Published in final edited form as:
J Res Adolesc. 2013 June 1; 23(2): 345–356. doi:10.1111/jora.12001.

Trajectories of Reinforcement Sensitivity During Adolescence and Risk for Substance Use

Craig R. Colder[1], **Larry W. Hawk Jr.**[1], **Liliana J. Lengua**[2], **William Wiezcorek**[3], **Rina Das Eiden**[1], and **Jennifer P. Read**[1]

[1]University at Buffalo

[2]University of Washington

[3]Buffalo State University

Abstract

Developmental neuroscience models suggest that changes in responsiveness to incentives contribute to increases in adolescent risk behavior, including substance use. Trajectories of sensitivity to reward (SR) and sensitivity to punishment (SP) were examined and tested as predictors of escalation of early substance use in a community sample of adolescents (N=765, mean baseline age 11.8 years, 54% female). SR and SP were assessed using a laboratory task. Across three annual assessments, SR increased, and rapid escalation was associated with increases in substance use. SP declined and was unrelated to substance use. Findings support contemporary views of adolescent brain development, and suggest that early adolescent substance use is motivated by approach responses to reward, rather than failure to avoid potential aversive consequences.

Keywords

adolescence; substance use; reward sensitivity; punishment sensitivity; trajectories

---

Adolescence is a time when many youth experiment with risky behaviors often with significant negative consequences (Steinberg & Monahan, 2007). Affective and motivational processes that emerge from maturational brain changes and a shift in incentive salience may play a key role in the etiology of adolescent risk behavior (Chambers, Taylor, & Potenza, 2003). Consistent with this general framework, adolescence is a period when substance use is typically initiated and escalates (Chen & Kandel, 1995; Colder, Campbell, Ruel, Flay, & Richardson, 2002). Many models of addiction emphasize the role of incentives via positive and negative reinforcement (e.g., Cox & Klinger, 2002; Koob & Volkow, 2010). Although these lines of research clearly suggest that normative changes in reward and punishment sensitivity increase the propensity to engage in drug use during adolescence, no studies have explicitly tested these associations. This is a notable omission given the importance of the dynamics of incentive salience for models of risk behavior and preventive interventions. The goal of the current study was to fill this critical gap by examining trajectories of reward and punishment sensitivity and their association with the emergence of substance use in early adolescence.

Correspondence regarding this article should be directed to Craig Colder, Department of Psychology, Park Hall, SUNY at Buffalo, Buffalo, NY 14260-4110. ccolder@buffalo.edu.

Changes in dopaminergic systems in adolescence are believed to underlie increases in the salience of reward (Chambers et al., 2003). These changes in incentive salience may in turn contribute to increases in risky behavior (Casey, Jones & Hare, 2008; Somerville, Jones, & Casey, 2010). From an evolutionary perspective, these changes may promote adolescent young leaving their home territory to establish non-familial bonds (and find potential mates) and independence, but they may also contribute to the emergence and escalation of substance use.

An increasing body of literature points to adolescence as a critical period of development and change in certain traits, many of which may be highly relevant to risk behavior and substance use (Blonigen, Carlson, Hicks, Krueger, & Iacono, 2008; Gullo & Dawe, 2008; Macpherson et al., 2010), including sensitivity to reward (SR). Several lines of evidence suggest that SR (sensitivity to positive incentives that increases the propensity for approach behavior) increases during adolescence. For instance, adolescents are more behaviorally and emotionally reactive to monetary incentives compared to adults (Ernst et al, 2005; Hardin, Schroth, Pine, & Ernst, 2007); they are more sensitive to positive feedback during affective decision making compared to adults and children (Cauffman et al., 2010); and they process reward and risk information in a way that increases the likelihood of risky behavior (Bjork, Smith, Danube, & Hommer, 2007; Van Leijenhorst et al., 2010).

Longitudinal studies of personality development also suggest that SR increases in adolescence. SR is thought to give rise to broader personality traits of sensation seeking (i.e., the need for varied and novel experiences and willingness to take risks for such experiences) and extraversion (dominance, sociability, positive emotionality, gregariousness) (Gullo & Dawe, 2008; Smillie, Pickering, & Jackson, 2006), and changes in these traits provide indirect evidence for changes in SR. Several studies have shown that sensation seeking increases during adolescence (Crawford, Pentz, Chou, Li, & Dwyer, 2003; Steinberg, 2008; Zuckerman, 1994). Extraversion may also increase during adolescence, but the evidence is mixed, and it appears that increases in extraversion are limited to the narrow-band facet of social dominance (Klimstra, Hale, Raaijmakers, Branje, & Meeus, 2009; Roberts, Walton, & Viechtbauer, 2006). Thus, it may be useful to focus on narrow-band individual differences, such as SR, to understand adolescent risk taking. Indeed, several authors have suggested the importance of focusing on narrow-band personality dimensions when considering personality development (e.g., Roberts et al., 2006; Wright, Pincus, & Lenzenweger, in press). To our knowledge no longitudinal studies have examined normative developmental trajectories of SR. This is a notable omission given the theoretical importance of reward sensitivity in developmental models of adolescent risk behavior. In the current study, a laboratory task was used to assess SR repeatedly over time and trajectories of SR were examined in a large unselected community sample of early adolescents.

With respect to drug use, there has been consistent evidence that SR is associated with adolescent substance use (Knyazev, 2004; Lopez et al., 2012; O'Connor & Colder, 2005). The intake of many drugs of abuse directly lead to the experience of euphoria (Koob & Le Moal, 2006), and using drugs because it is fun and exciting is a common motivation of drug use among adolescents (Charbol, Ducongè, Casas, Roura, & Carey, 2005; Kuntsche, Stewart, & Cooper, 2008). Adolescents characterized by high levels of SR may find the potential euphoric effects of drugs particularly appealing, increasing the likelihood of use. Importantly, existing studies focus on adolescents who are already engaged in substance use, this raises a number of interpretive concerns, including the possibility that frequent exposure to drugs may alter SR (Volkow, Fowler, & Wang, 2003). Accordingly, the current study tested the association between changes in SR and substance use in early adolescents who are in the early stages of initiation of use.

Although accumulated evidence increasingly suggests that adolescent risk behavior is reward driven, most incentive-based models of behavior emphasize the role of both reward and punishment in regulating behavior (e.g., Cloninger, 1987; Gray & McNaughton, 2000). Moreover, substance use is associated with potential benefits (e.g., euphoria) as well as aversive consequences (e.g., feeling sick, physical injury, and legal problems), and both are thought to be involved in regulation of substance use (Cox & Klinger, 2002; Millstein & Halpern-Felsher, 2002). Thus, sensitivity to punishment (e.g., sensitivity to potential aversive consequences that increases the propensity to inhibit behavior and experience emotional distress) may also play a role in adolescent substance use behavior.

In contrast to SR, much less research has considered potential age-related changes in sensitivity to punishment (SP). Cauffman et al. (2010) examined the influence of both reward and punishment in affective decision making in adolescents and adults. Compared to adults, adolescents were faster at making approach oriented decisions and slower to avoid risky decisions. From the perspective of incentive sensitivity, these findings suggest that adolescents may be characterized by greater sensitivity to reward and weaker sensitivity to punishment relative to adults.

Evidence for a link between SP and adolescent substance use has been mixed with some studies suggesting that SP is associated with both low (e.g., O'Connor et al., 2008; Simons & Arens, 2007) and high (e.g., Lopez et al, 2012) levels of substance use. Other studies have shown no association (e.g., Knyazev, 2004; O'Connor & Colder, 2005). The inconsistency of findings suggests that SP is weakly associated with substance use, and that this relationship is complex and potentially moderated by other factors (Genovese & Wallace, 2007; Wardell, O'Connor, Read, & Colder, 2011). The current study examined potential changes in SP during early adolescence, and how SP is associated with substance use. However, given the mixed findings regarding SP and the dearth of studies, no specific hypotheses are offered.

In summary, a hallmark feature of adolescence is an increase in a variety of risk behaviors, including substance use. Current developmental neuroscience accounts suggest that changes in responsiveness to incentives may partly account for increases in substance use during this period. The delineation of mechanisms which may confer risk for initiation and escalation of substance use is important as it may aid in both early identification of high risk youth and prevention efforts. Yet these processes seldom have been studied in early adolescence with long-term longitudinal designs. The aim of the current study was to model trajectories of SR and SP in a large community sample of early adolescents. The focus was on early adolescents because this is a critical time of initiation and the beginning of escalation of substance use (Chen & Kandel, 1995; Colder, Campbell, et al., 2002; Colder, Mehta, et al., 2001). It was hypothesized that SR would increase and that more rapid increases would be associated with a higher likelihood of substance use. Although changes in SP were considered, given the state of the literature, no hypotheses were offered about SP.

Method

Participants

Recruitment—Participants were taken from two longitudinal studies examining risk and protective factors for adolescent substance use initiation. Both samples were recruited utilizing a random-digit-dial (RDD) sample of telephone numbers from ASDE Survey Sampler, Inc., that was generated for Erie County, New York. Calls were made by trained telephone interviewers utilizing scripts that explained the nature of study participation, eligibility criteria (an English speaking child without any physical impairments or cognitive deficits that would preclude completion of the interview and a caregiver willing to participate), and the level of compensation for participation. Children were required to be between the ages 10 and 12 years old at the time of recruitment for the first sample and between the ages of 11 and 12 at the time of recruitment for the second sample. Recruitment began in December 2006 and April 2007 for samples one and two, respectively, and ended for both samples in February 2009. Participation rates were 48.7% and 52.1%, which are similar to the rates in population-based studies that require extended and extensive levels of subject involvement (Galea & Tracy, 2007), such as the Behavioral Risk Factor Surveillance Survey (about 50%) and the Survey of Consumer Attitudes (48%).

Description—Sample one included 378 families. Children (52% female) were 10-13 years old (mean = 11.1, SD = .85) at the first assessment. The majority were White and non-Hispanic (75%), 15% were Black or African-American, 3% were Hispanic, 2% were Asian or Pacific Islander, and 5% reported another ethnicity. Most children were from two parent families (72%). Median family income was $60,000 and 6.0% of the families received public assistance. The second sample included 387 families. Children (55% female) were 11-13 years old (mean = 11.6, SD = .55) at the first assessment. The majority were White/non-Hispanic (83%), 9% were Black/African-American, 2% were Hispanic, 1% were Asian/Pacific Islander, and 5% reported another race or ethnicity. Most children were from two parent families (75%). Median family income was $70,000 and 6.2% of the families received public assistance. The range of ages at the first assessment differed from the range of ages at recruitment because some participants had a birthday between recruitment and first assessment.

Procedure

Procedures were the same for both samples. Three annual assessments were completed in university research offices. After completing the consent (caregiver) and assent (adolescent) procedures, the adolescent and caregiver were taken to separate rooms to enhance confidentiality and privacy. Questionnaires were read aloud and responses were entered directly into a computer by the interviewer. Questions deemed "sensitive" (i.e., questions assessing substance use) were read aloud by the interviewer, but inputted directly into the computer by the adolescent to increase confidentiality. Each interview took approximately 2½ hours to complete. Interview procedures were the same at each wave of the study. Adolescents received a small prize (valued at $5 to $15) for their participation, and families were compensated $75 for the first assessment, $85 for the second assessment, and $100 or $125 for the third assessment for samples one and two, respectively. Most subsequent assessments (90%) were done within ± 2 months of the year anniversary of the prior assessment. Aggregating across samples, mean age at the first, second, and third assessments was 11.8 (SD=.79), 12.9 (SD=.79), and 13.9 (SD=.79), respectively.

Retention was strong with attrition from Wave 1 to Wave 3 of 7% and 4.4% in Samples 1 and 2, respectively. Combining the samples yielded a total sample of 765 with a 94% retention rate. In the combined sample, differences between participants with and without missing data on demographic and Wave 1 study variables were tested using chi-square and ANOVA. No statistically reliable differences were found (all ps > .25) for gender, age, family income, ethnicity, and parent education, and effect sizes were all small (phi coefficients < .02 and $\eta^2 < .01$). There was a statistically reliable difference between groups on Wave 1 adolescent smoking rates (χ^2 (1, 765) = 6.49, p < .05). Smoking was more prevalent among those with missing data (8% for the group with missing data and 2% for the group without missing data), but this difference was small (phi coefficient = .09). There was no statistically reliable difference on wave 1 adolescent alcohol use, and reaction times from the wave 1 PSRTT-CR (all ps > .35) and these differences were small (phi coefficient < .01, $\eta^2 < .01$). These results and the low attrition rate suggest that missing data had little or no impact on study findings. The total rate of missing data (missing values / total number of possible data values) for variables used in this study was < 1% at Wave 1, and 6% at Waves 2 and 3.

Measures

The laboratory task was programmed using E-Prime Version 2.0 and administered on a PC with 43-cm flat screen color monitor. Adolescents used a Psychology Software Tools Inc., response box, and earned points during the task, which were redeemed for a prize at the end of the session. Questionnaires were administered using MediaLab software (Jarvis, 2002).

Point Scoring Reaction Time Task for Children- revised (PSRTT-CR)—The PSRTT-CR (Colder et al., 2011) is based on a similar task developed for adults (Ávila, 2001), and assesses SP and SR in youth. The task starts with a practice block followed by four experimental blocks presented in a fixed order- no reward, reward, punishment, and post-punishment. Fixed order was used to examine change in behavior with the introduction of reward (SR), and how cues previously associated with punishment inhibited behavior in the post-punishment block (SP). The stimuli included a colored circle presented above a two-digit number. The participant's task was to discriminate odd and even numbers, and prior to each block they were asked to respond as quickly as possible. The practice block included 20 trials, and adolescents had to achieve 70% accuracy to proceed.

A summary of the task design is presented in Figure 1. The experimental blocks included 50 3-s trials. Incorrect discriminations resulted in a loss of 2 points in all experimental blocks. Feedback appeared on the screen for 500 ms. after each response in the form of an “X” for incorrect responses and an “O” for correct responses along with the points divided by earned lost during the trial and total point accumulation. Prior to starting the *no reward* block, adolescents were told to ignore the colored circles. Prior to starting the *reward* block, adolescents were told that correct discriminations earned a variable number of points, which depended on RT (points = 835 / RT in milliseconds). Earning points for correct discriminations remained in place for the remainder of the task (*reward*, *punishment*, and *post-punishment* blocks). Thus, points could not be earned during the *no reward* block, but could be earned during the other blocks. Before beginning the *punishment block*, adolescents were told that responding (correctly or incorrectly) when a red circle appeared would result in a loss of 50% of accumulated points. Thus, a red circle cued potential punishment. There were five red circle trials. Prior to initiating the *post-punishment block*, adolescents were told that a red circle would *not* cause a loss of points, and that they should respond during these trials to earn points. Thus, a red circle shifted from a punishment to reward cue. Of interest in this task was the degree to which RT declined during the *reward* compared to the *no reward* block (SR) and the degree to which RT increased on trials in which the punishment cue is presented relative to trials in which the punishment cue is not presented during the *post-punishment* block (SP).

The task remained unchanged for the 2^{nd} and 3^{rd} assessments with the exception that a different colored circle was used to cue potential loss of points during the *punishment* block (green at Wave 2 and white at Wave 3). This was done to avoid potential carry-over effects of the punishment cue from the previous assessment. RTs < 250 ms. were considered anticipations, and excluded from analysis. The rate of anticipations (on average < 1% of trials), non-response (average ranged from 2% to 5%), and incorrect discriminations (on average 7%) were low across all three assessments. RTs from trials with correct and incorrect responses were included to increase the number of trials used in computation of SR and SP indices.

Prior work using sample 1 and sample 2, as well as a third independent sample supports the validity of the PSRTT-CR. Using Wave 1 data from Sample 1, it was found that youth respond more quickly during the *reward* block relative to the *no reward* block (RTs decline) and respond more slowly during the punishment cue trials relative to the non-punishment cue trials in the *post punishment* block (RTs increase) (Colder et al., 2011; also see O'Connor & Colder, 2004 for results in an independent sample). This suggests empirical support for the task indices of SR and SP. PSRTT-CR indices are also associated with parent reports child SP and SR as expected, suggesting cross method convergent validity for this measure (in Wave 1 of sample 1, Colder et al., 2011; also see Colder & O'Connor, 2004 for results in an independent sample). Analysis of data from Wave 1 of sample 2 replicated these block and trial effects and associations with parent report of child SP and SR (results are available from the first author upon request). Furthermore, Rhodes et al. (2011) using sample 2 found that SP measured using the PSRTT-CR was distinguishable from parent reports of child effortful control and from general inhibition as measured using the Stop-Signal Task (Logan, Schachar, & Tannock, 1997), suggesting divergent validity for this measure of SP. Finally, using data from Sample 2, PSRTT-CR indices were found to be associated with child problem behavior (assessed using the Youth Self Report scales, Achenbach & Rescorla, 2001). For example, strong SR is prospectively associated with increases in externalizing problems, while weak SR and strong SP are prospectively associated with increases in depressive symptoms (Rhodes et al., in review).

Drug use—Items from the National Youth Survey (Elliot & Huizinga, 1983) were used to assess alcohol and drug use. For this study items from the first and third assessment were used to examine the prospective prediction of drug use from change in SR and SP. At both the first and third assessment, one item assessed lifetime alcohol use without parental permission (dichotomous no or yes), and two items assessed lifetime cigarette and marijuana use (dichotomous no or yes). Frequency of heavy alcohol use was assessed with one item at the third assessment ("How many times have you been drunk or high on alcoholic beverages in the past 12 months?") using a fill-in-the-blank response. Heavy alcohol use was not assessed at early waves given the expected low rates of use at these young ages. Indeed, rates of use were low as expected. Importantly, at the first assessment, only 6% of the sample reported lifetime alcohol use without parental permission, 2% of the sample reported cigarette use, and no participants reported marijuana use, thus allowing examination of the early stages of use. At the third assessment 29% of the sample reported alcohol use without parental permission, 12% reported cigarette use, and 9% of the sample reported marijuana use, indicating growth in substance use. As few participants (10%) experienced getting drunk or high from alcohol, this item was dichotomized to indicate whether any heavy drinking occurred in the past year at Wave 3.

Results

Data from the two samples were combined for analysis because the data analytic methods used require large sample sizes (e.g., Weighted Least Squares estimation). In preliminary analysis, SR and SP were examined at each assessment using repeated measures ANOVA. Next, change in SR and SP were examined using growth models. Finally, changes in SR and SP were tested as predictors of increases in substance use.

Preliminary Analysis

For analysis of SR, RTs from the *no reward* and *reward* blocks were analyzed at each assessment using repeated measures ANOVA (see Table 1). RTs declined during the reward block compared to the no reward block at each assessment, suggesting that the introduction of reward speeded responding as expected. An additional repeated measures ANOVA with

RTs as the dependent variable and block (*no reward* vs. *reward*) and time (3 levels) as within-subjects factors showed that the block x time interaction term was statistically reliable ($F(2,327) = 14.68$, $p < .01$). This suggests that the block effect was different across assessments, and as shown in Table 1, the size of the differences between RTs was large and increased over time. In sum, it appears that youth became more sensitive to the introduction of reward across assessments.

For analysis of SP, RTs from the *post-punishment* block were considered. Average RT was computed for the five trials that included the cue associated with punishment in the previous block (e.g., red circle trials at Wave 1, green circle trials at Wave 2, and white circle trials at Wave 3) and the immediately preceding trials that did not include the punishment cue. Trials preceding each punishment cue trial were used as the comparison condition to control for effect of position of the trials in the block (e.g., fatigue). Results from the repeated measures ANOVAs suggest that, as expected, the cue previously associated with punishment inhibited behavior in the form of slower RTs (see Table 1). An additional repeated measures ANOVA with RTs as the dependent variable, and trial type (punishment cue vs. preceding trial without a punishment cue) and time (3 levels) as within-subjects factors showed that the trial type x time interaction term was statistically reliable ($F(2,327) = 16.56$, $p < .01$). This suggests that the punishment cue effect was different across assessments, and as shown in Table 1, the size of the cue effect in the post-punishment block was moderate at the first assessment and declined over time. In sum, it appears that youth became less sensitive to the punishment cue across assessments.

Growth Models

Growth in SR and SP—Growth models with individual varying times of observation and time-varying covariates were used to analyze growth in SR and SP. Growth models with individual varying times were used to accommodate the variability in time intervals of follow-up assessments (i.e., not all participants were assessed at exactly the targeted one year interval). Mplus version 6.1 (Muthén & Muthén, 2010) was used to estimate the growth models with full information maximum likelihood to accommodate missing data. Given three repeated measures, linear trends were specified. The contrast codes were 0 for the first assessment, and values in units of years for the subsequent assessments. Thus the intercept represented levels of SR or SP at the first assessment. Participants interviewed on the exact annual anniversary dates had contrast codes of 0, 1, and 2. Growth models with individually varying times are similar to hierarchical linear models (HLMs) and multilevel models (MLMs), and accordingly, fit indices that are common for structural equation models are not provided. As such, the log likelihood was used for nested model tests to evaluate whether the addition of a random linear growth factor improved the model fit.

The growth model for SR specified mean RT from the *reward* block as the repeated measure with mean RT from the *no reward* block included as a time varying covariate. This allowed us to examine mean change in reward RTs above and beyond RTs during the *no reward* condition. Number of errors from the *reward* block was also included as a time-varying covariate because errors have been shown to be associated with RTs (Colder et al., 2011). The nested model test suggested that adding a random slope factor significantly improved model fit ($\Delta\ \chi^2(3) = 684.1$, $p < .01$). Mean reward RT at the first assessment was 750.2 ms and reward RTs declined over time (slope factor mean = -92.9, $p < .01$), suggesting that the impact of reward on behavior became stronger across assessment waves. That is, SR increased over time. Significant individual differences were observed in both initial reward RTs and rate of decline of reward RTs (Intercept $\sigma^2 = 66.7$, $p<.01$, and Slope $\sigma^2 = 8.5$, $p < .01$). The covariance between the intercept and slope factors was statistically reliable (Covariance = - 17.7, $p < .01$), suggesting that starting out at a slow RT at the first assessment (low levels of SR) was associated with a greater rate of decline in *reward* RTs (greater increases in SR).

The growth model for SP specified mean RT from punishment cue trials from the *post-punishment* block as the repeated measure with mean RT from the immediately preceding trials as a time-varying covariate. This allowed us to examine mean change in punishment cue RTs above and beyond RTs on trials in which the punishment cue was not presented. Number of errors from the post-punishment block were also included as a time-varying covariate as errors are associated with RT (Colder et al., 2011). Nested model test suggested that adding a random slope factor significantly improved model fit ($\Delta\ \chi^2$ (3) = 464.21, $p < .01$). Mean punishment cue RT at the first assessment was 815.5 ms and punishment cue reaction times declined over assessment waves (slope factor mean = -115.6 ms, $p < .01$), suggesting a decrease in SP. Significant individual differences were observed for initial punishment cue RTs (Intercept σ^2 = 52.2, $p<.01$), but not for change in punishment cue RTs (Slope σ^2 = 5.8, $p < .40$). The covariance between the intercept and slope factors was not statistically reliable (Covariance = - 12.8, $p < .20$). Growth trajectories for SR and SP are plotted in Figure 2.

Predicting substance use—Next, change in SR was tested as a predictor of increases in substance use from Wave 1 to Wave 3. First, a confirmatory factor model of the substance use items was estimated. Weighted Least Squares Mean and Variance Adjusted estimation in Mplus version 6.1 (Muthén & Muthén, 1998-2010) was used because of the dichotomous nature of the indicators. The model specified two factors, including Wave 1 substance use (indicated by lifetime alcohol and cigarette use) and Wave 3 substance use (indicated by lifetime alcohol use, cigarette use, and marijuana use, and past year heavy drinking). The model fit the data well (Model χ^2 (8) = 6.85, $p < .59$, Comparative Fit Index = 1.0, Root Mean Square Error of Approximation < .01). Factor loadings were all reliably different from 0 (ps< .05) and standardized loadings ranged from .78 to .93. The latent substance use factors were then combined with our reward RT growth model, and the Wave 3 substance use latent factor was regressed on the latent growth factors and the Wave 1 substance use latent factor. Adolescent age at the Wave 1 was included as a statistical control variable predicting the latent growth factors and Wave 1 and Wave 3 substance use. Gender was also considered as a potential statistical control, but it did not reliably predict the substance use factors, and so it was removed from the model. An additional model was estimated predicting Wave 3 substance use controlling for Wave 2 substance use, and the pattern of findings was the same as those controlling for Wave 1 substance use. Results are reported controlling for Wave 1 use as these analyses represent a longer developmental window.

A nested model test comparing models with and without paths from the growth factors to Wave 3 substance use suggested that model fit significantly improved (($\Delta\ \chi^2$ (2) = 13.39, $p < .01$) when these paths were included. Thus, these paths were retained in our final model. Age predicted high levels of Wave 1 substance use and faster reward RTs at the first assessment (β = .98 and -15.8, respectively, ps < .01). Age was unrelated to Wave 3 substance use above and beyond Wave 1 substance use and was unrelated to reward RT slope (β = -.24 and 3.6, $p < .63$ and < .17, respectively). Wave 3 substance use was reliably predicted by reward RT slope (β = -6.3, $p<.05$) and marginally predicted by the reward RT intercept (β = - .97, $p < .10$). That is, faster rate of decline in reward RTs (increases in SR) and fast initial reward RTs (high initial SR) were associated with an increased likelihood of substance use at Wave 3.

There were no individual differences in change in punishment cue RTs, thus, when drug use was introduced into the SP growth model, Wave 3 drug use was regressed on the SP intercept, age, and Wave 1 drug use. A nested model test suggested that inclusion of the path from the SP intercept to Wave 3 substance use did not improve model fit ($\Delta\ \chi^2$ (1) = .34, p < .57). Thus, initial levels of SP were not associated with Wave 3 substance use.

Discussion

One of the notable behavioral changes that occurs during adolescence is an increase in risk taking behavior, including substance use. Although increases in adolescent risk taking are undoubtedly determined by multiple factors, neuroscience accounts emphasize the role of brain maturation and shifts in incentive salience. The present study is the first longitudinal examination of developmental changes in sensitivity to reward and sensitivity to punishment, designed to capture an important period in early adolescence when youth initiate and escalate a common risk behavior, namely substance use. In addition, trajectories of sensitivity to reward and sensitivity to punishment during early adolescence were tested as predictors of the emergence and early escalation of substance use. Findings suggested that sensitivity to reward (SR) increased and sensitivity to punishment (SP) decreased, and that increases in SR were associated with increases in substance use. These findings will be discussed in turn.

On the behavioral task, adolescents responded more quickly when reward was available and fast responses yielded more reward. This was true at each assessment period. Importantly, RTs in response to reward declined across the three assessments, and this could not be attributed to generally faster responding with age or practice because reaction times when reward was not available and age were statistically controlled. Accordingly, findings suggest normative increases in motivation for reward (e.g., RTs in response to reward declined) during early adolescence. Although there is converging evidence that incentive salience shifts during adolescence to favor reward (Bjork et al., 2007; Casey et al., 2008), no prior study has examined trajectories of reward salience. Cross-sectional age comparisons that have characterized most of the literature on reward salience are informative, but they don't provide compelling evidence for a developmental phenomenon. SR has been proposed as part of the neurological underpinnings of the personality traits of sensation seeking and extraversion, and our findings are consistent with prior work suggesting that these traits increase during adolescence (Crawford, Pentz, Chou, Li, & Dwyer, 2003; Roberts et al., 2006). Accordingly, our longitudinal findings provide important behavioral evidence for what is expected from maturational brain changes during adolescence.

Many researchers have posited that increased reward salience is partly responsible for increases in risk behavior during adolescence (e.g., Casey et al., 2008; Steinberg & Monahan, 2007). However, Somerville et al. (2010) noted that reward-driven behavior during adolescence is “highly subject to individual differences.” Consistent with this view, significant individual variability was found in rates of change in motivation for reward. One implication of this variability is that reward salience increases more for some adolescents than others, and that those who do not experience much change in reward salience may be protected from risk behavior. Indeed, not all adolescents engage in risk behavior such as substance use. From a risk and protection framework, this raises the question of why reward salience increases more rapidly for some youth than others. This question was not examined, but understanding the mechanisms that account for rates of change in reward salience may be particularly informative for interventions targeting the prevention of adolescent risk behavior.

To our knowledge, this is the first study to test whether individual differences in change in motivation for reward were associated with substance use. Faster rates of increase in SR were associated with an increased likelihood of substance use. This is consistent with the contemporary view of the central importance of reward neural circuitry in addictive behaviors (Koob & Volkow, 2010) and with studies suggesting that increased motivation for reward underlies risk behavior in general (Casey et al., 2008), as well as specifically substance use (Doremus-Fitzwater, Varlinskaya, & Spear, 2010). Although prior studies have shown a consistent link between SR and adolescent substance use (Knyazev, 2004; Lopez et al., 2012; O'Connor & Colder, 2005; Pardo et al., 2007), this work has largely been cross-sectional or examined prospective effects across two points in time. None have examined how normative trajectories of reward motivation are associated with substance use. Thus, the findings provide important corroborating evidence for developmental neuroscience models of adolescent substance use.

Research examining incentive salience in adolescence has overwhelmingly focused on positive incentives. However, both sensitivity to reward (SR; sensitivity to positive incentives that increases the propensity for approach behavior) and sensitivity to punishment (SP; sensitivity to potential aversive consequences that increases the propensity to inhibit behavior and experience emotional distress) are thought to be central to regulation of behavior (e.g., Gray & McNaughton, 2000). The current study examined developmental trajectories of SP, and its association with substance outcomes. Results showed that cues for potential punishment were associated with inhibition of responding (slow RTs) at each assessment, and that the degree of slowing in response to punishment cues declined over time. This suggests that SP declined over time. Low SP may make it difficult to inhibit approach behaviors that associated with potential negative consequences (Fowles, 1994). Thus, low SP may increase the likelihood of risky behavior. Although SP declined on average in our sample, there were no individual differences in rates of change in SP, suggesting that normative development in SP may not be important in the escalation of adolescent substance use. The association between SP and adolescent substance use has been equivocal (e.g., Knayev, 2004; Lopez et al., 2012; O'Connor and Colder, 2005; O'Connor et al., 2008). Mixed findings suggest that SP is weakly associated with adolescent substance use, and that this relationship is complex and potentially moderated by other factors (Genovese & Wallace, 2007; Wardell et al., 2011). Thus, although normative development in SP may not predict adolescent substance use, SP may be predict adolescent substance use via a moderational model. Considering potential moderators is an important direction for future research.

It is important to consider some limitations of our study. First, three waves of data collection allowed only a test of linear change, and there is some suggestion in the literature that SR development is non-linear (Steinberg, 2008). If this is true, then there are likely individual differences in this pattern, and it would be important to examine how these more complex patterns of change map onto change in risk behavior with more long-term longitudinal designs. Second, it is well known that substance use is a multi-determined phenomenon (e.g., Hawkins, Catalano, & Miller, 1992). The focus of the current study was on SR and SP. It will be important for future research to consider how changes in response to incentives may interact with other individual differences and contextual factors to predict substance use. For example, Steinberg (2008) suggests that adolescent brain development and changing social context operate jointly to promote risk behavior. Specifically, he proposes that early increases in motivation for positive arousal (e.g., SR) and relatively late development of conscious control of behavior and emotion occurring when youth spend more unsupervised time with peers jointly influence adolescent risk behavior. Third, the current study examined normative changes in SR and SP among unselected community adolescents, and whether or not findings will generalize to other populations (e.g., clinical samples of substance abusers or samples with other demographic characteristics) requires future replication. Fourth, the current sample is best thought of as in the early stages of substance use. It will be important to extend this work into later adolescence to evaluate the relationship of SR development with later escalation into heavy use and abuse or dependence. Also, the influence SR may vary across drugs, and extending this study to older more drug involved samples will allow for the examination of individual drugs. Finally, the PSRTT-CR is a relatively new task, and although initial evidence supports its convergent and divergent validity, it will be important for future work to further validate these indices of SP and SR.

Despite these limitations, this study makes important contributions to the literature. Findings demonstrate that SR increases during early adolescence, and that individual differences in the rate of SR increase and initial high levels of SR predict the emergence of substance use. Although SP declined on average, there were no significant individual differences in the rate of change in SP. Thus, substance use during this period seems to be largely reward driven, and youth who start adolescence with high reward sensitivity and show rapid escalation in reward sensitivity are at particular risk. Accordingly, these may be important targets for intervention. An important direction for future research would be to develop brief screening tools that would be cost effective at identifying such adolescents. Effective preventive interventions strategies might emphasize the benefits of not using drugs and alcohol (e.g., enhanced athletic performance, improved academic performance, etc.) rather than emphasizing the risk of use. Another strategy might be to promoting alternative safe ways of increasing positive arousal (e.g., safely engaging in exhilarating physical activities). Interventions that are sensitive to the developmental context of adolescence, including shifts in incentive salience, may be more effective at preventing or slowing the emergence of drug use in early adolescence.

Acknowledgments

This research was funded by grants R01 DA020171 and R01 DA019631 from the National Institute on Drug Abuse awarded to Craig R. Colder. The authors thank the project coordinators (Dawn Keough and Jamee Foster) and the staff for their help with data collection, and all of the families who participated in the study.

References

Achenbach, TM.; Rescorla, LA. Youth self-report for ages 11-18. ASEBA; Burlington, VT: 2001.

Avila C. Distinguishing BIS-mediated and BAS-mediated disinhibition mechanisms: A comparison of disinhibition models of Gray (1981, 1987) and of Patterson and Newman (1993). Journal of Personality & Social Psychology. 2001; 80(2):311–324. doi: 10.1037/0022-3514.80.2.311. [PubMed: 11220448]

Bjork JM, Smith AR, Danube CL, Hommer DW. Developmental differences in posterior mesofrontal cortex recruitment by risky rewards. The Journal of Neuroscience. 2007; 27(18):4839–4849. doi: 10.1523/jneurosci.5469-06.2007. [PubMed: 17475792]

Blonigen DM, Carlson MD, Hicks BM, Krueger RFI, W.G. Stability and change in personality traits from late adolescence to early adulthood: A longitudinal twin study. Journal of Personality. 2008; 76(2):229–266. doi: 10.1111/j.1467-6494.2007.00485.x. [PubMed: 18331280]

Casey BJ, Jones RM, Hare TA. The Adolescent Brain. Annals of the New York Academy of Sciences. 2008; 1124(1):111–126. doi: 10.1196/annals.1440.010. [PubMed: 18400927]

Cauffman E, Shulman EP, Steinberg L, Claus E, Banich MT, Graham S. Age differences in affective decision making as indexed by performance on the Iowa Gambling Task. Developmental Psychology. 2010; 46(1):193–207. doi: 10.1037/a0016128. [PubMed: 20053017]

Chabrol H, Ducongé E, Casas C, Roura C, Carey KB. Relations between cannabis use and dependence, motives for cannabis use and anxious, depressive and borderline symptomatology. Addictive Behaviors. 2005; 30(4):829–840. doi: 10.1016/j.addbeh.2004.08.027. [PubMed: 15833585]

Chambers RA, Taylor JR, Potenza MN. Developmental neurocircuitry of motivation in adolescence: A critical period of addiction vulnerability. American Journal of Psychiatry. 2003; 160(6):1041–1052. doi: 10.1176/appi.ajp.160.6.1041. [PubMed: 12777258]

Chen K, Kandel DB. The natural history of drug use from adolescence to the mid-thirties in a general population sample. American Journal of Public Health. 1995; 85(1):41–47. doi: 10.2105/AJPH. 85.1.41. [PubMed: 7832260]

Cloninger RC. A systematic method for clinical description and classification of personality variants. Archives Gen. Psychiatry. 1987; 44:573–588. doi: 10.1001/archpsyc.1987.01800180093014.

Colder CR, Campbell RT, Ruel E, Richardson JL, Flay BR. A finite mixture model of growth trajectories of adolescent alcohol use: Predictors and consequences. Journal of Consulting & Clinical Psychology. 2002; 70(4):976–985. doi: 10.1037/0022-006X.70.4.976. [PubMed: 12182281]

Colder CR, Mehta P, Balanda K, Campbell RT, Mayhew K, Stanton WR. Identifying trajectories of adolescent smoking: An application of latent growth mixture modeling. Health Psychology. 2001; 20(2):127–135. doi: 10.1037//0278-6133.20.2.127. [PubMed: 11315730]

Colder CR, O'Connor RM. Gray's reinforcement sensitivity model and child psychopathology: Laboratory and questionnaire assessment of the BAS and BIS. Journal of Abnormal Child Psychology. 2004; 32(4):435–451. doi: 10.1023/B:JACP.0000030296.54122.b6. [PubMed: 15305548]

Colder CR, Trucco EM, Lopez HI, Hawk LW, Read JP, Lengua LJ. Revised reinforcement sensitivity theory and laboratory assessment of BIS and BAS in children. Journal of Research in Personality. 2011; 45(2):198–207. doi: 10.1016/j.jrp.2011.01.005. [PubMed: 21603055]

Cox WM, Klinger E. Motivational structure: Relationships with substance use and processes of change. Addictive Behaviors. 2002; 27(6):925–940. doi: 10.1016/S0306-4603(02)00290-3. [PubMed: 12369476]

Crawford AM, Pentz MA, Chou C-P, Li C, Dwyer JH. Parallel developmental trajectories of sensation seeking and regular substance use in adolescents. Psychology of Addictive Behaviors. 2003; 17(3): 179–192. doi: 10.1037/0893-164X.17.3.179. [PubMed: 14498812]

Doremus-Fitzwater TL, Varlinskaya EI, Spear LP. Motivational systems in adolescence: Possible implications for age differences in substance abuse and other risk-taking behaviors. Brain and Cognition. 2010; 72(1):114–123. doi: 10.1016/j.bandc.2009.08.008. [PubMed: 19762139]

Elliott DS, Huizinga D. Social class and delinquent behavior in a national youth panel: 1976-1980. Criminology. 1983; 21(2):149–177. doi: 10.1111/j.1745-9125.1983.tb00256.x.

Ernst M, Nelson EE, Jazbec S, McClure EB, Monk CS, Leibenluft E. Amygdala and nucleus accumbens in responses to receipt and omission of gains in adults and adolescents. NeuroImage. 2005; 25(4):1279–1291. doi: 10.1016/j.neuroimage.2004.12.038. [PubMed: 15850746]

Fowles, DC. Nebraska symposium on motivation, Vol. 41. Vol. 41. University of Nebraska Press, University of Nebraska Press; Lincoln, NE, US, Lincoln, NE, US: 1994. A motivational theory of psychopathology. In W. D. Spaulding (Ed.), Integrative views of motivation, cognition, and emotion.; p. 181-238.

Galea S, Tracy M. Participation rates in epidemiological studies. Annals of Epidemiology. 2007; 17(9):643–653. doi: 10.1016/j.annepidem.2007.03.013. [PubMed: 17553702]

Genovese JEC, Wallace D. Reward sensitivity and substance abuse in middle school and high school students. Journal of Genetic Psychology. 2007; 168(4):465–469. doi: 10.3200/GNTP. 168.4.465-469. [PubMed: 18232522]

Gray, JA.; McNaughton, N. The neuropsychology of anxiety: An enquiry into the functions of the septo-hippocampal system. 2nd ed.. Oxford University Press, USA; New York, NY: 2000.

Gullo MJ, Dawe S. Impulsivity and adolescent substance use: Rashly dismissed as “all-bad”? Neuroscience & Biobehavioral Reviews. 2008; 32:1507–1518. doi: 10.1016/j.neubiorev. 2008.06.003. [PubMed: 18588911]

Hardin MG, Schroth E, Pine DS, Ernst M. Incentive-related modulation of cognitive control in healthy, anxious, and depressed adolescents: development and psychopathology related differences. Journal of Child Psychology and Psychiatry. 2007; 48(5):446–454. doi: 10.1111/j. 1469-7610.2006.01722.x. [PubMed: 17501725]

Hawkins JD, Catalano RF, Miller JY. Risk and protective factors for alcohol and other drug problems in adolescence and early adulthood: Implications for substance abuse prevention. Psychological Bulletin. 1992; 112(1):64–105. doi: 10.1037/0033-2909.112.1.64. [PubMed: 1529040]

Jarvis, B. MediaLab (Version 2002.1.4) [Computer software]. Empirisoft; New York: 2002.

Klimstra TA, Hale WW III, Raaijmakers QAW, Branje SJT, Meeus WHJ. Maturation of personality in adolescence. Journal of Personality and Social Psychology. 2009; 96(4):898–912. doi: 10.1037/a0014746. [PubMed: 19309210]

Koob, GF. Neurobiology of addiction. Elsevier Academic; London: 2006.

Koob GF, Volkow ND. Neurocircuitry of addiction. Neuropsychopharmacology. 2010; 35(1):217–238. doi: 10.1038/npp.2009.110. [PubMed: 19710631]

Knyazev GG. Behavioural activation as predictor of substance use: Mediating and moderating role of attitudes and social relationships. Drug and Alcohol Dependence. 2004; 75(3):309–321. doi: 10.1016/j.drugalcdep.2004.03.007. [PubMed: 15283952]

Kuntsche E, Stewart SH, Cooper ML. How stable is the motive--alcohol use link? A cross-national validation of the drinking motives questionnaire revised among adolescents from Switzerland, Canada, and the United States. Journal of Studies on Alcohol and Drugs. 2008; 69(3):388–389. [PubMed: 18432381]

Logan GD, Schachar RJ, Tannock R. Impulsivity and Inhibitory Control. Psychological Science. 1997; 8(1):60–64. doi: 10.1111/j.1467-9280.1997.tb00545.x.

Lopez HI, Colder CR, Hawk LW, Wieczorek WF, Eiden RD, Lengua LJ. Reinforcement sensitivity theory and alcohol outcome expectancies in early adolescence. The American Journal of Drug and Alcohol Abuse, early online. 2012 doi: 10.3109/00952990.2011.643973.

MacPherson L, Magidson JF, Reynolds EK, Kahler CW, Lejuez CW. Changes in sensation seeking and risk-taking propensity predict increases in alcohol use among early adolescents. Alcoholism: Clinical and Experimental Research. 2010; 34(8):1400–1408. doi: 10.1111/j.1530-0277.2010.01223.x.

Millstein SB, Halpern-Felsher BL. Judgments about risk and perceived invulnerability in adolescents and young adults. Journal of Research on Adolescence. 2002; 12(4):399–422. doi: 10.1111/1532-7795.00039.

Muthén, LK.; Muthén, BO. Mplus(Version 6.1) [Computer Software]. Muthén & Muthén; Los Angeles, CA: 2010.

O'Connor RM, Colder CR. Predicting alcohol patterns in first-year college students through motivational systems and reasons for drinking. Psychology of Addictive Behaviors. 2005; 19(1):10–20. doi: 10.1037/0893-164x.19.1.10. [PubMed: 15783273]

O'Connor RM, Farrow S, Colder CR. Clarifying the anxiety sensitivity and alcohol use relation: Considering alcohol expectancies as moderators. Journal of Studies on Alcohol and Drugs. 2008; 69:765–772. [PubMed: 18781252]

Pardo Y, Aguilar R, Molinuevo B, Torrubia R. Alcohol use as a behavioural sign of disinhibition: Evidence from J.A. Gray's model of personality. Addictive Behaviors. 2007; 32(10):2398–2403. doi: 10.1016/j.addbeh.2007.02.010. [PubMed: 17407802]

Rhodes, JD.; Trucco, EM.; Colder, CR.; Speidel, C.; Hawk, LW., Jr.; Lengua, LJ.; Eiden, RD. Effortful control, reinforcement sensitivity, and childhood behavioral problems.. Poster session presented at the Society for Research in Child Development Meeting; Montreal, Canada. 2011, April;

Rhodes, JD.; Trucco, EM.; Colder, CR.; Speidel, C.; Hawk, LW., Jr.; Lengua, LJ.; Eiden, RD. The interaction between self-regulation and motivation prospectively predicting problem behavior in adolescence. (in review)

Roberts BW, Walton KE, Viechtbauer W. Patterns of mean-level change in personality traits across the life course: A meta-analysis of longitudinal studies. Psychological Bulletin. 2006; 132(1):1–25. doi: 10.1037/0033-2909.132.1.1. [PubMed: 16435954]

Smillie LD, Pickering A, Jackson CJ. The new reinforcement sensitivity theory: Implications for personality measurement. Personality and Social Psychology Bulletin. 2006; 10(4):320–335. doi: 10.1207/s15327957pspr1004_3.

Simons JS, Arens AM. Moderating effects of sensitivity to punishment and sensitivity to reward on associations between marijuana effect expectancies and use. Psychology of Addictive Behaviors. 2007; 21(3):409–414. doi: 10.1037/0893-164x.21.3.409. [PubMed: 17874892]

Somerville LH, Jones RM, Casey BJ. A time of change: Behavioral and neural correlates of adolescent sensitivity to appetitive and aversive environmental cues. Brain and Cognition. 2010; 72(1):124–133. doi: 10.1016/j.bandc.2009.07.003. [PubMed: 19695759]

Steinberg L. A social neuroscience perspective on adolescent risk-taking. Developmental Review. 2008; 28(1):78–106. doi: 10.1016.j.dr.2007.08.002. [PubMed: 18509515]

Steinberg L, Monahan KC. Age differences in resistance to peer influence. Developmental Psychology. 2007; 43(6):1531–1543. doi: 10.1037/0012-1649.43.6.1531. [PubMed: 18020830]

Van Leijenhorst L, Zanolie K, Van Meel CS, Westenberg PM, Rombouts SARB, Crone EA. What Motivates the Adolescent? Brain Regions Mediating Reward Sensitivity across Adolescence. Cerebral Cortex. 2010; 20(1):61–69. doi: 10.1093/cercor/bhp078. [PubMed: 19406906]

Volkow ND, Insel TR. What are the long-term effects of methylphenidate treatment? Biological Psychiatry. 2003; 54:1307–1309. doi: 10.1016/j.biopsych.2003.10.019. [PubMed: 14675792]

Wardell JD, O'Connor RM, Read JP, Colder CR. Behavioral approach system moderates the prospective association between the behavioral inhibition system and alcohol outcomes in college students. Journal of Studies on Alcohol and Drugs. 2011; 72(6):1028–1036. [PubMed: 22051217]

Wright AGC, Pincus AL, Lenzenweger MF. Interpersonal development, stability, and change in early adulthood. Journal of Research on Personality. (in press).

Zuckerman, M. Impulsive unsocialized sensation seeking: The biological foundations of a basic dimension of personality.. In: Bates, JE.; Wachs, TD., editors. Temperament: Individual differences at the interface of biology and behavior. APA science volumes. American Psychological Association; Washington, DC, USA: 1994. p. 219-255.

Practice Block

- 20 trials
- No points earned or lost
- Participants had to achieve 70% accuracy to move on to the experimental blocks.

Experimental Block 1: No Reward

- No opportunity to earn points
- Instructed to ignore colored circles and to respond as quickly as possible.

Experimental Block 2: Reward

- Correct discriminations rewarded with variable number of points depending on speed of response
- Instructed to ignore colored circles

Experimental Block 3: Punishment

- Correct discriminations rewarded with variable number of points depending on speed of response
- Instructed to not respond on trials with the punishment cue and told that responding when the punishment cued was present would result in loss of ½ accumulated points.
- There were five punishment cue trials

Experimental Block 4: Post-Punishment

- Correct discriminations rewarded with variable number of points depending on speed of response
- Instructed to ignore the punishment cue and to respond on all trials even those that include the cue previously associated with punishment.
- There were five trials with cues previously associated with punishment.

Figure 1.

Design of the Point Scoring Reaction Time Task for Children Revised (PSRTT-CR). Note: Each experimental block included 50 trials (3 seconds each). Feedback was provided on all trials in experimental blocks for 500 ms, including whether the response was correct or incorrect, points earned, and total accumulated points. Incorrect discriminations resulted in a loss of 2 points in all experimental blocks.

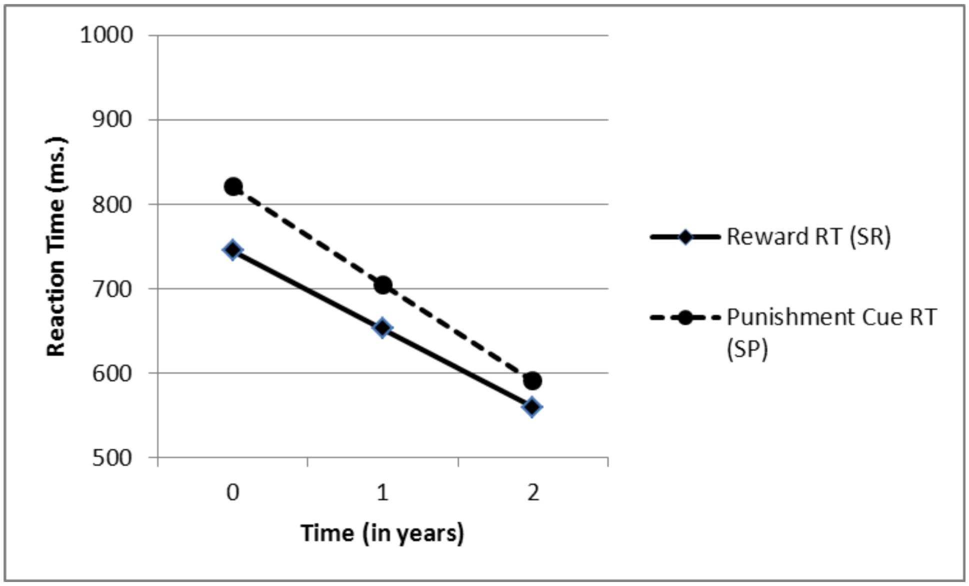

Figure 2.
Model Implied Growth Trajectories of senstivity to reward (SR) and senstivity to punishment (SP). Note: Declines in reaction time in the reward condition corresponds to increases in SR, and declines reaction in response to punishment cues corresponds to declines in SP.

Table 1

Mean Reaction Times in ms. and Tests of Condition Effects for the Point Scoring Reaction Time Task Revised for Children

	No Reward Block	Reward Block		Post Punishment Block		
				Non-punishment cue trials	Punishment cue trials	
Wave 1	866.5 (192.9)	761.2 (177.9)	$F(1,758)=557.8$ Cohen's $d = .85$	734.9 (207.3)	823.2 (260.0)	$F(1,758)=214.5$ Cohen's $d = .53$
Wave 2	754.3 (166.7)	636.4 (142.5)	$F(1,701)=812.6$ Cohen's $d = .85$	618.8 (166.5)	682.9 (220.9)	$F(1,701)=133.8$ Cohen's $d = .22$
Wave 3	688.4 (153.5)	572.0 (127.4)	$F(1,681)=962.8$ Cohen's $d = 1.06$	562.1 (151.8)	581.8 (175.1)	$F(1,681)=18.02$ Cohen's $d = .16$

Note: N = 759 for Wave 1, N=710 for Wave 2, N=685 for Wave 3. Standard deviations are in parentheses.