Published in final edited form as:
J Youth Adolesc. 2018 September ; 47(9): 1992–2005. doi:10.1007/s10964-018-0891-9.

Modeling Trajectories of Sensation Seeking and Impulsivity Dimensions from Early to Late Adolescence: Universal Trends or Distinct Sub-groups?

Atika Khurana[1], **Daniel Romer**[2], **Laura M. Betancourt**[3], and **Hallam Hurt**[3]

[1]College of Education, University of Oregon

[2]Annenberg Public Policy Center, University of Pennsylvania

[3]Neonatology, Children's Hospital of Philadelphia

Abstract

Developmental imbalance models attribute the rise in risk-taking during adolescence to a universal imbalance between rising reward sensitivity and lagging cognitive control. This study tested predictions of an alternate Lifespan Wisdom Model that distinguishes between exploratory/adaptive (e.g., sensation seeking) and maladaptive (e.g., acting-without-thinking, delay discounting) risk-taking propensities and attributes the latter to a sub-set of youth with weak cognitive control. Latent trajectory modeling of six waves of data from 387 adolescents (52% females; spanning average ages of 11–18 years) revealed distinct sub-groups with heterogeneous

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Corresponding Author: Atika Khurana, PhD, Associate Professor, College of Education, 369 HEDCO, 1655 Alder Street, University of Oregon, Eugene, OR 97403, Ph: (541) 346-5540, Fax: (541) 346-0683.

Author Affiliations and Research Interests

Dr. Atika Khurana Associate Professor in the College of Education at the University of Oregon. Her research interests include adolescent development and risk behavior prevention, neuropsychological precursors of adolescent risk-taking as well as parental and contextual influences on adolescent risk behaviors.

Dr. Daniel Romer Director of Research at the Annenberg Public Policy Center of the University of Pennsylvania. His research focuses on policy relevant strategies to improve the mental and behaviorial health of adolescents, with a particular focus on social and media influences on adolescent development.

Dr. Laura Betancourt Practicing Licensed Clinical Psychologist and Clinical Research Associate at the Children's Hospital of Philadelphia. Her clinical and research endeavors are focused on understanding psychological, neurocognitive, and social-emotional function in the context of caregiver, neighborhood, and socioeconomic influences over time.

Dr. Hallam Hurt Professor of pediatrics in the Division of Neonatology at the Children's Hospital of Philadelphia, Perelman School of Medicine, University of Pennsylvania. Her research interests include effects of maternal substance use on child and adolescent outcome, neural and developmental effects of poverty in infants, and long term outcome of preterm and high-risk infants.

Authors' Contributions: AK and DR conceived the study and participated in its design and coordination; AK conducted the statistical analyses and prepared the first draft of the manuscript; LB and HH led the data collection efforts and participated in the interpretation of the data; DR, HH, and LB edited and provided feedback on the manuscript. All authors read and approved the final manuscript.

Data Sharing Declaration

The data sets analyzed in the current study are not publicly available but are available from the corresponding author on reasonable request.

Compliance with Ethical Standards

The study was approved by the Institutional Review Board of the Children's Hospital of Philadelphia. All procedures performed involving human participants were in accordance with the ethical standards of the institutional review committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed Consent

Informed consent was obtained from all participants at age 18 or older. Parental consent and child assent was obtained when the participants were under age 18.

Conflicts of Interest

The authors report no conflicts of interest.

trajectory patterns for acting-without-thinking and delay-discounting. Only those trajectory groups with weak cognitive control, characterized as “high-increasing” acting-without thinking and “high-stable” delay discounting were predictive of a maladaptive risk-taking outcome, namely substance use disorder. Sensation seeking demonstrated a universal peak, but high levels of sensation seeking were not associated with weakness in cognitive control and were unrelated to substance use disorder, controlling for impulsivity. The findings suggest that maladaptive risk-taking characterized by weak cognitive control over reward-driven impulses is a phenomenon limited to only a sub-set of youth.

Introduction

Adolescence is a life stage characterized by increased prevalence of risk behaviors that can lead to morbidity and mortality. Recent theories based on the neurobiology of adolescent brain development attribute this rise to an imbalance between early-maturing limbic motivational neurocircuitry and later-maturing cognitive control neurocircuitry (Shulman et al., 2016; Somerville & Casey, 2010). This developmental imbalance is proposed to be greater during adolescence than during either childhood, when these systems are still developing, or adulthood, when cognitive control circuitry is fully on board and reward-sensitive motivation has returned to pre-adolescent levels (Casey, 2015).

Although this model is appealing and has received widespread attention (Shulman et al., 2016; Steinberg et al., 2017), an alternative model known as the Lifespan Wisdom Model (Romer, Reyna, & Satterthwaite, 2017) challenges the proposition that brain development during adolescence entails a normative, universal imbalance between reward and cognitive control systems. Consistent with recent research focused on differentiating different types of adolescent risk-taking (e.g., Maslowsky, Keating, Monk, & Schulenberg, 2011), the Lifespan Wisdom Model distinguishes between adaptive/exploratory risk-taking (characterized by sensation seeking) and maladaptive forms of risk-taking (characterized by poor impulse control). Maladaptive risk-taking includes behaviors that are more likely to be associated with avoidable and unhealthy outcomes, such as substance dependence and unintended pregnancy. The Lifespan Wisdom Model builds on evidence suggesting that only a sub-group of adolescents engage in such maladaptive risk-taking (Bjork & Pardini, 2015; Romer, 2010). These adolescents often have early behavioral control difficulties (e.g., disruptive and aggressive tendencies) that can be exacerbated in the context of heightened dopamine expression during adolescence. In support of these claims, many longitudinal studies have found that adolescents with early indicators of behavioral control difficulties are more likely to engage in maladaptive forms of risk-taking with long-term health consequences than those without weakness in behavioral control (Bjork & Pardini, 2015; Iacono, Malone, & McGue, 2008; Moffitt et al., 2011).

Empirical tests of imbalance models use self-report measures of sensation seeking as a behavioral marker of reward motivation, and find that this biological drive shows a universal peak during adolescence (Duell et al., 2016; Harden & Tucker-Drob, 2011; Quinn & Harden, 2013; Shulman, Harden, Chein, & Steinberg, 2014; Steinberg et al., 2008). The Lifespan Wisdom Model interprets this trend as a rise in an exploratory drive that is developmentally normative and necessary for developing wisdom/gist-based reasoning by trying out and learning from novel experiences (Romer et al., 2017). Furthermore, because sensation seeking tends to be positively related to indicators of cognitive control such as working memory (Khurana et al., 2012), risk-taking driven by sensation seeking is not necessarily characterized by an imbalance between the control and reward systems. Indeed, sensation seeking does not predict maladaptive risk-taking in adolescents controlling for its positive association with impulsivity (Boyer & Byrnes, 2009; Khurana et al., 2015a; Magid, MacLean, & Colder, 2007). The Lifespan Wisdom Model proposes that maladaptive risk-taking in adolescence is attributable to high levels of impulsivity that tend to be clustered in youth with early weakness in cognitive control.

To test the predictions of the Lifespan Wisdom Model requires a longitudinal design in which unique trajectories of sensation seeking and different dimensions of impulsivity can be modeled across adolescence and examined in relation to baseline differences in cognitive control and long-term associations with maladaptive risk-taking outcomes. Previous studies modeling trajectories of these dimensions have either been limited to cross-sectional cohort data (e.g., Steinberg et al., 2008) or have relied on datasets that did not have strong measures of these variables (e.g., Quinn & Harden, 2013). This research presents the findings of a study that followed a community cohort of adolescents starting at an average age of 11 through age 18 with repeated assessments of sensation seeking and different forms of impulsivity that permitted the identification of distinct trajectory groups that were examined in relation to baseline differences in working memory (an indicator of cognitive control) and long-term predictive associations with a maladaptive risk-taking outcome, namely substance use disorder.

Of the various dimensions of impulsivity (Whiteside & Lynam, 2001), acting-without-thinking and delay discounting, have consistently been linked with maladaptive risk-taking outcomes during adolescence (Romer, Reyna, & Pardo, 2016), including substance abuse and dependence (deWit, 2009; Reynolds, 2006). Acting-without-thinking reflects motor impulsivity or “impulsive action”, i.e., acting on the spur of the moment without adequate consideration of the consequences, and is generally assessed using self-report scales like the Barratt (Patton, Stanford, & Barratt, 1995) or Eysenck (Eysenck, Easting, & Pearson, 1984). Delay discounting is reflective of “impulsive choice” in the context of known risks and rewards, and is assessed using behavioral tasks that measure the ability to choose between two competing rewards, a smaller reward received immediately vs. another that is larger but received with varying delays (Green, Fry, & Myerson, 1994; Madden & Bickel, 2010). Both of these forms of impulsivity are inversely related to indicators of cognitive control, such as working memory (Khurana et al., 2013; Shamosh et al., 2008). Acting-without-thinking is also positively associated with sensation seeking as impulsive action is often driven by rewarding urges (e.g., using an addictive substance) (Khurana et al., 2012; Romer et al., 2011). Delay discounting, however, is not as sensitive to individual differences in sensation seeking given that both choices in the delay discounting task include a reward (Romer, 2010; van den Bos, Rodriguez, Schweitzer, & McClure, 2015; Wilson & Daly, 2006).

Current Study

In this study, developmental trajectories of sensation seeking, acting-without-thinking, and delay discounting were modeled to test four critical predictions stemming from the Lifespan Wisdom Model. First, only a subset of youth will exhibit a peak in impulsive action (acting-without-thinking) during adolescence. This sub-group is expected to enter adolescence with pre-existing weaknesses in cognitive control making them more vulnerable to impulsive action in the context of a rising exploratory drive. As a consequence, adolescents in this sub-group are also more likely to engage in maladaptive risk-taking, such as early and progressive drug use that results in substance use disorder. There is mixed support for the prediction of a peak in acting-without-thinking, with some studies observing a peak (Collado et al., 2014; Kasen, Cohen, & Chen, 2011; Shulman et al., 2016; White et al., 2011) and others observing a decline (Duell et al., 2016; Harden & Tucker-Drob, 2011; Quinn & Harden, 2013; Steinberg et al., 2008). However, no study to date has examined heterogeneity in adolescent trajectories of acting-without-thinking that might help to identify those at greatest risk for maladaptive outcomes. Given its positive association with sensation seeking and negative association with indicators of cognitive control, the acting-without-thinking dimension of impulsivity distinctly captures the imbalance between the reward and control systems. However, the Lifespan Wisdom Model proposes that a developmental peak in this propensity will only be exhibited by a sub-set of adolescents, especially those who enter adolescence with preexisting weakness in cognitive control. Those without preexisting cognitive control deficits will exhibit low levels of acting-without-thinking throughout adolescence (without any peaks); will not experience an imbalance between the reward and control systems; and will not be at greater risk for substance use disorder.

Second, most adolescents are expected to exhibit a peak in sensation seeking due to the normative rise in dopamine expression during adolescence. Previous studies have documented such a peak (Duell et al., 2016; Harden & Tucker-Drob, 2011; Quinn & Harden, 2013; Romer & Hennessy, 2007; Shulman, Harden, Chein, & Steinberg, 2014; Steinberg et al., 2008). Nevertheless, qualitative trends in sensation seeking have not been previously explored, likely due to its biological basis. Given its positive correlation with acting-without-thinking, we explored any potential heterogeneity in sensation seeking trajectories in our sample.

Third, delay discounting is expected to decline for most adolescents given the developmental improvements in cognitive control during these years. Since delay discounting is not correlated with sensation seeking, it is unlikely to peak during adolescence. Past studies have reported a decline in delay discounting from childhood to adulthood (Green, Fry, & Myerson, 1994; Romer, Duckworth, Sznitman, & Park, 2010; Steinberg et al., 2009; van den Bos et al., 2015), however, these studies are not conclusive owing to their cross-sectional nature. Individual differences in delay discounting are expected in our sample, but these are likely to be present prior to entry into adolescence. Youth with high levels of delay discounting will be at greater risk for substance use disorder (Reynolds, 2006). Given lack of empirical or theoretical evidence, we do not have a-priori hypothesis about the presence or absence of distinct trajectory groups for delay discounting.

Finally, based on the Lifespan Wisdom Model, we predict that controlling for its association with acting-without-thinking, sensation seeking is unlikely to predict substance use disorder. These predictions were tested in a study of 387 adolescents followed over a period of eight years from early adolescence (Mean age=11±0.46 years) to late adolescence (Mean age=18±0.46 years). We modeled unique trajectories of sensation seeking, acting-without-thinking, and delay discounting, and examined them in relation to baseline differences in cognitive control (assessed using working memory performance) and predictive associations with substance use disorder as a maladaptive risk-taking outcome.

Methods

Present study used data from 387 adolescents recruited as part of the Philadelphia Trajectory Study (PTS) in 2004–2005 and assessed over a period of eight years, including five annual assessments from 2004–2010 (wave 1–5; mean baseline age=11.41±0.88 years) and a final follow-up after a gap of two years (wave 6; mean age=18.41±0.64 years). Data from all six waves was included in present analyses. The sample was recruited primarily from schools in the Philadelphia area, and included 52% females, 56% Non-Hispanic Whites, 26% non-Hispanic Blacks, 9% Hispanics, and 9% other races primarily Native American and Asian. Majority of the participants came from low-middle SES backgrounds as assessed by the Hollingshead Two-Factor Index of Social Status (M=47.0±15.8; reverse scored). Two-thirds of the sample (66%) was from two-parent households with a median parental education of 14 years.

There was 25% attrition across the six waves, with 13% loss to follow-up over the first five waves, and an additional 12% attrition from wave 5–6. Missingness was unrelated to participant demographics or key study variables and was handled using Full Information Maximum Likelihood which yields reliable estimates when data are missing at random (Schafer & Graham, 2002). The study was approved by the Institutional Review Board of the Children's Hospital of Philadelphia. Further details about sample recruitment can be found elsewhere (Romer et al., 2009).

Measures

Acting without thinking.—Acting without thinking was assessed using a 9-item self-report measure adapted from the Junior Eysenck Impulsivity Scale (Eysenck et al., 1984) that assesses predisposition towards rapid, unplanned reactions to impulsive urges without thinking through the consequences (e.g., do you usually do or say things without thinking?) with binary (Y/N) response options. Responses on the nine items were averaged to create a composite score ranging from 0–1 at each of the six waves. Cronbach α across the 6 waves was 0.74, 0.77, 0.79, 0.80, 0.79, and 0.82, respectively.

Delay discounting.—Delay discounting was assessed using a hypothetical monetary choice task where the participant is asked in the context of payment for a job to select an amount between $10 and $90 that if received immediately would be equivalent to receiving $100 six months later (Green et al., 1994). Respondents are initially asked if they would accept an immediate payment of $50. Using an iterative procedure, those who accept/reject this offer are asked if they would accept an amount lower/higher than $50 in $10 decrements. Scores on this variable ranged from 10–100, which were reverse-scored such that higher scores were indicative of greater discounting. The test-retest reliability of this measure across the assessments was high (*r*'s=0.42–0.52, *p*<0.001). Delay discounting was assessed starting at wave 3 of the study; thus, we were only able to use the last four waves (waves 3–6) of data to model trajectories.

Sensation seeking.—Sensation seeking was assessed using respondents' level of agreement with four items (e.g., "I like to do frightening things"), each on a Likert-type scale ranging from 1 (strongly disagree) to 4 (strongly agree). These items were taken from the Brief Sensation Seeking Scale (Hoyle, Stephenson, Palmgreen, Lorch, & Donohew, 2002) and represented each of the four dimensions (i.e., experience seeking, boredom susceptibility, thrill/adventure seeking, and disinhibition) of the original sensation seeking scale (Zuckerman, 1971). Cronbach α across the 6 waves was 0.74, 0.73, 0.76, 0.79, 0.81, and 0.79, respectively. Participants' scores on the four items were averaged to create a composite index ranging from 1–4 for each of the six waves.

Working memory.—Individual differences in cognitive control were assessed at wave 1 using performance on the following working memory tasks that were largely nonverbal and thus not dependent on differences in reading comprehension: (1) Digit span backwards (2) Corsi-block tapping (3) Letter-two-back, and (4) a spatial working memory task. The four tasks loaded significantly on a single latent factor, with loadings ranging from 0.40–0.60. All four tasks (described below) have been linked to activation in executive control brain regions and are reliable indicators of individual differences in cognitive control abilities (Romer et al., 2009). Cognitive control is typically defined as the ability to engage in top-down control over behavior and involves active maintenance of goal-relevant information. As such, individual differences in working memory performance are a sensitive indicator of cognitive control abilities (Engle, 2002; Miller & Cohen, 2001). Other executive functions like inhibitory control (measured using Go/No-Go, Stop signal tests) are also used as indicators of cognitive control, but they tend to be highly correlated with working memory measures because successful inhibition relies on active maintenance of what is goal-relevant (Munakata et al., 2011). We chose working memory because it is a more sensitive indicator of the ability to actively maintain goal relevant information while ignoring distractions and suppressing irrelevant information. The latent working memory factor was included as a predictor of sensation seeking, acting without thinking, and delay discounting trajectories.

Digit Span.: This task tests the auditory-verbal working memory of participants by having them repeat back in reverse order, sequences of digits to the experimenter. The test was administered in standard format according to the procedures listed in the Wechsler Intelligence Scale for Children–Fourth Edition (WISC-IV) manual (Wechsler, 2003).

Corsi-block tapping.: This task is a non-verbal variant of the digit span task (Milner, 1971). Participants view a set of identical blocks that are spatially dispersed on the screen, and are individually lit up in a random sequence. Participants are asked to tap each box in the *reverse* order of the sequence of lit boxes. This task assesses spatial working memory as the visual sequence must be maintained and reversed in working memory in order to guide the response.

Letter two-back.: This task involves monitoring a series of letters for a repeat “two-back.” Letters are presented for 500 milliseconds each, separated by a 1 second interval. Participants must continually update their working memory in order to compare the current letter to the letter shape presented two trials back. This task was adapted for children by Casey et al. (1995).

Spatial Working Memory.: This self-directed computerized task requires the participant to search for hidden tokens one at a time within sets of four to eight randomly positioned boxes. Working memory skills are tapped as the participant while searching must hold in working memory the locations already checked and as tokens are found, must remember and update information about the locations of those tokens (Owen, Downes, Sahakian, Polkey, & Robbins, 1990). *Between-search* errors are made if the participant returns to a box where a token had already been found during a *previous* search sequence, and was used as a measure of working memory performance.

Substance use disorder (SUD) severity.—SUD severity was assessed at wave 6 using indicators of abuse and dependence from the DSM-4 (SAMSHA, 2011). Participants who reported use of a specific drug in the past year were asked questions pertaining to abuse (e.g., did you continue to drink alcohol even though you thought your drinking caused problems with family or friends?) and dependence (e.g., did you need to drink more alcohol than you used to in order to get the effect you wanted?) related to that specific drug from the National Survey on Drug Use and Health (NSDUH). NSDUH items are based on the DSM-4 criteria. DSM-5 has replaced the abuse and dependence classifications with SUD. We matched the DSM-5 criteria to questions from the NSDUH to generate SUD criterion scores for each substance (alcohol, marijuana, tobacco). DSM-5 defines mild disorder as meeting 2–3 criteria. Given the relatively low criterion scores in our sample (only about 25.2% of our sample reported sufficient criteria for a mild SUD), we used the continuous criterion scores for alcohol, marijuana, and tobacco as indicators for the latent SUD factor. Given the co-morbidity in early-onset SUD (Jackson, Sher, & Wood, 2000) and evidence of a single underlying factor for consumption, dependence, and abuse (Jackson et al., 2014), we used the latent SUD severity factor as our main outcome variable. Confirmatory factor analyses revealed that the SUD criterion scores for the three drugs did indeed load on a single latent factor (Khurana et al., 2017), with loadings ranging from 0.31–0.65.

Analytic Technique.—Latent Growth Class Analysis (LGCA) was used to examine potential heterogeneity in the developmental trajectories of sensation seeking, acting without thinking, and delay discounting (Muthén & Muthén, 2000). Several indices of model fit were employed to compare between models with increasing number of classes, including the Bayesian information criterion (BIC), Akaike information criterion (AIC), Lo–Mendell–Rubin likelihood ratio test (LMR-LRT), bootstrap LRT, and entropy. Final decisions were made based on evaluation of model fit criteria as well as the interpretability of the latent classes. If there was no evidence of heterogeneity, developmental trends were modeled using latent growth curve modeling (LGCM).

To test predictions regarding the trajectory groups, we examined their relation with working memory and SUD in a structural equation modeling framework. If there was evidence of significant heterogeneity in personality dimensions, then we used class membership for that particular dimension as the predictor variable. Participants were assigned to the latent class to which they had the highest likelihood of belonging based on their posterior probabilities. If there was no significant heterogeneity, then latent intercept and slope factors were used as predictors of SUD.

Results

Mean scores of sensation seeking, acting without thinking, and delay discounting across all waves are provided in Table 1, and correlations in Table 2. Mean values of acting without thinking showed an increase from waves 1–4, with a decline thereafter. Delay discounting showed a gradual decline on average across the last 4 waves, with a steeper drop from wave 5 to 6. Mean sensation seeking scores increased from wave 1–5, followed by a decline from wave 5 to 6. Overall, the average trends were similar for boys and girls, although boys reported significantly higher acting without thinking at wave 4, and significantly greater sensation seeking across all waves, as compared to girls. At a bivariate level, SUD risk was greater among males as compared to females, B(SE) = −0.18 (0.07), $p = 0.02$.

Latent Growth Modeling Results

Acting without thinking.—Analysis of latent trajectories of acting without thinking yielded clear evidence of heterogeneity with a two-class solution providing the best fit. Compared to the 3-class solution, this model had smaller log-likelihood value (−355.46 vs. 3.16) and a non-significant bootstrap likelihood ratio test (p=1.0), suggesting that the more parsimonious 2-class solution provided a better fit to the data. Visual inspection of the observed and estimated trajectories also suggested that there were only two qualitatively distinct patterns. The latent classes were well defined and distinguishable based on their unique change patterns as well as the average posterior probabilities of class membership (0.94, 0.96), and high entropy scores (0.83). The first class (44%; n=171) was labeled as “High Increasing” given that members of this group had higher scores at baseline, with a quadratic growth pattern that peaked around wave 4 and declined thereafter (see Figure 1). The “Low stable” group (56%; n=216) was characterized by lower levels at baseline and a relatively flat trajectory across the six waves. Females were less likely to be in the “High increasing” acting without thinking class as compared to males, but this difference was not significant at $p < 0.05$, B (SE) = −0.39 (0.23), $p = 0.09$. Adolescents from high SES backgrounds were significantly less likely to be in the “High increasing” acting without thinking class as compared to their peers from low SES backgrounds, B (SE) = −0.03 (0.01), $p = 0.001$. Adolescents in the “High increasing” acting without thinking class had lower working memory score, B (SE) = −0.08 (0.03), $p = 0.02$, and higher SUD risk, B (SE) = 0.12 (0.04), $p = 0.001$, as compared to those in the “Low stable” group.

Delay discounting.—Analysis of latent trajectories of delay discounting using four waves of data (waves 3–6) yielded evidence for significant heterogeneity. Specifically, the 4-class solution provided the best fit to the data, as indexed by lower AIC values (3 vs. 4 class=12459 vs. 12439) and lower BIC values (3 vs. 4 class=12505 vs. 12498), significant LMR-LRT (4 vs. 3 class=p <0.05; 3 vs. 2 class=p <0.001), significant bootstrap LRT (4 vs. 3 class=p <0.001; 3 vs. 2 class=p <0.001). The average posterior probabilities of class membership (0.83, 0.91, 0.78, 0.81) and entropy score (0.69) were reasonably high. The latent classes were well defined and had distinct change patterns. The first class (34%; n= 125) was defined as “Low Stable” given that participants in this class had low rates of delay discounting at baseline, with flat trajectories across the 4 waves. The second class (14%; n = 52) was labeled “High Stable” given that they had high delay discounting scores at baseline that remained stable across the 4 waves. The third class (14%; n = 52) was characterized by an increasing trend of delay discounting across the 4 waves and was labeled as “Low Increasing”. Finally, the fourth class (38%; n = 138) was characterized by high delay discounting scores at baseline with a gradual decline over time and was labeled as “High Declining” (See Figure 2). There were no significant gender differences in delay discounting class membership. However, SES effects were significant, with adolescents from high SES backgrounds being less likely to be in the “High stable” group, *B* (SE) = −0.07 (0.02), $p = 0.001$, and less likely to be in the “High declining” group, *B* (SE) = −0.03 (0.01), $p = 0.004$, as compared to the “Low stable” delay discounting group. Further, adolescents in the “High stable” group had lower working memory score, *B* (SE) = −0.09 (0.03), $p < 0.001$, and higher SUD risk, *B* (SE) = 0.07 (0.03), $p = 0.001$, as compared to those in the “Low stable” group.

Sensation seeking.—There was no significant heterogeneity in sensation seeking trajectories modeled using six waves of data, suggesting a more universal developmental progression in this dimension. The average trend modeled using LGCM was characterized by a quadratic curve, with a gradual increase in sensation seeking across the early years, a peak around wave 5, and a declining trend thereafter. The mean trajectory depicted in Figure 3 had significant mean intercept, linear and quadratic slope factors (M_{Int}=2.10, M_{Slp}=0.14, M_{quad}=−0.01; *p*s<0.001) and variances (Var_{Int}=0.31, Var_{Slp}=0.06, *p*s<0.001; Var_{quad}=0.001, p=0.001). The intercept and slope factors were significantly correlated, r=−0.30, p<0.001. Gender was a significant predictor of individual differences in the intercepts, *B*(SE)=−0.19 (0.05), p<0.001; β=−0.23, and slopes, *B*(SE)=−1.18 (0.37), p=0.001; β=−0.24, with females reporting lower levels than males. SES differences were not significantly associated with sensation seeking intercepts and slopes. Further, at a bivariate level, sensation seeking intercepts were positively associated with working memory, *B*(SE) = 0.09 (0.04), p=0.03, and SUD risk, *B*(SE) = 0.17 (0.07), p=0.01.

Final model with working memory and SUD

In the final model, we examined associations of observed trajectory groups of acting-without-thinking and delay discounting, and latent intercepts and slopes of sensation seeking with (a) baseline differences in working memory (as predictor) and (b) rates of SUD at final follow-up (as outcome). As shown in Figure 4, adolescents in the “High increasing” acting without thinking group, *B*(SE)= −0.43 (0.18), $p = 0.02$, and “high stable” delay discounting group, *B*(SE) = −0.80 (0.23), $p = 0.001$, had lower levels of working memory (at wave 1) suggesting that adolescents who experienced a peak or high levels of impulsivity had early indicators of weak cognitive control. Individual differences in latent intercepts of sensation seeking were positively related to working memory, *B*(SE)= 0.09 (0.04), $p<0.05$; but not the latent slopes of sensation seeking, *B*(SE)=0.003 (0.01), $p=0.78$. Controlling for gender, the association between sensation seeking intercepts and working memory dropped in significance, *B*(SE)=0.08 (0.04), $p=0.06$ (see Figure 4). Due to the high correlation between the linear and quadratic slope factors of sensation seeking ($r=-0.89$, $p<0.001$), and related model convergence issues, the variance in the quadratic factor was fixed to 0.

In the same model, the latent SUD factor was regressed on acting without thinking class membership (2 classes with “Low stable” as reference group), delay discounting class membership (4 classes with “Low Stable” as reference group), and latent intercepts and slopes of sensation seeking. Adolescents in the “High increasing” acting without thinking class were more likely to develop SUD at wave 6 as compared to those in the “Low Stable” class, *B*(SE)=0.45 (0.22), $p=0.04$. Similarly, adolescents in the “High Stable” delay discounting class had significantly higher rates of SUD as compared to the “Low Stable” reference class, *B*(SE)=0.96 (0.40), $p=0.02$. The “Low Increasing” and “High Declining” delay discounting groups were not at significantly greater risk for developing SUD as compared to the “Low Stable” reference class. We also explored delay discounting trajectory class differences by defining the “High Declining” class as the reference group considering that 38% of our sample belonged to this class, and prior research suggests a gradual decline in delay discounting trajectories. When doing so, the “High Stable” delay discounting group was still a significant predictor of SUD, *B*(SE)=0.71 (0.33), $p=0.03$, as compared to the “High Declining” reference class. The remaining delay discounting classes were not significant predictors of the SUD outcome. Individual differences in latent intercepts and slopes of sensation seeking did not predict the SUD outcome, *B*(SE)=0.40 (0.28), $p=0.14$ and *B*(SE)=0.87 (1.67), $p=0.60$, respectively. Working memory did not have a significant direct effect on the SUD outcome, *B*(SE)=−0.16 (0.16), $p=0.32$. Model effects depicted in Figure 4 were significant controlling for gender, race-ethnicity, and SES, all of which were non-significant except that Black adolescents in our sample had significantly lower SUD risk as compared to their White counterparts, *B*(SE) = −0.77 (0.26), $p = 0.003$.

We also tested alternate models where we regressed the residuals of individual drug criterion scores for alcohol, marijuana, and tobacco, on the trajectory classes for acting without thinking, delay discounting, and latent intercepts and slopes of sensation seeking. The rationale for testing these effects was that there could be unique associations of the individual criterion scores (i.e., alcohol, marijuana, tobacco criterion scores) with impulsivity and sensation seeking trajectories that were not captured by the latent factor. There were no significant associations between the impulsivity and sensation seeking trajectories and criterion score residuals suggesting that whatever longitudinal associations were present between the impulsivity trajectory classes and SUD are being captured by the latent factor. There was no left-over variance related to impulsivity or sensation seeking trajectories that was unique to a particular drug.

Discussion

Imbalance models of adolescent risk-taking (e.g., the dual systems model of Steinberg et al., 2008 and maturational imbalance model of Casey et al., 2008) attribute the rise in adolescent risk-taking to a *universal* imbalance between heightened reward sensitivity (associated with an early maturing limbic brain system) and weak cognitive control (associated with protracted development of the prefrontal brain system). Despite the popularity and heuristic appeal of these models, a number of critiques have challenged their overly-simplistic interpretations of adolescent risk taking (e.g., Pfeifer & Allen, 2012; Romer, 2010). The present study empirically tested predictions of an alternative Lifespan Wisdom Model (Romer et al., 2017), which emphasizes the exploratory nature of adolescent risk taking and challenges imbalance accounts of adolescent risk-taking by predicting that only a sub-set of adolescents experience an imbalance that is characterized by heightened reward sensitivity and weak cognitive control. For these youth, heightened sensation seeking during adolescence, a form of reward sensitivity, in combination with early weakness in cognitive control results in a peak in one type of impulsivity (acting without thinking). Another form of impulsivity (e.g., delay discounting) that is not as sensitive to heightened sensation seeking is predicted not to exhibit a peak during adolescence. Regardless, both forms of impulsivity reflect weakness in cognitive control, and it is this underlying weakness that is expected to predict maladaptive risk-taking outcomes in adolescence and beyond (Moffitt et al., 2011; Romer et al., 2017). Although sensation seeking is expected to peak during adolescence due to the rise in dopamine expression (Wahlstrom, Collins, White, & Luciana, 2010), this peak is not characteristic of an imbalance and is not expected to predict maladaptive risk-taking outcomes in adolescents apart from high levels of impulsivity.

To test this model, we identified developmental trajectories of sensation seeking and two dimensions of impulsivity (acting without thinking and delay discounting) using six waves of data from early to late adolescence and examined these trajectories in relation to baseline differences in cognitive control and a maladaptive risk outcome (substance use disorder) at final follow-up. Overall, we found significant heterogeneity in developmental trajectories of acting without thinking and delay discounting, with only some adolescents experiencing a peak or persistent high levels of impulsivity. Sensation seeking, on the other hand, showed an average curvilinear trend for all adolescents, with a peak around mid-adolescence. Sensation seeking intercepts were positively correlated with baseline working memory scores. In contrast, trajectory groups with high levels of acting without thinking and delay discounting were negatively associated with working memory and were the only groups at increased risk for substance use disorder.

Our findings are consistent with the predictions of the Lifespan Wisdom Model. In case of sensation seeking, we found a universal peak around mid-adolescence, with only quantitative deviations from the average trend. For acting without thinking and delay discounting, sub-groups with distinct change patterns were observed. Some adolescents had low levels at baseline and stayed low throughout adolescence, while others evidenced high baseline levels and escalating or peaking trajectories.

For the most part, delay discounting scores either declined or remained stable across adolescence (72%). This is consistent with the predictions of the Lifespan Wisdom Model in that the ability to engage in rational decision-making in the context of known risks and rewards shows a gradual increase across adolescence (Defoe et al., 2016). The “high stable” and “low stable” delay discounting groups may reflect early levels of impulsivity that continue to persist (Casey, 2015; Casey et al., 2011). The high stable delay discounting group was the only group at greater risk for substance use disorder. The high declining group was the largest sub-group comprised of 38% of the sample. Adolescents in this group showed a gradual decline in delay discounting, consistent with the maturation of cognitive control. The presence of a low increasing group is a novel finding – the adolescents in this group showed an increased preference for smaller immediate rewards across the waves. It is possible that their choices are not an indication of their cognitive maturity, but instead reflect choices that are rational given their contexts. For instance, Kidd and colleagues (2013) and McGuire & Kable (2013) have found that for children whose contexts are unpredictable or risky, choosing the smaller immediate reward is the rational option.

A sub-set of youth (44%) exhibited a peak in acting without thinking around mid-adolescence. This group had preexisting weakness in cognitive control at baseline, which likely made it more challenging for them to engage in impulse control (hence the peak) in the context of rising dopamine levels. This group also reported significantly higher levels of substance use disorder. The remaining 56% of the sample had low levels of acting without thinking throughout adolescence. As such, these adolescents did not experience a propensity to engage in impulsive action driven by an imbalance between the reward and control systems. They were also not at higher risk for substance use disorder. These findings are in line with the propositions of the Lifespan Wisdom Model which argues that the imbalance that characterizes maladaptive risk-taking is only experienced by a sub-set of adolescents (see also Bjork & Pardini, 2015). It is not a universal phenomenon. Our longitudinal design allowed us to test these predictions that may not always appear in studies that only examine aggregate trends. The present findings demonstrate that it is misleading to characterize adolescent risk-taking tendencies based on aggregate age trends, especially those that focus on maladaptive outcomes.

Although sensation seeking was positively related to acting without thinking, individual variation in trajectories of sensation seeking did not predict substance use disorder risk apart from acting without thinking, and baseline differences in sensation seeking were positively related to working memory. This finding is consistent with the interpretation of sensation seeking as an indicator of rising dopamine expression that leads to heightened reward sensitivity (Wahlstrom et al., 2010) but that is also a critical modulator of working memory performance (Cools & D’Esposito, 2011). These patterns are also consistent with the Lifespan Wisdom Model, which interprets the rise in sensation seeking as an indicator of developmentally normative and adaptive exploration that characterizes the adolescent period (Romer et al., 2016). Although sensation seeking can be positively associated with risk taking, such as experimentation with drugs, it tends not to lead to maladaptive outcomes like substance use progression (Khurana et al., 2015a) or dependence (Khurana et al., 2017) apart from its association with acting without thinking.

Our findings in regard to acting without thinking diverge from some studies that have reported a decline in this tendency during adolescence (Harden & Tucker-Drob, 2011; Steinberg et al., 2008). This discrepancy may be due to the use of limited measures of acting without thinking that may not have adequately captured this dimension, or reliance on a cross-sectional cohort design. For instance, although Harden and colleagues (2011) analyzed a national longitudinal data set, their sample over-represented older youth, which could be another reason why they failed to adequately capture the variability in this impulsivity dimension at younger ages. Research using longitudinal community samples (similar to ours) with robust measures has reported a quadratic trend with a peak around mid-adolescence (Collado et al., 2014; Kasen et al., 2011; White et al., 2011).

By exploring heterogeneity in sensation seeking, acting without thinking, and delay discounting change during adolescence and examining these trajectories in relation to cognitive control and a maladaptive risk outcome, our findings suggest that imbalance models overgeneralize patterns of poor impulse control that only characterize a subset of youth (see also Bjork & Pardini, 2015). Furthermore, it is common to attribute imbalance to the rise in sensation seeking, but as we find, this behavioral indicator is not related to weakness in cognitive control and the rise in sensation seeking by itself does not predict substance use disorder or other negative health outcomes (Khurana et al., 2013, 2015a, 2015b, 2017).

It is also important to note that we did not find gender differences in trajectory groups of acting without thinking and delay discounting, although we did find that males had higher rates of acting without thinking at some assessment time points. In case of sensation seeking, males reported higher intercepts and faster growth in sensation seeking than females. Other studies have similarly found higher rates of sensation seeking among males than females (Cross, Copping, & Campbell, 2011; Romer & Hennessy, 2007; Shulman et al., 2014), and higher levels of impulsivity among males than females (Côté, Tremblay, Nagin, Zoccolillo, & Vitaro, 2002; Shulman et al., 2014). Still others using community-based samples of adolescents have found no gender differences in trajectories of sensation seeking and impulsivity (Collado et al., 2014), or faster growth in sensation seeking among females than males (Littlefield, Stevens, Ellingson, King, & Jackson, 2016). These inconsistencies could be due to the variability in measures used across studies, or sample-specific effects. In terms of risk for substance use disorder, male and female adolescents tend to have similar rates (Wagner & Anthony, 2007), as was the case in our sample where we found that the effect of gender on substance use disorder risk dropped to non-significance, B(SE) = −0.16 (0.23), $p = 0.48$, controlling for other predictors.

The following limitations should be noted when interpreting current results. First, although we assessed a large and diverse community sample of adolescents from mean ages 11 – 18, our sample may not be representative of all youth, especially those from higher SES backgrounds. Second, we used substance use disorder as the risk behavior outcome given its public health significance; as such our findings cannot be generalized to other outcomes even though similar associations of sensation seeking and impulsivity have been reported with progressive substance use, and risky sexual behaviors (Khurana et al., 2015a; Khurana et al., 2015b). Finally, we could only model trajectories for delay discounting using four waves of data, given that this measure was introduced at wave 3 of the study. Nevertheless, even if there was an earlier peak in delay discounting that we did not observe, only one of the delay discounting trajectory groups predicted substance use disorder risk, suggesting that peaks in this form of impulsivity (if any) are unlikely to be a major source of later maladaptive health. Indeed, the dominant pattern of change in delay discounting is a gradual decline from childhood to early adulthood (Green et al., 1994; Steinberg et al., 2009; van den Bos et al., 2015).

Conclusion

Developmental imbalance models attribute the rise in risk-taking during adolescence to a universal imbalance between rising reward sensitivity and lagging cognitive control. An alternate Lifespan Wisdom Model distinguishes between exploratory/adaptive (e.g., sensation seeking) and maladaptive (e.g., acting-without-thinking, delay discounting) risk-taking propensities and attributes the latter to a sub-set of youth with weak cognitive control. Present findings support the Lifespan Wisdom Model’s hypothesis that the risk-taking characterized by an imbalance between the reward and control systems is a phenomenon restricted to a subset of youth. Further, these youth appear to possess this vulnerability of weak top-down behavioral control prior to adolescence (cf. Iocono et al., 2008; Moffitt et al., 2011) and continue to do so beyond this age period. The finding that only adolescents with high levels of impulsivity were at risk for substance use disorder also suggests that individual differences in cognitive control are likely to get amplified during adolescence (given the concomitant rise in reward seeking) and may play a more important role in predicting maladaptive risk-taking. Although a developmental peak in sensation seeking was observed in our sample, it was unrelated to maladaptive risk outcomes. Taken together, our results suggest that it is possible to identify youth with either emergent or early forms of impulsivity so that interventions may be targeted to the groups most at risk for negative outcomes.

Acknowledgments:

The project was supported by grants R01DA018913 and R01DA033996 from the National Institute on Drug Abuse. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health. We thank Kristin Arena, Nancy Brodsky, and Joan Giannetta for their invaluable contributions to the execution of the study.

References

Abuse Substance and Mental Health Services Administration (2011). Results from the 2010 National Survey on Drug Use and Health: Summary of National Findings (No. NSDUH Series H-41, HHS Pub No (SMA) 11–4658). Substance Abuse and Mental Health Services Administration.

Bjork JM , & Pardini DA (2015). Who are those “risk-taking adolescents”? Individual differences in developmental neuroimaging research. Developmental Cognitive Neuroscience, 11, 56–64. 10.1016/j.dcn.2014.07.008 [PubMed: 25176616]

Boyer TW , & Byrnes JP (2009). Adolescent risk-taking: Integrating personal, cognitive, and social aspects of judgment. Journal of Applied Developmental Psychology, 30(1), 23–33. 10.1016/j.appdev.2008.10.009

Casey BJ (2015). Beyond simple models of self-control to circuit-based accounts of adolescent behavior. Annual Review of Psychology, 66, 295–319. 10.1146/annurev-psych-010814-015156

Casey BJ , Cohen JD , Jezzard P , Turner R , Noll DC , Trainor RJ , Rapoport JL (1995). Activation of prefrontal cortex in children during a nonspatial working memory task with functional MRI. NeuroImage, 2(3), 221–229. 10.1006/nimg.1995.1029

Casey BJ , Somerville LH , Gotlib IH , Ayduk O , Franklin NT , Askren MK , … Shoda Y (2011). Behavioral and neural correlates of delay of gratification 40 years later. Proceedings of the National Academy of Sciences, 108(36), 14998–15003. 10.1073/pnas.1108561108

Collado A , Felton JW , MacPherson L , & Lejuez CW (2014). Longitudinal trajectories of sensation seeking, risk taking propensity, and impulsivity across early to middle adolescence. Addictive Behaviors, 39(11), 1580–1588. 10.1016/j.addbeh.2014.01.024 [PubMed: 24566195]

Cools R , & D'Esposito M (2011). Inverted-u–shaped dopamine actions on human working memory and cognitive control. Biological Psychiatry, 69(12), e113–e125. 10.1016/j.biopsych.2011.03.028 [PubMed: 21531388]

Côté S , Tremblay RE , Nagin D , Zoccolillo M , & Vitaro F (2002). The development of impulsivity, fearfulness, and helpfulness during childhood: Patterns of consistency and change in the trajectories of boys and girls. Journal of Child Psychology and Psychiatry, 43(5), 609–618. 10.1111/1469-7610.00050 [PubMed: 12120857]

Cross CP , Copping LT , & Campbell A (2011). Sex differences in impulsivity: A meta-analysis. Psychological bulletin, 137(1), 97–130. 10.1037/a0021591 [PubMed: 21219058]

Defoe IN , Dubas JS , Figner B , & van Aken MA (2015). A meta-analysis on age differences in risky decision making: Adolescents versus children and adults. Psychological bulletin, 141(1), 48–84. doi: 10.1037/a0038088 [PubMed: 25365761]

De Wit H (2009). Impulsivity as a determinant and consequence of drug use: a review of underlying processes. Addiction Biology, 14(1), 22–31. 10.1111/j.1369-1600.2008.00129.x [PubMed: 18855805]

Donohew L , Zimmerman R , Cupp PS , Novak S , Colon S , & Abell R (2000). Sensation seeking, impulsive decision-making, and risky sex: Implications for risk-taking and design of interventions. Personality and Individual Differences, 28(6), 1079–1091. 10.1016/S0191-8869(99)00158-0

Duell N , Steinberg L , Chein J , Al-Hassan SM , Bacchini D , Lei C , … Alampay LP (2016). Interaction of reward seeking and self-regulation in the prediction of risk taking: A cross-national test of the dual systems model. Developmental Psychology, 52(10), 1593–1605. 10.1037/dev0000152 [PubMed: 27598251]

Engle RW (2002). Working memory capacity as executive attention. Current Directions in Psychological Science, 11(1), 19–23. 10.1111/1467-8721.00160

Eysenck SBG , Easting G , & Pearson PR (1984). Age norms for impulsiveness, venturesomeness and empathy in children. Personality and Individual Differences, 5(3), 315–321. 10.1016/0191-8869(84)90070-9

Green L , Fry AF , & Myerson J (1994). Discounting of delayed rewards: A life-span comparison. Psychological Science, 5(1), 33–36. 10.1111/j.1467-9280.1994.tb00610.x

Harden KP , & Tucker-Drob EM (2011). Individual differences in the development of sensation seeking and impulsivity during adolescence: Further evidence for a dual systems model. Developmental Psychology, 47(3), 739–746. 10.1037/a0023279 [PubMed: 21534657]

Hoyle RH , Stephenson MT , Palmgreen P , Lorch EP , & Donohew RL (2002). Reliability and validity of a brief measure of sensation seeking. Personality and Individual Differences, 32(3), 401–414. 10.1016/S0191-8869(01)00032-0

Iacono WG , Malone SM , & McGue M (2008). Behavioral disinhibition and the development of early-onset addiction: Common and specific influences. Annual Review of Clinical Psychology, 4(1), 325–348.10.1146/annurev.clinpsy.4.022007.141157

Jackson KM , Bucholz KK , Wood PK , Steinley D , Grant JD , & Sher KJ (2014). Towards the characterization and validation of alcohol use disorder subtypes: integrating consumption and symptom data. Psychological Medicine, 44(01), 143–159. 10.1017/S0033291713000573 [PubMed: 23551901]

Jackson KM , Sher KJ , & Wood PK (2000). Trajectories of Concurrent Substance Use Disorders: A Developmental, Typological Approach to Comorbidity. Alcoholism: Clinical and Experimental Research, 24(6), 902–913. 10.1111/j.1530-0277.2000.tb02072.x

Kasen S , Cohen P , & Chen H (2011). Developmental course of impulsivity and capability from age 10 to age 25 as related to trajectory of suicide attempt in a community cohort. Suicide and Life-Threatening Behavior, 41(2), 180–192. 10.1111/j.1943-278X.2011.00017.x [PubMed: 21342218]

Khurana A , Romer D , Betancourt LM , Brodsky NL , Giannetta JM , & Hurt H (2013). Working memory ability predicts trajectories of early alcohol use in adolescents: the mediational role of impulsivity. Addiction, 108(3), 506–515. 10.1111/add.12001 [PubMed: 23033972]

Khurana A , Romer D , Betancourt LM , Brodsky NL , Giannetta JM , & Hurt H (2015a). Experimentation versus progression in adolescent drug use: A test of an emerging neurobehavioral imbalance model. Development and Psychopathology, 27(3), 901–913. 10.1017/S0954579414000765 [PubMed: 25154377]

Khurana A , Romer D , Betancourt LM , Brodsky NL , Giannetta JM , & Hurt H (2015b). Stronger working memory reduces sexual risk taking in adolescents, even after controlling for parental influences. Child Development, 86(4), 1125–1141. 10.1111/cdev.12383 [PubMed: 26081926]

Khurana A , Romer D , Betancourt LM , & Hurt H (2017). Working memory ability and early drug use progression as predictors of adolescent substance use disorders. Addiction. 10.1111/add.13792

Khurana A , Romer D , Hurt H , Betancourt L , Brodsky NL , & Giannetta JM (2012). Early adolescent sexual debut: The mediating role of working memory ability, sensation seeking and impulsivity. Developmental Psychology, 48(5), 1416–1428. 10.1037/a0027491 [PubMed: 22369334]

Kidd C , Palmeri H , & Aslin RN (2013). Rational snacking: Young children’s decision-making on the marshmallow task is moderated by beliefs about environmental reliability. Cognition, 126(1), 109–114.10.1016/j.cognition.2012.08.004 [PubMed: 23063236]

Littlefield AK , Stevens AK , Ellingson JM , King KM , & Jackson KM (2016). Changes in negative urgency, positive urgency, and sensation seeking across adolescence. Personality and individual differences, 90, 332–337. 10.1016/j.paid.2015.11.024 [PubMed: 26949280]

Madden GJ , & Bickel WK (Eds.). (2010). Impulsivity: the behavioral and neurological science of discounting. Washington, DC: American Psychological Association.

Magid V , MacLean MG , & Colder CR (2007). Differentiating between sensation seeking and impulsivity through their mediated relations with alcohol use and problems. Addictive Behaviors, 32(10), 2046–2061. 10.1016/j.addbeh.2007.01.015 [PubMed: 17331658]

Martin CA , Kelly TH , Rayens MK , Brogli BR , Brenzel A , Smith WJ , & Omar HA (2002). Sensation seeking, puberty, and nicotine, alcohol, and marijuana use in adolescence. Journal of the American Academy of Child and Adolescent Psychiatry, 41(12), 1495–1502. 10.1097/00004583-200212000-00022 [PubMed: 12447037]

Maslowsky J , Keating DP , Monk CS , & Schulenberg J (2011). Planned versus unplanned risks: Neurocognitive predictors of subtypes of adolescents’ risk behavior. International Journal of Behavioral Development, 35(2), 152–160. 10.1177/0165025410378069 [PubMed: 22679340]

McGuire JT , & Kable JW (2013). Rational temporal predictions can underlie apparent failures to delay gratification. Psychological Review, 120(2), 395–410. 10.1037/a0031910 [PubMed: 23458085]

Miller EK , & Cohen JD (2001). An integrative theory of prefrontal cortex function. Annual Review of Neuroscience, 24(1), 167–202. 10.1146/annurev.neuro.24.1.167

Milner B (1971). Interhemispheric differences in the localization of psychological processes in man. British Medical Bulletin, 27(3), 272–277. [PubMed: 4937273]

Moffitt TE , Arseneault L , Belsky D , Dickson N , Hancox RJ , Harrington H , …et al. (2011). A gradient of childhood self-control predicts health, wealth, and public safety. Proceedings of the National Academy of Sciences, 108(7), 2693–2698.

Munakata Y , Herd SA , Chatham CH , Depue BE , Banich MT , & O’Reilly RC (2011). A unified framework for inhibitory control. Trends in cognitive sciences, 15(10), 453–459. 10.1016/j.tics.2011.07.011 [PubMed: 21889391]

Murty VP , Calabro F , & Luna B (2016). The role of experience in adolescent cognitive development: Integration of executive, memory, and mesolimbic systems. Neuroscience & Biobehavioral Reviews, 70, 46–58. 10.1016/j.neubiorev.2016.07.034 [PubMed: 27477444]

Muthén B , & Muthén LK (2000). Integrating person-centered and variable-centered analyses: Growth mixture modeling with latent trajectory classes. Alcoholism: Clinical and Experimental Research, 24(6), 882–891. 10.1111/j.1530-0277.2000.tb02070.x

Owen AM , Downes JJ , Sahakian BJ , Polkey CE , & Robbins TW (1990). Planning and spatial working memory following frontal lobe lesions in man. Neuropsychologia, 28(10), 1021–1034. 10.1016/0028-3932(90)90137-D [PubMed: 2267054]

Patton JH , Stanford MS , & Barratt ES (1995). Factor structure of the barratt impulsiveness scale. Journal of Clinical Psychology, 51(6), 768–774. 10.1002/1097-4679 [PubMed: 8778124]

Quinn PD , & Harden KP (2013). Differential changes in impulsivity and sensation seeking and the escalation of substance use from adolescence to early adulthood. Development and Psychopathology, 25(s1), 223–239. 10.1017/S0954579412000284 [PubMed: 22824055]

Reynolds B (2006). A review of delay-discounting research with humans: Relations to drug use and gambling. Behavioural pharmacology, 17(8), 651–667. doi: 10.1097/FBP.0b013e3280115f99 [PubMed: 17110792]

Romer AL , Reyna VF , & Pardo ST (2016). Are rash impulsive and reward sensitive traits distinguishable? A test in young adults. Personality and individual differences, 99, 308–312. 10.1016/j.paid.2016.05.027 [PubMed: 28867853]

Romer D (2010). Adolescent risk taking, impulsivity, and brain development: Implications for prevention. Developmental Psychobiology, 52(3), 263–276. 10.1002/dev.20442 [PubMed: 20175097]

Romer D , Betancourt L , Giannetta JM , Brodsky NL , Farah M , & Hurt H (2009). Executive cognitive functions and impulsivity as correlates of risk taking and problem behavior in preadolescents. Neuropsychologia, 47(13), 2916–2926. 10.1016/j.neuropsychologia.2009.06.019 [PubMed: 19560477]

Romer D , Betancourt LM , Brodsky NL , Giannetta JM , Yang W , & Hurt H (2011). Does adolescent risk taking imply weak executive function? A prospective study of relations between working memory performance, impulsivity, and risk taking in early adolescence. Developmental Science, 14(5), 1119–1133. 10.1111/j.1467-7687.2011.01061.x [PubMed: 21884327]

Romer D , Duckworth AL , Sznitman S , & Park S (2010). Can adolescents learn self-control? Delay of gratification in the development of control over risk taking. Prevention Science, 11(3), 319–330. 10.1007/s11121-010-0171-8 [PubMed: 20306298]

Romer D , & Hennessy M (2007). A biosocial-affect model of adolescent sensation seeking: the role of affect evaluation and peer-group influence in adolescent drug use. Prevention Science, 8(2), 89–101. 10.1007/s11121-007-0064-7 [PubMed: 17286212]

Romer D , Reyna VF , & Satterthwaite TD (2017). Beyond stereotypes of adolescent risk taking: Placing the adolescent brain in developmental context. Developmental Cognitive Neuroscience, In press.

Schafer JL , & Graham JW (2002). Missing data: Our view of the state of the art. Psychological Methods, 7(2), 147–177. 10.1037/1082-989X.7.2.147 [PubMed: 12090408]

Shamosh NA , Deyoung CG , Green AE , Reis DL , Johnson MR , Conway AR , Gray JR (2008). Individual differences in delay discounting: Relation to intelligence, working memory, and anterior prefrontal cortex. Psychological Science, 19(9), 904–11. 10.1111/j.1467-9280.2008.02175.x [PubMed: 18947356]

Shulman EP , Harden KP , Chein JM , & Steinberg L (2014). Sex differences in the developmental trajectories of impulse control and sensation-seeking from early adolescence to early adulthood. Journal of Youth and Adolescence, 1–17. 10.1007/s10964-014-0116-9

Shulman EP , Smith AR , Silva K , Icenogle G , Duell N , Chein J , & Steinberg L (2016). The dual systems model: Review, reappraisal, and reaffirmation. Developmental Cognitive Neuroscience, 17, 103–117. 10.1016/j.dcn.2015.12.010 [PubMed: 26774291]

Somerville LH , & Casey B (2010). Developmental neurobiology of cognitive control and motivational systems. Current Opinion in Neurobiology, 20(2), 236–241. 10.1016/j.conb.2010.01.006 [PubMed: 20167473]

Spear L (2010). The Behavioral Neuroscience of Adolescence. New York, NY: W. W. Norton & Company.

Steinberg L , Albert D , Cauffman E , Banich M , Graham S , & Woolard J (2008). Age differences in sensation seeking and impulsivity as indexed by behavior and self-report: evidence for a dual systems model. Developmental Psychology, 44(6), 1764–1778. 10.1037/a0012955 [PubMed: 18999337]

Steinberg L , Graham S , O'Brien L , Woolard J , Cauffman E , & Banich M (2009). Age differences in future orientation and delay discounting. Child Development, 80(1), 28–44. 10.1111/j.1467-8624.2008.01244.x [PubMed: 19236391]

Steinberg L , Icenogle G , Shulman EP , Breiner K , Chein J , Bacchini D , … Takash HMS . (2017). Around the world, adolescence is a time of heightened sensation seeking and immature self-regulation. Developmental Science, n/a-n/a. 10.1111/desc.12532

Telzer EH (2016). Dopaminergic reward sensitivity can promote adolescent health: A new perspective on the mechanism of ventral striatum activation. Developmental Cognitive Neuroscience, 17, 57–67. 10.1016/j.dcn.2015.10.010 [PubMed: 26708774]

van den Bos W , Rodriguez CA , Schweitzer JB , & McClure SM (2015). Adolescent impatience decreases with increased frontostriatal connectivity. Proceedings of the National Academy of Sciences, 112(29), E3765–E3774. 10.1073/pnas.1423095112

Wagner FA , & Anthony JC (2007). Male–female differences in the risk of progression from first use to dependence upon cannabis, cocaine, and alcohol. Drug & Alcohol Dependence, 86(2), 191–198. 10.1016/j.drugalcdep.2006.06.003 [PubMed: 17029825]

Wahlstrom D , Collins P , White T , & Luciana M (2010). Developmental changes in dopamine neurotransmission in adolescence: Behavioral implications and issues in assessment. Brain and Cognition, 72(1), 146 10.1016/j.bandc.2009.10.013 [PubMed: 19944514]

Wechsler D (2003). Wechsler Intelligence Scale for Children® — Fourth Edition (WISC®-IV). San Antonio, TX: The Psychological Corporation.

White HR , Marmorstein NR , Crews FT , Bates ME , Mun EY , & Loeber R (2011). Associations between heavy drinking and changes in impulsive behavior among adolescent boys. Alcoholism: Clinical and Experimental Research, 35(2), 295–303. 10.1111/j.1530-0277.2010.01345.x

Whiteside SP , & Lynam DR (2001). The Five Factor Model and impulsivity: Using a structural model of personality to understand impulsivity. Personality and Individual Differences, 30(4), 669–689. 10.1016/S0191-8869(00)00064-7

Wilson M , & Daly M (2006). Are juvenile offenders extreme future discounters? Psychological Science, 17(11), 989–994. 10.1111/j.1467-9280.2006.01817.x [PubMed: 17176432]

Zuckerman M (1971). Dimensions of sensation seeking. Journal of Consulting and Clinical Psychology, 36(1), 45–52. 10.1037/h0030478

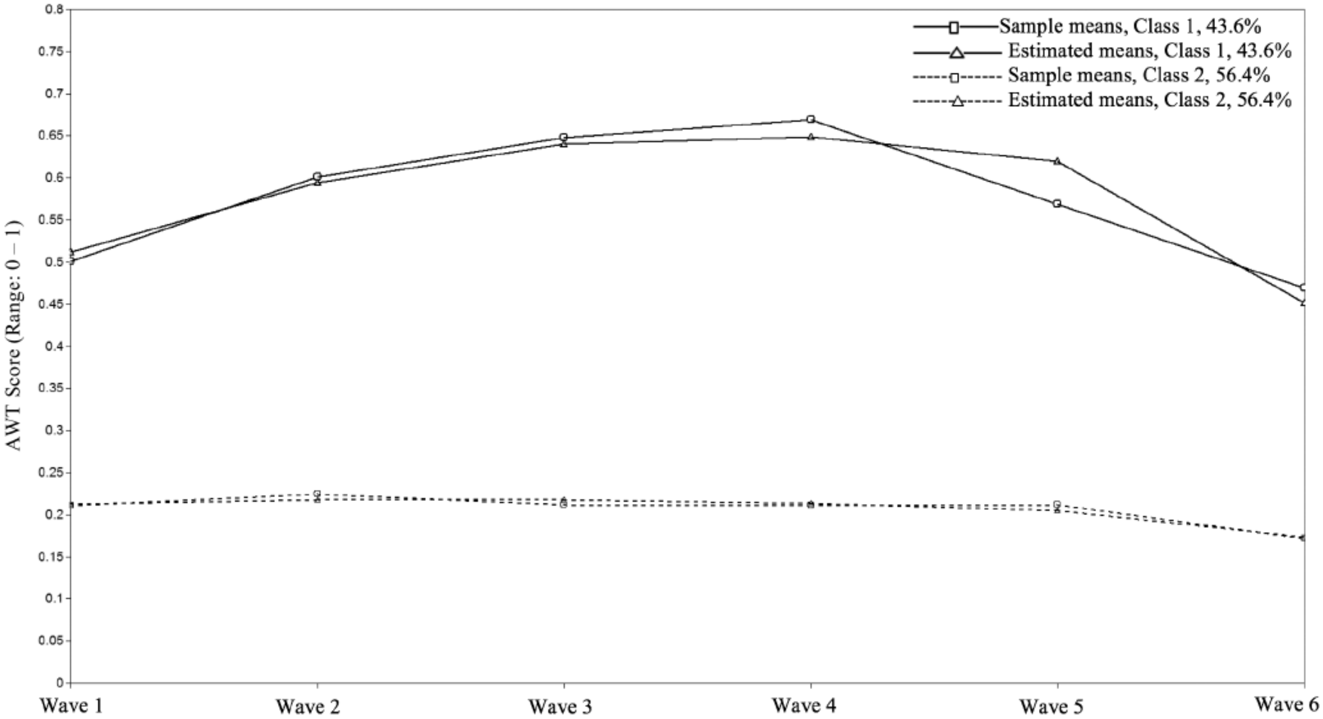

Figure 1.

Latent trajectory classes of Acting Without Thinking (AWT) from waves 1–6.

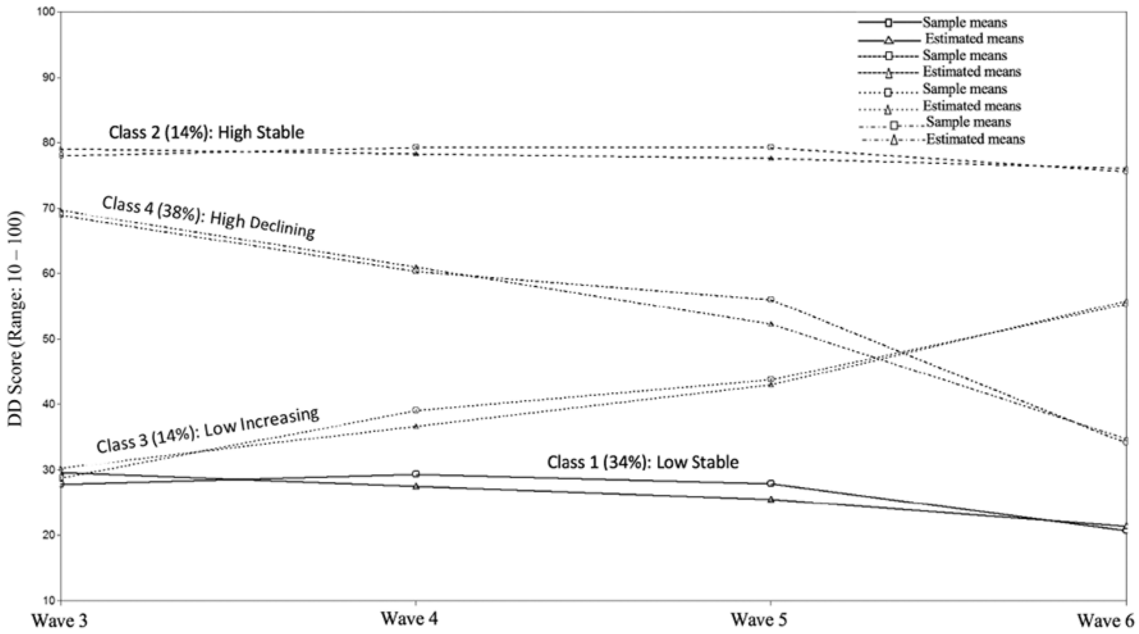

Figure 2.

Latent trajectory classes of Delay Discounting (DD) from waves 3–6.

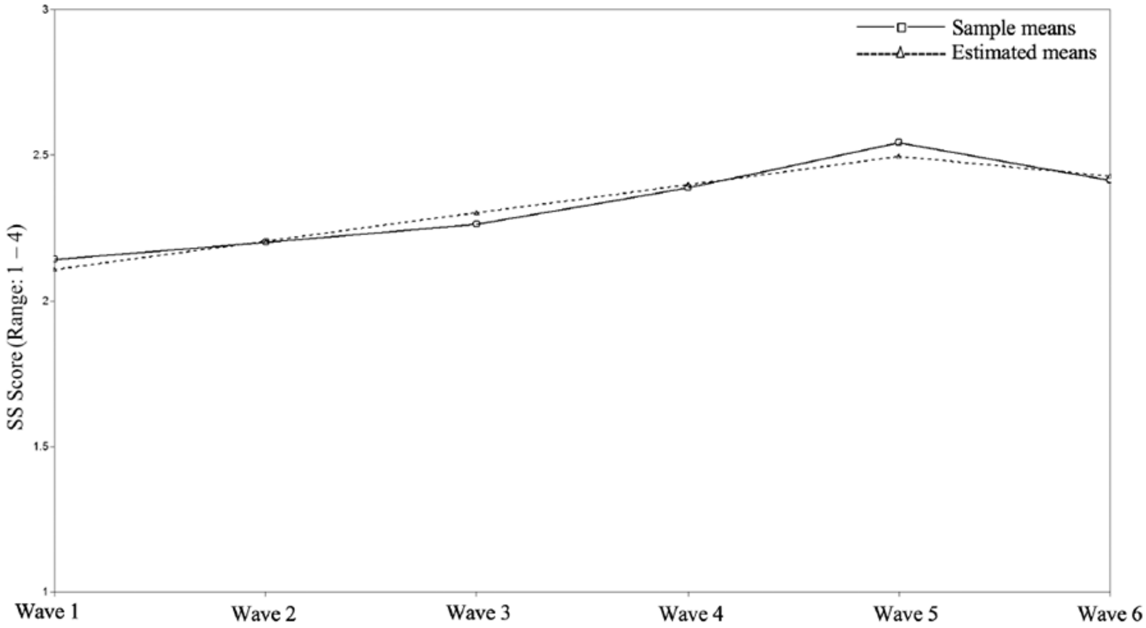

Figure 3.
Latent trajectories of Sensation Seeking (SS) from waves 1–6.

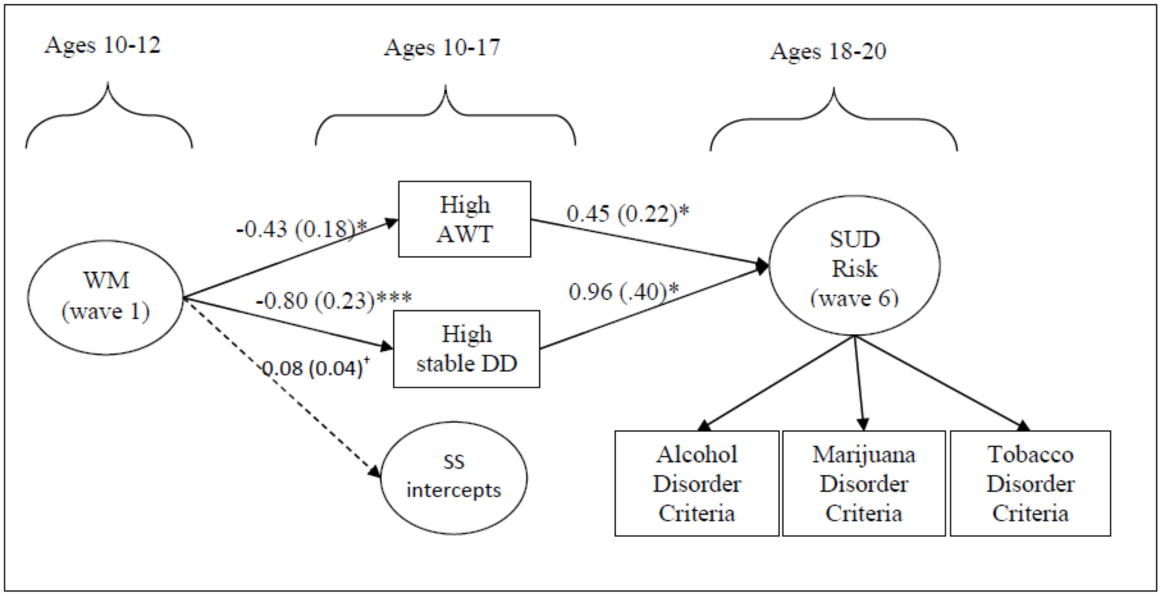

Figure 4.

Final model showing significant pathways of influence with WM and SUD in relation to latent trajectories of AWT, DD, and SS. *Note*. WM = Working Memory; AWT = Acting Without Thinking; DD = Delay Discounting; SUD = Substance Use Disorder. $^*p<0.05$, $^\dagger p=0.06$. Sensation seeking slope was included in model but it was not related to working memory or SUD risk.

Table 1.

Mean (SD) scores of AWT, SS, and DD across the six waves.

PTS waves (*N*; mean ages in years)	**AWT (mean, sd)**			**SS (mean, sd)**			**DD (mean, sd)**		
	Full Sample	**Boys**	**Girls**	**Full Sample**	**Boys**	**Girls**	**Full Sample**	**Boys**	**Girls**
Wave 1 (387; 11.41±0.88)	0.34 (0.26)	0.35 (0.27)	0.33 (0.26)	2.14 (0.77)	**2.26 (0.81)**	**2.03 (0.71)**	–	–	–
Wave 2 (373; 12.61±0.89)	0.39 (0.28)	0.42 (0.29)	0.37 (0.27)	2.21 (0.72)	**2.32 (0.75)**	**2.10 (0.69)**	–	–	–
Wave 3 (366; 13.52±0.95)	0.40 (0.30)	0.42 (0.29)	0.39 (0.30)	2.27 (0.77)	**2.36 (0.83)**	**2.17 (0.70)**	50.58 (29.10)	51.66 (29.04)	49.25 (29.08)
Wave 4 (365; 14.45±0.95)	0.41 (0.31)	**0.46 (0.30)**	**0.36 (0.30)**	2.39 (0.76)	**2.54 (0.76)**	**2.26 (0.74)**	49.28 (28.76)	51.28 (29.29)	47.4 (28.29)
Wave 5 (335; 15.75±0.95)	0.36 (0.29)	0.39 (0.30)	0.34 (0.28)	2.55 (0.81)	**2.70 (0.78)**	**2.42 (0.81)**	47.99 (28.44)	50.65 (27.57)	46.14 (29.05)
Wave 6 (291; 18.41±0.64)	0.30 (0.29)	0.33 (0.30)	0.28 (0.28)	2.43 (0.77)	**2.65 (0.73)**	**2.23 (0.75)**	38.34 (23.25)	40.30 (22.07)	36.56 (24.24)

Note. AWT=Acting Without Thinking; SS=Sensation Seeking; DD=Delay Discounting. Gender differences significant at $p<0.05$ are highlighted in bold. Higher values signify greater AWT, DD, and SS respectively. DD was assessed starting at wave 3 of the study.

Table 2.

Correlation matrix of repeated assessments of sensation seeking and impulsivity.

	AWT1	AWT2	AWT3	AWT4	AWT5	AWT6	SS1	SS2	SS3	SS4	SS5	SS6	DD3	DD4	DD5	DD6
AWT1	–															
AWT2	0.54	–														
AWT3	0.48	0.62	–													
AWT4	0.48	0.59	0.69	–												
AWT5	0.37	0.42	0.53	0.64	–											
AWT6	0.30	0.41	0.44	0.51	0.54	–										
SS1	0.38	0.25	0.12	0.21	0.19	0.17	–									
SS2	0.29	0.38	0.25	0.30	0.14	0.11	0.55	–								
SS3	0.29	0.32	0.36	0.37	0.15	0.13	0.42	0.62	–							
SS4	0.30	0.35	0.28	0.44	0.26	0.17	0.46	0.60	0.68	–						
SS5	0.24	0.24	0.19	0.33	0.28	0.26	0.40	0.41	0.57	0.67	–					
SS6	0.12	0.12	0.11	0.20	0.15	0.24	0.32	0.41	0.53	0.56	0.64	–				
DD3	0.14	0.11	0.14	0.18	0.14	0.12	0.11	0.04	0.03	0.02	−0.03	−0.03	–			
DD4	0.12	0.10	0.12	0.16	0.15	0.04	0.06	−0.05	−0.03	−0.04	−0.07	−0.12	0.43	–		
DD5	0.15	0.09	0.14	0.16	0.17	0.15	0.03	−0.10	−0.09	−0.08	−0.09	−0.13	0.40	0.52	–	
DD6	0.18	0.09	0.09	0.16	0.07	0.19	0.08	−0.01	0.04	0.03	−0.04	−0.02	0.31	0.35	0.42	–

Note. AWT1-AWT6=Acting Without Thinking (wave1–6); SS1-SS6=Sensation Seeking (wave1–6); DD3-DD6=Delay Discounting (wave3–6). All values significant at $p < 0.05$ except for those shaded in grey.