffman et al. (2008) reported no age differences in reward sensitivity after age 17 as indexed by performance on the Iowa Gambling Task; to the extent that sensation seeking in the Stoplight game is driven by reward seeking, the absence of age differences in the present study after age 16 is consistent with the Cauffman et al. findings. Further research is needed to examine whether age differences in sensation seeking are amplified or diminished as a function of the emotional and social context in which the trait is assessed.

To our knowledge, only one previous study (Galvan et al., 2007) has examined age differences in self-reported impulsivity over an age range comparable to that studied here. The linear decline in self-reported impulsivity seen across the entire age span we studied is consistent with the Galvan et al. investigation and with findings reported in studies of self-reported impulsivity that have included middle adolescents and adults (e.g., Leshem & Glicksohn, 2007). Our finding of a linear decline in hasty behavior on the Tower of London is consistent with previous studies using this paradigm (e.g., Asato et al., 2006); numerous behavioral studies that compare children, adolescents, and adults on a range of self-regulatory tasks such as the antisaccade, flanker, go/no go, and Stroop (see Casey et al., 2008); and strong evidence of structural and functional maturation over the course of adolescence and well into the 20s of brain regions that subserve impulse control and other aspects of self-regulation (see Paus, 2005). Thus, converging evidence from questionnaire, behavioral, and neurobiological studies indicates that impulse control not only improves between childhood and adolescence but between adolescence and adulthood as well.

Aristotle (350 B.C./1954) famously observed that youth “are hot-tempered, and quick-tempered, and apt to give way to their anger” (Book II, Part 12, ¶2), and there is a long history of anecdotal evidence, empirical investigation, and actuarial analysis indicating that adolescence is a time of heightened risk taking and recklessness (Steinberg, 2007). One impetus for the present study was to better understand developmental differences in factors believed to contribute to this pattern. Although opportunity factors (e.g., less vigilant parental monitoring, legal driving privileges, the availability of sex partners) undoubtedly influence the extent to which individuals actually take risks (Byrnes, 1998), most indicators of risk taking (reckless driving, delinquent behavior, attempted suicide, substance abuse, unprotected sex) follow an inverted-U shaped pattern over development, with risky behavior generally higher in middle or late adolescence than in preadolescence or adulthood. This pattern is especially true with respect to risky behavior that is not regulated by laws governing minors’ access to potentially harmful or dangerous substances or situations, such as antisocial behavior (Piquero, Farrington, & Blumstein, 2003) or attempted suicide (Mościcki, 2001).

To the extent that vulnerability to risk taking is the product of high sensation seeking and low impulse control, the findings of the present study suggest why risk taking may follow this inverted U-shaped pattern. The first half of the adolescent decade—between 10 and 15—appears to be a time of growing vulnerability to risky behavior, as this period is characterized by relatively higher sensation seeking in the context of relatively lower impulse control; heightened sensation seeking impels adolescent toward risky activity, and immature self-regulatory capabilities do not restrain this impulse. As to the other side of the inverted-U function, vulnerability toward risky behavior would be expected to decline from age 15 on, since both sensation seeking and impulsivity diminish linearly after this age.

The research reported here suggests that vulnerability toward heightened risk taking during middle adolescence is likely to be normative, which poses a challenge to those interested in the health and well-being of this age group. It is important to remember, however, that individuals of the same age vary in their sensation seeking and impulse control and that variations in these characteristics are related to variations in risky and antisocial behavior (Steinberg, 2008). Understanding how contextual factors influence the development of sensation seeking and self-regulation, and the neural underpinnings of these processes, should be a high priority for those interested in the physical and psychological well-being of young people.

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Received February 1, 2008
Revision received May 2, 2008
Accepted May 9, 2008 ■