

Puberty Predicts Approach But Not Avoidance on the Iowa Gambling Task in a Multinational Sample

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According to the dual systems model of adolescent risk taking, sensation seeking and impulse control follow different developmental trajectories across adolescence and are governed by two different brain systems. The authors tested whether different underlying processes also drive age differences in reward approach and cost avoidance. Using a modified Iowa Gambling Task in a multinational, cross-sectional sample of 3,234 adolescents (ages 9–17; $M = 12.87$, $SD = 2.36$), pubertal maturation, but not age, predicted reward approach, mediated through higher sensation seeking. In contrast, age, but not pubertal maturation, predicted increased cost avoidance, mediated through greater impulse control. These findings add to evidence that adolescent behavior is best understood as the product of two interacting, but independently developing, brain systems.

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Adolescents tend to be more reward sensitive and sensation seeking than children or adults. This period of heightened reward sensitivity is thought to have evolved to encourage youth to seek out novel and stimulating experiences (Zuckerman, 1994), and explore resources away from the family (Ellis et al., 2012; Steinberg, 2008). Thus, adolescence can be a time of opportunity and development fostered by the desire to seek out new experiences, but this same proclivity may result in *too* much focus on seeking novel or exciting experiences, manifested in greater proclivity to take risks (Shulman et al., 2016). Because adolescent risk taking often carries costs for both individuals and society, investigating the underlying mechanisms of risky decision making is important for informing efforts to prevent physical and psychological harm, and promote positive development during this period.

Although research highlights contextual factors that facilitate or encourage risk taking, including lack of supervised time (Osgood & Anderson, 2004) and the presence of peers (e.g., Chein, Albert, O'Brien, Uckert, & Steinberg, 2011), recent work has focused on elucidating the contributions of two brain systems undergirding psychological functioning that lead to risk-taking behavior. Specifically, researchers assert that adolescent risk taking is a function of increased levels of sensation seeking coupled with relatively insufficient self-regulation (Casey, Jones, & Somerville, 2011; Steinberg, 2008). Often referred to as "maturational imbalance" or "dual systems" model (Casey et al., 2011; Steinberg, 2008), this perspective posits that at the time of pubertal onset, brain regions vital to social and affective processing, as well as the evaluation and experience of reward, mature rapidly (Steinberg, 2008). Changes in these regions, especially the ventral striatum (VS), are associated with increased neural sensitivity to reward (Luciana & Collins, 2012), which is manifested psychologically as sensation seeking, defined as the desire or propensity to seek out novel or exciting sensations and experiences (Shulman et al., 2016; Zuckerman, 1994).

That neural reward sensitivity and sensation seeking begin to increase around pubertal onset is not a coincidence. Recent studies (in humans) demonstrate positive associations between levels of sex hormones (i.e., testosterone and estrogen) and brain activity in reward regions (e.g., the VS; Braams, van Duijvenvoorde, Peper, & Crone, 2015; Op de Macks et al., 2011; but see Forbes et al., 2010), although this relation may be more robust among boys than girls (Peters, Jolles, van Duijvenvoorde, Crone, & Peper, 2015). These findings are

consistent with studies of nonhuman animals showing that pubertal hormones reorganize the brain's dopamine system, effectively sensitizing reward circuitry through modulation of dopaminergic activity in subcortical regions (Crone & Dahl, 2012; for review of dopaminergic functioning in adolescence, see Wahlstrom, Collins, White, & Luciana, 2010). Importantly, studies documenting the relation between pubertal development and reward activity in human adolescents find that pubertal development—beyond the effects of age—has a unique relation to reward processing and is a better predictor of developmental changes in reward processing than age alone (Op de Macks et al., 2011; Peters et al., 2015).

Consistent with the observed link between puberty and reward sensitivity, pubertal maturation is also associated with sensation seeking (Gunn & Smith, 2010; Martin et al., 2002; Steinberg et al., 2008). For example, pubertal status is related to scores on scales assessing the behavioral activation system (BAS; Carver & White, 1994). Although the BAS scale comprises subscales that measure "Drive" (e.g., "I go out of my way to get things I want") and "Reward Responsiveness" (e.g., "When I get something I want, I feel excited and energized"), pubertal development is related most strongly to the third subscale, "Fun Seeking" (e.g., "I crave excitement and new sensations"; Vermeersch, T'Sjoen, Kaufman, & Vincke, 2009), which is also highly correlated with other measures of sensation seeking (Smillie, Jackson, & Dalgleish, 2006). Thus, in addition to its link to neural reward reactivity, puberty predicts increases in self-reported motivation to approach potentially exciting experiences (Wahlstrom et al., 2010).

Adolescence is also a time of gains in self-regulation. Self-regulation encompasses the ability to decisively control thoughts, feelings, and actions, and is associated with functioning of the cognitive control regions of the brain, especially the dorsolateral prefrontal cortex (Luna, 2009; Shulman et al., 2016). Maturation of these regions is associated with improved impulse control and coordination of emotion and cognition owing to both synaptic pruning and myelination within cognitive control regions of the brain in early and midadolescence and improved connectivity between cortical and subcortical regions (i.e., top-down control; Casey et al., 2011). Unlike the rapid changes that occur during adolescence within subcortical reward regions, however, cognitive control regions and their connections to reward regions undergo protracted development into adulthood (Casey et al., 2011;

Mills, Goddings, Clasen, Giedd, & Blakemore, 2014; for a review, see Shulman et al., 2016).

Although the relation between age and self-regulation is well documented, findings are mixed as to whether pubertal development predicts improvements in impulse control. Studies have found that pubertal maturation is correlated with *less* top-down control (Peters et al., 2015) and greater activity in cognitive control regions (Op de Macks et al., 2011), and still others find that pubertal maturation is unrelated to cortical functioning (Peters, Braams, Raijmakers, Koolschijn, & Crone, 2014) or self-reported impulsivity (Steinberg et al., 2008). Variations in the assessment of self-control may partly explain these findings. For example, sex hormone levels have been linked to impulsive aggression (Mehta & Beer, 2010) as well as impulsive behavior that is rewarded (e.g., Diekhof, 2015). However, such tasks conflate the role that puberty may play in reward processing and emotional arousal with its role in cognitive control.

Despite improvements in impulse control during adolescence, which, in theory, should dampen risk taking, adolescents take more risks in the real world (although not always on laboratory tasks; Defoe, Dubas, & van Aken, 2015) than children or adults. The resolution of this contradiction comes from understanding that even though adolescents have the *capacity* to engage behavioral control, they are less able than adults to do so when the context is arousing or “hot” (e.g., when adolescents are emotionally stimulated or in the presence of peers; Chein et al., 2011; Figner, Mackinlay, Wilkening, & Weber, 2009; Luciana & Collins, 2012). When the motivation to seek out rewarding and exciting experiences increases quickly, as it does during the first part of adolescence, the ability to regulate and inhibit sensation seeking is compromised. It is important to note that these behavioral changes, including increased sensation seeking and risk taking, are not inherently maladaptive (Ellis et al., 2012; Steinberg, 2008). Evolutionarily speaking, risk taking secures social status and attracts potential mates, particularly among young men and boys. Even in modern contexts, this propensity toward risk taking and sensation seeking is sometimes problematic (e.g., reckless driving) but sometimes valuable (e.g., in athletic competitions).

In order to better understand the underlying affective processes that influence adolescents’ risky decision making, researchers have employed a variety of tasks on which performance in the laboratory is correlated with real-world risk taking, such as the Iowa Gambling Task (IGT; Bechara, Damasio,

& Anderson, 1994). On the IGT, individuals must determine which two of four decks of cards are advantageous and which two are disadvantageous. The advantageous decks, which yield smaller rewards and smaller losses, are less enticing than the disadvantageous ones, which couple larger rewards but even larger losses. Successful performance therefore involves both learning to approach the less exciting, but ultimately advantageous, decks and learning to resist the more tempting but ultimately disadvantageous ones (Hooper, Luciana, Conklin, & Yarger, 2004). Individuals who perform poorly on the IGT (i.e., who have difficulty resisting the disadvantageous decks) are more likely to engage in real-world risk taking, including substance use (see Verdejo-Garcia, Bechara, Recknor, & Perez-Garcia, 2006).

Cross-sectional studies indicate that performance on the IGT (i.e., attraction to advantageous decks, avoidance of disadvantageous decks) improves with age between late childhood and early adulthood (Cauffman et al., 2010; Hooper et al., 2004; Prencipe et al., 2011). It is not clear whether age differences in IGT performance are related to increases in sensation seeking (which might motivate individuals to search for advantageous decks), in self-control (which might enable individuals to resist drawing from disadvantageous decks), or both. Prencipe et al. (2011) found a modest but significant relation between IGT performance and performance on a color–word Stroop task, suggesting that response inhibition may play a role in IGT success. However, Hooper et al. (2004) failed to find a relation between IGT performance and response inhibition on a Go/No-Go task.

An unfortunate limitation of both the Hooper et al. (2004) and Prencipe et al. (2011) studies is their use of versions of the IGT, which, like the original task, conflate approaching advantageous decks with avoiding disadvantageous ones. When participants are allowed to choose freely among the four decks in the IGT, choosing one type of deck (advantageous or disadvantageous) necessarily requires not choosing the other. Addressing this limitation, Cauffman et al. (2010) used a modified, computerized version of the task that requires the participant to make a play or pass decision on one of the four decks that has been pseudorandomly preselected, which allows separate analyses of plays on advantageous versus disadvantageous decks. Importantly, Cauffman et al. (2010) found that approach and avoidance behavior follow different age patterns. In their cross-sectional sample spanning ages 10–30, approach toward advantageous

decks followed an inverted U-shaped age function, peaking in late adolescence and declining in early adulthood. In contrast, avoidance of disadvantageous decks increased linearly over the entire age range. Notably, these two patterns are reminiscent, respectively, of the developmental trajectories of reward sensitivity (which is thought to be driven by pubertal maturation) and impulse control (thought to be driven by age-related maturation). However, the focus of Cauffman et al. (2010) was on age differences in IGT performance not the underlying causes.

The present study explores the mechanisms through which age and pubertal development impact approach and avoidance on the IGT among adolescents. Because the IGT is designed to examine how participants change their behavior in response to gains and losses over time, we focus on overall performance based on rates of change in plays on advantageous and disadvantageous decks over the course of six blocks, as did Cauffman et al. (2010). As in previous studies, we anticipate that participants will increase plays on advantageous decks and decrease plays on disadvantageous decks over time. Given that pubertal status predicts increases in approach to potential rewards, we anticipate that pubertal status, independent of age, will predict how quickly participants increase their plays from advantageous decks. Furthermore, we hypothesize that the impact of puberty on how quickly participants learn to play on advantageous decks will be mediated through sensation seeking.

In parallel, we expect that age, independent of pubertal status, will predict how quickly participants come to avoid disadvantageous decks. That is, we hypothesize that age-related improvements in cognitive control, manifested as higher impulse control, will facilitate inhibition of plays from the disadvantageous decks. However, in light of evidence linking puberty to impulsivity, particularly in emotionally arousing situations, we also consider an alternative hypothesis—that pubertal status, independent of age, may actually predict less avoidance of the disadvantageous decks because they contain enticing rewards.

Although our hypotheses apply to both male and female adolescents, we also propose several sex-related predictions. Male adolescents evince higher sensation seeking (Quinn & Harden, 2013; Shulman, Harden, Chein, & Steinberg, 2014; Steinberg et al., 2008) and lower impulse control (Quinn & Harden, 2013; Shulman et al., 2014) than female adolescents. However, the puberty-related increase in sensation seeking (Gunn & Smith, 2010; Martin et al., 2002)

and the age-related increase in impulse control (Steinberg et al., 2008) do not typically differ across genders (but see Shulman et al., 2014). Accordingly, we anticipate higher sensation seeking and lower impulse control among male than female adolescents. Because male evince greater sensation seeking than female, we anticipate that males will show relatively steeper increases in draws from advantageous decks. Similarly, because male adolescents evince lower impulse control, we anticipate that they will show relatively less steep decreases in their avoidance of disadvantageous decks than female adolescents. Finally, despite these predicted sex differences in rates of change, we do not expect sex differences in the relation between age or pubertal status and either sensation seeking or impulse control, or between age or puberty and either choices of advantageous or disadvantageous decks.

In summary, using the same version of the IGT as Cauffman et al. (2010) but with a sample that is considerably larger (3,000 adolescents vs. 500), the present study examines the mechanisms through which age and pubertal development impact approach and avoidance behaviors in a sample of adolescents, aged 9 through 17 years, from 11 countries. The present study takes advantage of the play or pass choice presented in the modified IGT (Cauffman et al., 2010) to examine developmental mechanisms underlying different facets of IGT choice behavior. We examine whether approach behavior, regardless of whether it is ultimately beneficial or detrimental, is predicted by pubertal status and heightened sensation seeking and whether avoidance behavior—whether beneficial or detrimental—is predicted by age and impulse control. Our diverse, multinational sample of individuals from 11 countries significantly extends earlier, single-country research (e.g., Cauffman et al., 2010).

Method

Participants

Most of the present sample was recruited from a group of countries participating in an ongoing longitudinal study of parenting across cultures (PAC; Lansford & Bornstein, 2011). The PAC countries were selected because they differ in how children are disciplined, a focus of the PAC project. Although the current study has a different focus (i.e., age differences in decision making), collaborating with the PAC investigators permitted us to take advantage of a cross-national research infrastructure that was already in place. Two additional countries,

Cyprus and India, which were not in the PAC study, were involved in the current one (see Supporting Information for further details). The sample for the present analyses ($N = 3,359$) comprises adolescents between 9 and 17 years in 11 countries: Guang-Zhou and Shanghai, China ($N = 321$); Medellin, Colombia ($N = 341$); Nicosia, Cyprus ($N = 233$); Delhi, India ($N = 240$); Naples and Rome, Italy ($N = 376$); Amman and Zarqa, Jordan ($N = 308$); Kisumu, Kenya ($N = 303$); Manila, the Philippines ($N = 309$); several cities in the west of Sweden ($N = 243$); Chang Mai, Thailand ($N = 321$); and Durham and Winston-Salem, the United States ($N = 364$). Data collection began in 2011 and terminated in 2014. Parental consent and adolescent assent were obtained for all youth under age 18 with the exception of Sweden, where parental consent is not required for participants aged 15 and older. Local institutional review boards (IRBs) approved all procedures.

By design, the proportions of male and female adolescents were nearly even within the whole sample (50.9% male, $n = 1,650$; 49.1% female, $n = 1,709$), within each country (range: 47.7%–53.5% female), and across the ages studied. Participants in each country came from households with similar levels of parental education, which averaged “some college.” Other than in the United States, where we tried to recruit approximately equal numbers of Black, Latino, and White participants, the ethnic composition of the sample reflected the dominant ethnicity of the country. Although the study included adults (total age range: 9–30 years), the focus of the present study is the impact of puberty on behavior, thus the current analyses use data only from preadolescents and adolescents, among whom pubertal status was assessed ($M_{\text{age}} = 12.87$, $SD = 2.36$). Because it is unusual for individuals to complete puberty after 17, pubertal status was not assessed among individuals 18 and older.

Participants completed a 2-hr session that included several computerized tasks, self-report measures, and tests of executive functions, as well as an intelligence assessment and a demographic questionnaire. These sessions were completed individually in participants’ homes, schools, or other locations designated by the participants. In order to maintain participants’ interest in the study questionnaires and tasks, they were told they would receive a base payment (in the United States, \$30) for participating in the study but that they could earn a bonus (equal to 50% of the base payment; \$15 in the United States) based on their performance on the computer tasks. In actuality, all

participants received this bonus. After testing, participants were debriefed regarding this deception in countries where local IRBs deemed such disclosure necessary. In all countries, base payments were set by local investigators to be enticing but not coercive; the participating university in Sweden prohibits paying research participants, so these participants were given a base payment of two movie tickets and a bonus of one additional ticket.

Measures were administered in the predominant language at each site, following forward and back translation and meetings to resolve any item by item ambiguities in linguistic or semantic content (Erkut, 2010; Maxwell, 1996). The consistency of study procedures across sites was ensured in several ways. First, investigators from each site attended an in-person meeting once a year to discuss procedures and measures in detail and resolve any questions or concerns. These investigators trained and supervised interviewers at each site. Second, ongoing progress and questions were discussed in weekly communications through e-mail and Skype calls. Finally, data from all sites were received electronically and checked on a weekly basis by a central coordinating center.

Measures

Of central interest in the present analyses are the demographic questionnaire, the measure of intellectual functioning, two measures of impulse control (and a composite based on their average), two measures of sensation seeking (and a composite based on their average), self-reported pubertal status, and the IGT. In our model, age and pubertal status are primary predictors, the sensation-seeking and impulse control composites are mediators, and IGT performance on advantageous and disadvantageous decks (specifically, the rate of change in play frequency from each deck type) are the outcomes of interest.

Demographic

Participants reported their age, sex, and the level of education of each of their parents. Average parental education was used to estimate and control for the home environment in which children and adolescents develop (Steinberg, Mounts, Lamborn, & Dornbusch, 1991). Because information on parental education was gathered from the parents of the PAC participants, we were able to assess the reliability of the youngest participants’ reports of their parents’ educational attainment;

the correlation between children's and parents' reports is high and significant ($r = .76, p < .001$). Owing to small but significant differences among age groups, parental education was added as a covariate in all analyses.

Intellectual Functioning

The Matrix Reasoning subtest of the Wechsler Abbreviated Scale of Intelligence (WASI; Psychological Corporation, 1999), administered on a laptop, was used to produce an estimate of *nonverbal intellectual functioning*. (Other subtests, which rely on or assess verbal ability, were not used due to the variability in language across sites.) The WASI has been normed for individuals between the ages of 6 and 89 years; an age-normed score (t score) was computed for each participant. Although we cannot compare the current WASI scores of our participants, which were based on a computerized administration of the measure, to those derived from the noncomputerized procedures used to establish WASI age norms, it was important to control for differences in intellectual functioning across age groups that might influence task performance. Scores on this measure were highly correlated with other measures of executive functioning (e.g., with spatial working memory $r = .34$, working memory $r = .35$, verbal fluency $r = .30$), suggesting that, despite deviation from standardized procedures, the matrix reasoning assessment serves as a reasonable index of intellectual functioning.

Pubertal Status

Pubertal status was assessed among participants aged 9–17 using the Pubertal Development Scale (PDS; Petersen, Crockett, Richards, & Boxer, 1988), a widely used and well-validated self-report measure. Four items ask about perceived pubertal changes in skin, height, underarm hair, breast growth (for girls), and voice (for boys). Each item has four options, scored 1 (*has not yet started*) through 4 (*definitely completed*). For girls, an additional yes or no question about onset of menarche is included (1 = *no* and 4 = *yes*) in the computation of a scaled score. Item scores were averaged to create a continuous score for physical maturation ranging from 1 (*puberty has not started*) to 4 (*puberty seems complete*). PDS scores are correlated with Tanner staging derived from physician examination (Schmitz et al., 2004).

For display purposes only, we categorized PDS scores as pre-, early, mid-, and postpubertal.

Outcome Variables

Composite measures of sensation seeking and impulse control were computed by averaging standardized scores from a self-report and a behavioral measure of each. Self-report and performance measures of the same construct are often (if not typically) weakly correlated—here, the correlation between sensation-seeking measures is .04 ($p < .05$) and between impulse control measures is .07 ($p < .01$). This may be because different measures capture different aspects of the construct, or because some aspects are contextually sensitive. Because of this concern, we incorporate both kinds of measures to help ensure that we have coverage of the full range of the construct.

Self-reported sensation seeking. Self-reported sensation seeking was assessed using scores on a subset of six items (Steinberg et al., 2008) from the Sensation Seeking Scale (SSS; Zuckerman, 1994) that clearly index thrill or novelty seeking (e.g., “I like doing things just for the thrill of it”; see Table S1 for all items), which were used to create a latent variable indexing this construct. Response options were *true* (1) or *false* (0). Because the larger study from which the data for the present analyses come included a wide age range, we used the same version for all participants in order to facilitate developmental comparisons. Confirmatory factor analysis (CFA) indicated good model fit ($\chi^2[9] = 80.59, p < .0001$, root mean square error of approximation [RMSEA] = .05, 90% CI [.04, .06], comparative fit index [CFI] = .97, Tucker Lewis index [TLI] = .95). Factor scores were extracted from the CFA, with higher factor scores reflecting greater sensation seeking.

The Stoplight task. A behavioral index of sensation seeking was obtained using a computerized driving game known as the Stoplight task (Steinberg et al., 2008). This task requires participants to “drive” through a series of intersections in as little time as possible, while choosing whether to brake at or drive through a series of yellow lights. If the participant chooses to stop, he or she must wait 3 s before restarting. If the participant decides to run the light, this will result either in a crash (and a loss of 6 s) or a successful crossing (with no loss of time). Performance on the task is associated with self-reported sensation seeking (Chein et al., 2011; Steinberg et al., 2008; but see Kahn, Peake, Dishion, Stormshak, & Pfeifer, 2015).

Self-reported impulse control. Scores on six items from the impulsivity subset of the SSS (Zuckerman, 1994) were used to derive a latent variable indexing

self-reported impulse control. (Although the SSS is used primarily to assess sensation seeking, many of the items actually measure impulse control [for a discussion, see Steinberg et al., 2008].) Items included in the impulse control subset reflect a lack of planning (e.g., “I hardly ever spend much time on the details of planning ahead,” reversed) and acting without thinking (e.g., “I often act without thinking,” reversed; See Table S1 for items). Response options were *true* (1) or *false* (0). CFA indicated good model fit ($\chi^2[9] = 100.42, p < .0001$, RMSEA = .06, 90% CI [.05, .07], CFI = .96, TLI = .93). Factor scores were extracted from a CFA, with higher factor scores reflecting greater impulse control. Scores on this measure were strongly correlated with related constructs assessed in the study (e.g., the planning ahead subscale of the Future Orientation Scale [Steinberg et al., 2009], $r = .50, p < .001$), indicating convergent validity.

Tower of London task. A computerized version of the Tower of London task (Shallice, 1982) was used to generate a behavioral measure of impulse control (Steinberg et al., 2008). One of the capacities assessed by the Tower of London is whether one can inhibit acting before a plan is fully formed. 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 can hold two balls, and the last, only one ball. The first picture shows the starting positioning of the three balls and the second picture depicts the goal position. The participant is asked to move the balls in the starting arrangement to match the goal arrangement in as few moves as necessary. 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. An index of impulse control is extracted from this task by averaging the amount of time (in ms) that elapsed between the presentation of each difficult problem (i.e., those requiring at least six moves to complete) and the participant’s first move. Longer latencies to first move indicate greater impulse control.

Modified IGT

The IGT was used to generate measures of *reward approach* and *cost avoidance*. Participants play from four decks of cards in an attempt to earn money. Two of the decks result in a monetary gain over repeated play (advantageous decks), whereas the other two result in a net loss over repeated play (disadvantageous decks). We used a modified IGT (Bechara et al., 1994) that differed from the original

task in two ways. First, rather than having participants freely draw from any of the decks, on each trial, one deck was highlighted with an arrow, and participants were given 4 s to decide to play or pass on that card (see Cauffman et al., 2010 for details). This “play or pass” modification allowed us to independently track affinity for advantageous decks and avoidance of disadvantageous ones (Peters & Slovic, 2000). Second, although gains and losses of a single card are presented separately in the original IGT (e.g., “you won \$100,” “you lost \$300”), our version presented only the net amount for each card (e.g., “you lost \$200”). The task was administered in 6 blocks of 20 trials. If the participants played on a trial, they saw the amount of money won or lost. If they passed, no feedback was provided. If participants did not respond within 4 s, the trial was considered invalid. A running total of each participant’s earnings remained on the screen throughout the task.

Reward approach was operationalized as the rate of linear change across blocks in how often the participant chose to play (rather than pass) on the advantageous decks (i.e., the slope for the percentage of advantageous plays). Cost avoidance was operationalized as the rate of linear change across blocks in how often the participant avoided the disadvantageous decks (i.e., the slope for the percentage of disadvantageous plays). These slopes were estimated simultaneously in a bivariate latent growth curve model. Optimal IGT performance is achieved by exhibiting approach toward advantageous decks (positive slopes) and avoidance of disadvantageous decks (negative slopes).

Measurement Invariance

To ensure that self-report measures of puberty, sensation seeking, and impulse control were appropriate to use within our diverse sample, we tested for measurement invariance of factor loadings and intercepts across the 11 countries using the alignment technique (Muthén & Asparouhov, 2014); details on this procedure are provided in the Supporting Information). As per Muthén and Asparouhov (2014), approximate measurement invariance can be assumed if < 25% of the parameters are non-invariant for a given measure. No more than 7% of parameters—intercepts as well as loadings—were noninvariant for any self-report measure (i.e., pubertal development, sensation seeking, and impulse control; see Tables S2–S4). These results suggest that these questionnaires are valid across countries in our sample.

Data Analyses

Of the original 3,359 adolescents included in the sample, 122 were excluded based on interviewer feedback (e.g., the participant did not appear to understand tasks or did not demonstrate adequate effort). Three participants failed to report their age and were dropped from the sample. Of the remaining 3,234 participants, 77 (2.38%) lacked information on parental education, 23 (0.71%) lacked intellectual functioning scores, 100 (3.09%) lacked pubertal status data, 232 (7.17%) lacked Tower of London data, 28 (0.87%) lacked self-reported impulse control scores, 30 (0.93%) lacked sensation-seeking scores, 84 (2.60%) were missing data on the Stoplight game, and 28 (0.87%) were missing IGT data. Analyses were completed using Mplus statistical software (version 7.31; Muthén & Muthén, 1998–2010) using full-information maximum likelihood (FIML) to handle missing data. Because FIML makes assumptions about normality, parental education—which was negatively skewed—was reflected over 0 and log transformed.

The final sample comprised 3,234 adolescents, of which 317 were from China ($M_{\text{age}} = 12.61$, $SD = 2.57$; 50.8% female), 366 from Italy ($M_{\text{age}} = 12.55$, $SD = 2.30$; 49.5% female), 300 from Kenya ($M_{\text{age}} = 13.10$, $SD = 2.24$; 53.3% female), 303 from the Philippines ($M_{\text{age}} = 12.88$, $SD = 2.43$; 49.2% female), 320 from Thailand ($M_{\text{age}} = 12.63$, $SD = 2.10$; 50% female), 236 from Sweden ($M_{\text{age}} = 13.55$, $SD = 2.47$; 50.4% female), 354 from the United States ($M_{\text{age}} = 12.54$, $SD = 2.24$; 47.7% female), 331 from Colombia ($M_{\text{age}} = 12.52$, $SD = 2.50$; 52% female), 271 from Jordan ($M_{\text{age}} = 13.02$, $SD = 2.27$; 52.4% female), 234 from India ($M_{\text{age}} = 13.52$, $SD = 2.25$; 50.4% female), and 202 from Cyprus ($M_{\text{age}} = 13.25$, $SD = 2.36$; 53.5% female). See Tables S5 and S6 for other demographic information on the analytic sample.

To examine our research questions, we specified five models. First, we specified an unconditional, parallel process latent growth model, which simultaneously estimated the average growth trajectories for advantageous and disadvantageous decks, as well as the degree of correlation among the latent growth parameters (intercepts and slopes) for these trajectories. In this and all other models, the intercept was set at Block 6 so that the mean of the intercept was the estimated average percentage of plays on advantageous or disadvantageous decks at the end of the task. The slope for the advantageous decks represented the average level of change in reward approach and the slope for the

disadvantageous decks represented the average level of change in cost avoidance. Intercepts and slopes were “random” meaning that individual deviations from the average intercepts and slopes were modeled. Second, we reran the model including the individual difference variables (intellectual functioning, parental education, age, pubertal status, sex) as predictors of the latent intercepts and slopes. (Age was centered at 13, puberty was centered at 2—corresponding approximately to early pubertal development—intellectual functioning and parental education were grand mean centered to create meaningful values of “0.” Female adolescents were coded as “0,” male as “1.”) This model allowed us to observe the main effects of these variables on IGT performance. Third, we tested for Age \times Sex and Puberty \times Sex interactions in predicting slopes and intercepts on advantageous and disadvantageous decks by running Model 2 as a two-group model (i.e., male and female).

Fourth, we reran Model 2 (a single-group model) with the addition of two mediators: sensation seeking and impulse control. We hypothesized that pubertal status would predict approach toward advantageous decks and that this relation would be mediated through sensation seeking (pubertal status \rightarrow sensation seeking \rightarrow approach toward advantageous decks). Accordingly, we added a path specifying that pubertal status predicted sensation seeking. Our other main hypothesis was that age would predict cost avoidance on disadvantageous decks and that this relation would be explained by impulse control (age \rightarrow impulse control \rightarrow cost avoidance on disadvantageous decks). To model this association, we added a path specifying that age predicted impulse control. To rule out other mediational pathways (i.e., pubertal status \rightarrow impulse control \rightarrow approach toward advantageous decks and age \rightarrow sensation seeking \rightarrow cost avoidance on disadvantageous decks), we regressed impulse control and sensation seeking on all other individual difference variables as well (Figure S1 illustrates the model specification). Indirect effects were computed using the “model indirect” command in Mplus that estimates the indirect effect of the predictor on the dependent variable through each of the specified mediators. Statistical significance of indirect effects is evaluated using bias-corrected confidence intervals with 3,000 bootstrapped replications (Preacher & Hayes, 2008).

Fifth, we tested for sex differences in the relations between age, puberty, impulse control, sensation seeking, and IGT performance and the indirect effects using a two-group model (i.e., male and female). In

other words, we tested for Age \times Sex and Puberty \times Sex interactions in predicting slopes and intercepts on advantageous and disadvantageous decks—and their relations with age, puberty, sensation seeking, and impulse control—as well as mean levels of sensation seeking and impulse control.

Testing for Differences Across Cultures

Although cultural differences were not of primary relevance to our research question, we conducted two preliminary analyses of cultural and country differences. First, in order to maximize our power to detect cultural differences in the final models, we grouped participants into broad cultural clusters: Western countries (Italy, Sweden, Cyprus, Colombia, and the United States) and Asian countries (China, India, Thailand, and the Philippines). Jordan and Kenya, which do not fit distinctly into either of these categories, were excluded from this exploratory analysis. Second, we conducted similar analyses using country membership without clustering countries into larger groups. In each analysis, we computed a fully nested model, in which all estimates were fixed across groups (i.e., across the Western and Asian groups, or across all 11 countries), and a comparison model. Because we were interested only in whether our predictors of interest (age, puberty, sensation seeking, and impulse control) differed among groups, our comparison models were constrained so that our control variables (parental education and intellectual functioning) had uniform influences across groups, whereas all other parameters were freed. If model fit is significantly worse in the nested model than in the comparison model, we deduce that there are significant differences across groups on at least one of the parameters that is free to vary in the comparison model.

Results

Initial Analyses

Bivariate correlations and descriptive statistics are summarized in Table 1. Age and puberty were highly correlated, $r = .68$, $p < .001$. Consistent with previous findings (Quinn & Harden, 2013), sensation seeking and impulse control were negatively correlated, $r = -.13$, $p < .001$.

Trajectories of IGT Performance (Model 1)

Unconditional growth models were fit simultaneously (i.e., in one model) for advantageous decks

Table 1
Descriptive Statistics for Independent Variables

| | Age | Puberty | IC comp. | SS comp. | Intell. | Par. ed. |
|-----------|-------|---------|----------|----------|---------|----------|
| Age | — | .68*** | .04* | .08*** | -.07*** | .01 |
| Puberty | | — | .01 | .13*** | .01 | .03 |
| IC comp. | | | — | -.13*** | .10*** | .01 |
| SS comp. | | | | — | .08*** | .06** |
| Intell. | | | | | — | .23*** |
| Par. Ed. | | | | | | — |
| <i>M</i> | 12.87 | 2.32 | 0.00 | 0.00 | 47.20 | 11.95 |
| <i>SD</i> | 2.36 | 0.78 | 0.73 | 0.72 | 10.99 | 2.92 |

Note. IC comp. = impulse control composite; SS comp. = sensation-seeking composite; Intell. = intellectual functioning; Par. ed. = parental education (mean of parental education). * $p < .05$. ** $p < .01$. *** $p < .001$.

and disadvantageous decks, permitting covariance paths to be estimated among intercept and slope parameters (see Table S8). Model fit was acceptable ($\chi^2[64] = 1,075.77$, $p < .0001$, RMSEA = .07, 90% CI [.066, .074], CFI = .93). Rate of change (slopes) for both advantageous ($b = 1.09$, $SE = .07$, $p < .001$) and disadvantageous decks ($b = -0.71$, $SE = .08$, $p < .001$) evinced significant linear increases in plays on advantageous decks and significant decreases in plays on disadvantageous decks. There were significant individual differences in these slopes for both advantageous and disadvantageous plays (variance component = 9.47, $SE = .47$, $p < .001$ and variance component = 11.26, $SE = .57$, $p < .001$, respectively), suggesting that predictors could be added to the model. Results of intercept as outcome are summarized in Tables S8 through S12, but not discussed.

Predictors of IGT Performance: Main Effects (Model 2)

Next, we added age, pubertal status, intellectual functioning, parental education, and sex as predictors of the intercepts and slopes for advantageous and disadvantageous decks simultaneously (model fit was acceptable: $\chi^2[104] = 1,171.09$, $p < .0001$, RMSEA = .056, 90% CI [.053, .059], CFI = .93). The main findings are presented here. Full results can be found in Supporting Information (including partial correlations of overall play propensity).

Puberty ($b = 0.40$, $SE = .13$, $p = .003$), but not age ($b = 0.01$, $SE = .04$, $p = .79$), predicted approach toward advantageous decks (see Table S9), controlling for the other predictors in the model. Thus, individuals who were relatively further along in puberty approached advantageous decks more than

did less physically mature individuals of the same age. Additionally, male adolescents approach these decks more quickly than female adolescents ($b = 0.40, SE = .15, p = .008$). However, age ($b = -0.25, SE = .05, p < .001$), but not puberty ($b = 0.21, SE = .15, p = .18$), predicted the degree to which participants decreased plays on disadvantageous decks. Specifically, holding pubertal status constant, being older was associated with a steeper decline in plays from disadvantageous decks. We did not find sex differences in avoidance of disadvantageous decks ($b = 0.23, SE = .17, p = .16$; see Figure 1 for IGT performance by pubertal status and age, respectively).

Predictors of IGT Performance: Age × Sex and Puberty × Sex Interactions (Model 3)

Because Models 3 and 5 provide equivalent information regarding the moderating role of sex, some specific results of Model 3 are omitted here but can be found in Table S10.

Indirect Effects: Single Group (Model 4)

We investigated the *mechanism* through which puberty and age impact the rate of change in deck choices. Results of the mediation analysis—where

male and female adolescents were analyzed together—indicated that puberty predicted significant increases in sensation seeking ($b = 0.13, SE = .02, p < .001$), whereas age did not ($b = -0.002, SE = .01, p = .75$; see Tables 2 and S11; model fit was acceptable: $\chi^2[113] = 1,252.88, p < .0001, RMSEA = .056, 90\% CI [.053, .059], CFI = .93$). In addition, sensation seeking ($b = 0.29, SE = .11, p = .008$) and puberty ($b = 0.26, SE = .13, p = .04$), but not age ($b = 0.04, SE = .04, p = .37$), predicted approach toward advantageous decks. Furthermore, there was a significant indirect effect of puberty on approach toward advantageous decks via sensation seeking ($b = 0.04, 95\% CI [.01, .07], p = .02$). More advanced pubertal status was associated with greater sensation seeking, which in turn predicted a steeper rate of increase in percentage of plays on advantageous decks. Impulse control did not mediate the effect of puberty on approach toward advantageous decks ($b = 0.003, 95\% CI [-.007, .02], p = .63$).

The indirect effect of age on avoidance of disadvantageous decks was mediated through impulse control ($b = -0.01, SE = .01, 95\% CI [-.02, -.004], p = .02$). Age was associated with increases in impulse control ($b = 0.03, SE = .01, p < .001$), which in turn were associated with a steeper decline in plays on disadvantageous decks ($b = -0.42,$

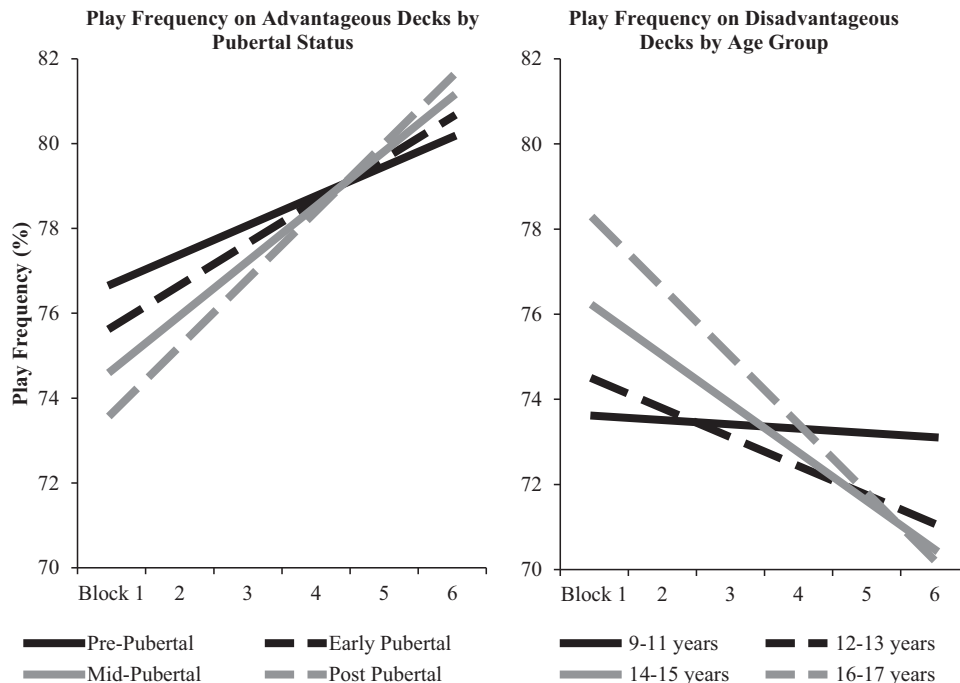


Figure 1. On left, more advanced pubertal status, independent of age, predicts a steeper increase in plays on advantageous decks. On right, greater age, independent of pubertal status, predicts a steeper decrease in plays on disadvantageous decks. Both graphs show trajectories computed from a model that includes both male and female adolescents and controls for intellectual functioning and parental education.

Table 2
Model 4: Growth Parameters of Conditional Parallel Process Growth Models With Mediators

| | Advantageous decks | | | Disadvantageous decks | | |
|--------------------------|--------------------|-------|----------------|-----------------------|-------|----------------|
| | Estimate | SE | <i>p</i> Value | Estimate | SE | <i>p</i> Value |
| Intercept@Bl6 as outcome | | | | | | |
| <i>M</i> | 80.76 | 0.38 | < .001 | 70.86 | 0.44 | < .001 |
| Age | 0.61 | 0.19 | .001 | -0.73 | 0.21 | .001 |
| Puberty | 0.09 | 0.57 | .87 | -1.06 | 0.65 | .10 |
| IC comp. | -0.64 | 0.46 | .16 | -2.47 | 0.53 | < .001 |
| SS comp. | 2.70 | 0.46 | < .001 | 2.94 | 0.52 | < .001 |
| Slope as outcome | | | | | | |
| Slope | 1.01 | 0.09 | < .001 | -0.77 | 0.10 | < .001 |
| Age | 0.04 | 0.04 | .37 | -0.22 | 0.05 | < .001 |
| Puberty | 0.26 | 0.13 | .04 | 0.10 | 0.15 | .51 |
| IC comp. | -0.06 | 0.11 | .58 | -0.42 | 0.13 | .001 |
| SS comp. | 0.29 | 0.11 | .01 | 0.21 | 0.11 | .07 |
| Variance components | | | | | | |
| Intercept | 250.99 | 10.21 | < .001 | 299.75 | 11.54 | < .001 |
| Slope | 9.10 | 0.58 | < .001 | 10.73 | 0.67 | < .001 |

| | IC comp. as outcome | | | SS comp. as outcome | | |
|---------------------|---------------------|------|----------------|---------------------|------|----------------|
| | Estimate | SE | <i>p</i> Value | Estimate | SE | <i>p</i> Value |
| <i>M</i> | 0.02 | 0.02 | .14 | -0.04 | 0.02 | .01 |
| Age | 0.03 | 0.01 | < .001 | -0.002 | 0.01 | .75 |
| Puberty | -0.05 | 0.02 | .02 | 0.13 | 0.02 | < .001 |
| Variance components | 0.52 | 0.02 | < .001 | 0.51 | 0.01 | < .001 |

| Indirect effects | Estimate | SE | <i>p</i> Value | 95% Confidence interval | |
|---------------------------|----------|-------|----------------|-------------------------|-------|
| | | | | LB | UB |
| Puberty → SS comp. → Adv. | 0.04 | 0.02 | .02 | .01 | .07 |
| Puberty → IC comp. → Adv. | 0.003 | 0.01 | .63 | -.007 | .02 |
| Age → SS comp. → Disadv. | 0.00 | 0.002 | .77 | -.005 | .002 |
| Age → IC comp. → Disadv. | -0.01 | 0.01 | .02 | -.02 | -.004 |

Note. Intercept values and slopes represent play propensity for age = 13, pubertal status = 2 (puberty is continuous; "2" is approximately early puberty), average intellectual functioning, parental education, SS, and IC. Control variables omitted for space (but see Table S11). IC comp. = impulse control composite; SS comp. = sensation-seeking composite.

SE = .13, *p* = .001). However, pubertal status predicted significantly lower levels of impulse control (*b* = -0.05, *SE* = .02, *p* = .02). The direct effect of age on avoidance of disadvantageous decks was

also significant (*b* = -0.22, *SE* = .05, *p* < .001). The indirect effect of age on avoidance of disadvantageous decks through sensation seeking was *not* significant (*b* = 0.00, 95% CI [-.005, .002], *p* = .77).

Indirect Effects: Age × Sex and Puberty × Sex Interactions (Model 5)

We found no evidence of sex differences in the role of age or puberty in predicting the rate of change on advantageous decks (see Table S12). On disadvantageous decks, the relation between age and slope, and between puberty and slope, differed between male and female adolescents (for age, *b* = -0.22, *SE* = .10, *p* = .02; for puberty, *b* = 1.01, *SE* = .30, *p* = .001; Figure S2). The relation between age and avoidance of disadvantageous decks was stronger among male (*b* = -0.36, *SE* = .07, *p* < .001) than female adolescents (*b* = -0.13, *SE* = .07, *p* = .04). Puberty did not predict rate of change among female adolescents (*b* = -0.27, *SE* = .19, *p* = .16), but predicted significantly *more* approach toward the disadvantageous decks among male adolescents (*b* = 0.74, *SE* = .24, *p* = .002).

Although male and female adolescents did not differ in levels of impulse control (*b* = 0.02, *SE* = .03, *p* = .59), male adolescents evinced significantly higher sensation seeking (*b* = 0.14, *SE* = .03, *p* < .001). Although the relation between age and impulse control and between puberty and impulse control did not differ between male and female adolescents, the relation between puberty and sensation seeking did (*b* = -0.10, *SE* = .05, *p* = .03). Puberty predicted a steeper increase in sensation seeking among female (*b* = 0.20, *SE* = .03, *p* < .001) than male adolescents (*b* = 0.09, *SE* = .04, *p* = .01). Finally, we found no evidence of sex differences in the mechanisms that explain the relations between age or puberty and approach or avoidance behavior (i.e., indirect effects).

Differences Across Cultures

Chi-square tests revealed significant differences in the model between broad cultural units, ($\Delta\chi^2 = 64.14$, $\Delta p = 20$, *p* < .05), as well as across individual countries ($\Delta\chi^2 = 179.02$, $\Delta p = 100$, *p* < .05). However, chi-square tests are very sensitive in large samples. Therefore, we relied on the Index of Root Deterioration per Restriction (RDR; Hildebrandt, Wilhelm, & Robitzsch, 2009) and changes in CFI and RMSEA to evaluate changes in model fit. The computation for RDR rescales the chi-square difference between models into an

RMSEA metric. Simulation work supports using CFI and RMSEA changes of $< .015$, and RDR values of $< .05$, to support nonsignificant differences in model fit (Chen, 2007; Hildebrandt et al., 2009). Our observed differences in model fit were within these limits when countries were grouped as Western or Asian ($\Delta\text{CFI} = .003$; $\Delta\text{RMSEA} = .001$; $\text{RDR} = .03$) as well as when they were considered individually ($\Delta\text{CFI} = .005$; $\Delta\text{RMSEA} = .003$; $\text{RDR} = .02$). These results indicate that the differences we observed among countries are relatively minor, whether considered separately or clustered into broad cultural groups.

Discussion

Contemporary models of adolescent risk taking link heightened risky behavior during this period to the interplay between two brain systems—one that governs reward sensitivity and one that governs self-regulation—that follow distinct developmental courses. Reward sensitivity increases steeply in early and middle adolescence (Steinberg, 2008), inclining teenagers toward sensation seeking, the pursuit of exciting and potentially rewarding experiences. Meanwhile, cognitive control improves gradually across this period, slowly improving adolescents' ability to restrain these inclinations (Casey et al., 2011). Based on a large and diverse sample, the findings of the present study support the idea that different forces may drive these two developmental processes (Steinberg, 2008). On our modified version of the IGT, designed to separate reward approach and cost avoidance, beneficial reward approach (i.e., increases in plays from advantageous decks) was more closely related to pubertal maturation (mediated through sensation seeking) than to age, whereas beneficial cost avoidance (i.e., decreases in plays from disadvantageous decks) was more closely related to age (mediated through impulse control) than pubertal maturation. Among boys, however, pubertal status was also associated with more plays on disadvantageous decks, indicating that in boys, pubertal development may stimulate approach behaviors even in the face of negative feedback.

That reward processes are correlated with puberty is consistent with past studies showing that self-reported sensation seeking increases with pubertal maturation (e.g., Gunn & Smith, 2010) and that, even after controlling for chronological age, pubertal status predicts reward-seeking behaviors on laboratory tasks (Kretsch & Harden, 2014;

Steinberg et al., 2008). Consistent with past research linking puberty to reward processes in both genders, these relations between puberty, sensation seeking, and reward approach on advantageous decks are evident among boys and girls (e.g., Gunn & Smith, 2010). It is interesting to note, however, that pubertal status is a stronger predictor of sensation seeking among girls, whereas previous studies did not find comparable sex differences (Gunn & Smith, 2010; Martin et al., 2002).

Top-down processes play a role in IGT performance as well. As stated previously, learning to avoid disadvantageous decks on the IGT is an age-related phenomenon (Cauffman et al., 2010), likely due to maturation of prefrontal regulatory systems. However, these improvements may not be sufficient to temper the influence of puberty among boys. That pubertal status predicts less avoidance of, and more approach toward, the disadvantageous decks among adolescent boys is consistent with literature linking puberty to self-regulation in emotionally arousing situations (e.g., when reward is at stake; Diekhof, 2015). That puberty is not related to avoiding disadvantageous decks in adolescent girls, in contrast, is consistent with literature reporting no link between puberty and self-regulation (Nelson, Leibenluft, McClure, & Pine, 2005; Peters et al., 2014). We suggest that for teenage boys, inhibiting the impulse to pursue rewards in disadvantageous situations may be undermined by puberty through a bottom-up process through which subcortical systems disrupt executive function. This supposition is consistent with neuroimaging studies linking testosterone, which circulates at higher levels in male than female adolescents, to the suppression of cortical regions responsible for behavioral regulation (Mehta & Beer, 2010; Peters et al., 2015).

This sex difference may explain why boys tend to take more risks than girls in the real world and on laboratory tasks (Byrnes, Miller, & Schafer, 1999; Figner & Weber, 2011). Girls may be less aroused by rewards (whether beneficial or harmful), thus requiring less top-down regulation of affective arousal to effectively regulate behavior. It may also be the case that the IGT, though affectively based, does not elicit so much arousal so as to overwhelm cognitive resources among girls. Alternatively, boys may be more tolerant of the costs associated with disadvantageous decks (i.e., they are more willing to incur the greater costs for the sake of greater gains). Thus, the kind of reward-seeking behavior that puberty predicts may depend not only on task contingencies (gains or losses that require approach or avoidance) but also task intensity and sex.

Despite the effect of puberty on disadvantageous reward seeking among boys, age predicts avoidance of disadvantageous decks more among boys than girls. Although Cauffman et al. (2010) found no evidence of sex differences in the avoidance of disadvantageous decks, this finding is consistent with studies documenting a male advantage among adults on the original version of the IGT (van den Bos, Homberg, & de Visser, 2013).

Withdrawal from disadvantageous decks also may be driven by age-related changes in avoidance circuitry, undergirded by the amygdala. The amygdala, which develops through adolescence (e.g., Mills et al., 2014), integrates changes in the value of environmental cues, both rewarding and aversive (Spear, 2011). With age, the ability of the amygdala to assign value to a stimulus (e.g., to associate monetary loss with the disadvantageous decks) improves (Ernst & Fudge, 2009; Gupta, Koscik, Bechara, & Tranel, 2011). Alternatively, younger adolescents, compared to their older peers, find disadvantageous decks to be less aversive (Spear, 2011). That age significantly predicts withdrawal from disadvantageous decks, even after accounting for impulse control, may be due to the development of this avoidance system. That puberty predicts impulse control—measured using self-report and a behavioral task—is unexpected in light of literature suggesting that puberty generally is not associated with self-regulatory functions (Gunn & Smith, 2010; Nelson et al., 2005; Peters et al., 2014), particularly in the absence of emotionally arousing stimuli (e.g., reward; Diekhof, 2015). Future work should explore under what circumstances pubertal development impacts self-regulation.

The present study has several important limitations. First, although ours is a multinational sample, we did not examine specific differences among countries in IGT performance, which was not the focus of this article. Nevertheless, our analyses suggest that the mechanisms responsible for increased risk behavior during adolescence are likely to be similar across cultures. Still, it will be important for future studies to test specific *a priori* hypotheses about differences across cultures in the development and behavioral manifestations of these constructs. For example, some cultures, particularly those in Asia, emphasize the development of self-control starting at an early age (Chen, Cen, Li, & He, 2005; Weisz, Chaiyasi, Weiss, Eastman, & Jackson, 1995). One might hypothesize that this cultural tradition may reduce impulsive behaviors within a culture as a whole, but that we would still see greater impulse control among adults compared to

adolescents due to commonalities in the development of cognitive control brain regions. Most tests of hypotheses derived from the dual systems model have been conducted in North America and, to a lesser extent, Western Europe. The fact that we found the expected relations between puberty, age, reward approach, and cost avoidance in this multinational sample, of which only one-fourth of the participants were from the United States or Western Europe, is noteworthy.

Second, self-reported pubertal status, which is the only feasible way of measuring puberty in a sample this large, is not a perfect measure of puberty. Self-report measures of puberty can only imply a link between pubertal hormones and behavioral data, and thus we cannot say with certainty that the observed effect of pubertal status on reward approach in this study is attributable to hormones as opposed to social factors. As adolescents develop physically, others in the environment (e.g., parents) may respond to their more adult-like appearance by granting more autonomy, which could afford the adolescent more opportunities for reward-driven behavior (Schelleman-Offermans, Knibbe, & Kuntsche, 2013).

Third, although the findings of this study are statistically significant and theoretically consistent with current models of adolescent decision making, the mediation models explain only a small proportion of the total variance in IGT performance (between 3% and 5%; not tabled). This suggests that though developmental factors matter, their effects on behavior may be subtle—at least in the relatively unexciting context of a laboratory task. Future studies should compare the relative contributions of puberty and age to measures of reward, cost, and cognitive control under conditions that vary in arousal in order to determine whether puberty more strongly predicts behavior in highly arousing tasks (e.g., when in the presence of a peer). We predict that, among adolescents, age would be a less salient predictor of behavior in highly arousing situations wherein activation of the reward system may overwhelm both the cognitive control system and brain systems sensitive to loss (Ernst, 2014; Figner et al., 2009; Luciana & Collins, 2012).

Fourth, our analyses are based on cross-sectional data, which necessarily limits our ability to draw causal conclusions about the effects of age and puberty. This is particularly relevant for the mediation analyses because we are unable to establish a temporal sequence, which may over- or underestimate the true indirect effect as it unfolds longitudinally (Maxwell, Cole, & Mitchell, 2011). Finally, the

present study assessed the underlying mechanisms of risk taking but did not measure actual risky behavior. Future studies should explore links among laboratory measures of reward approach, cost avoidance, and real-world risk taking.

Above all, the current study suggests not only that adolescence is an important time of learning, but that puberty may facilitate this process—at least with respect to detecting rewards. We also view these findings as further evidence of adolescent flexibility in “cognitive engagement” (Crone & Dahl, 2012). That is, optimal behavior relies on a balance of knowing when it is a good idea to indulge or inhibit one’s appetites. Although it makes sense that pubertal maturation would lead to exploration and novelty seeking, an inability to restrain such proclivities when self-control is necessary for survival is dangerous. For adolescent boys, pubertal maturation may tip the scales in favor of reward approach even in disadvantageous contexts. From an evolutionary standpoint, this finding is consistent with hypotheses that men have more to gain from risk taking because their reproductive success hinges on their ability to attract women and ultimately reproduce (Ellis et al., 2012). For better and worse, puberty stimulates adolescents to engage in sensation seeking, while cognitive control permits them to inhibit these impulses—at least some of the time—when contingencies change.

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Supporting Information

Additional supporting information may be found in the online version of this article at the publisher's website:

Figure S1. Mediation Models

Figure S2. (A) Pubertal Status Predicts More Approach of Disadvantageous Decks Among Males, But Is Not Related to Rate of Change on Disadvantageous Decks Among Females; (B) Age Predicts Greater Avoidance of the Disadvantageous Decks Among Males and Females, and This Relation Is Stronger Among Males; (C) Males, Regardless of Pubertal Status, Increase Their Plays on Advantageous Decks More Quickly Than Females

Table S1. Self-Reported Sensation Seeking and Impulse Control Items

Table S2. Results of Alignment Approach to Measurement Invariance: Self-Reported Pubertal Status

Table S3. Results of Alignment Approach to Measurement Invariance: Self-Reported Sensation Seeking and Impulse Control

Table S4. Alignment Fit Statistics for Self-Reported Pubertal Development Scale (PDS), Sensation Seeking, and Impulse Control

Table S5. Sample Breakdown by Age Group and Pubertal Status

Table S6. Breakdown of Pubertal Stage by Sex Within Age Bands

Table S7. Partial Correlations of Age and Puberty With Overall Play Propensity

Table S8. Model 1: Growth Parameters of Unconditional Parallel Process Growth Models

Table S9. Model 2: Growth Parameters of Conditional Parallel Process Growth Models Without

Mediators (Main Effects)

Table S10. Model 3: Growth Parameters of Conditional Parallel Process Growth Models Without Mediators (Age \times Sex and Puberty \times Sex Interactions)

Table S11. Model 4: Conditional Growth Models of Iowa Gambling Task (IGT) Performance With Mediating Variables and Control Variables

Table S12. Model 5: Growth Parameters of Conditional Parallel Process Growth Models With Mediators (Age \times Sex and Puberty \times Sex Interactions)