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Risky Decision Making From Childhood Through Adulthood: Contributions of Learning and Sensitivity to Negative Feedback

Kathryn L. Humphreys
University of California, Los Angeles

Eva H. Telzer
University of Illinois, Urbana-Champaign

Jessica Flannery
University of Oregon

Bonnie Goff
University of California, Los Angeles

Laurel Gabard-Durnam
Columbia University

Dylan G. Gee and Steve S. Lee
University of California, Los Angeles

Nim Tottenham
Columbia University

Decision making in the context of risk is a complex and dynamic process that changes across development. Here, we assessed the influence of sensitivity to negative feedback (e.g., loss) and learning on age-related changes in risky decision making, both of which show unique developmental trajectories. In the present study, we examined risky decision making in 216 individuals, ranging in age from 3–26 years, using the balloon emotional learning task (BELT), a computerized task in which participants pump up a series of virtual balloons to earn points, but risk balloon explosion on each trial, which results in no points. It is important to note that there were 3 balloon conditions, signified by different balloon colors, ranging from quick- to slow-to-explode, and participants could learn the color–condition pairings through task experience. Overall, we found age-related increases in pumps made and points earned. However, in the quick-to-explode condition, there was a nonlinear adolescent peak for points earned. Follow-up analyses indicated that this adolescent phenotype occurred at the developmental intersection of linear age-related *increases* in learning and *decreases* in sensitivity to negative feedback. Adolescence was marked by intermediate values on both these processes. These findings show that a combination of linearly changing processes can result in nonlinear changes in risky decision making, the adolescent-specific nature of which is associated with developmental improvements in learning and reduced sensitivity to negative feedback.

Keywords: risky decision making, sensitivity to negative feedback, development

Decision making is a complex behavior (Rangel, Camerer, & Montague, 2008). Perhaps it is not surprising that effective decision making in the context of risk is slow to develop, exhibits nonlinear paths across development (Boyer, 2006), and reaches maturity in adulthood (Byrnes, 2002). Decision making under risk consists of multiple psychological processes, including learning from experience (i.e., associative learning), which increases with development (e.g., Dumas, 2005), and sensitivity to negative feedback (e.g., loss), which decreases across development (e.g., Cassotti, Aïte, Osmont, Houde, & Borst, 2014; Levin, Hart, Weller, & Harshman, 2007). Characterizing these two processes may provide insight into developmental patterns of decision making (e.g., nonlinear paths toward mature performance). In the current study, we examined the roles of associative learning and sensitivity to neg-

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Kathryn L. Humphreys, Department of Psychology, University of California, Los Angeles; Eva H. Telzer, Department of Psychology, University of Illinois, Urbana-Champaign; Jessica Flannery, Department of Psychology, University of Oregon; Bonnie Goff, Department of Psychology, University of California, Los Angeles; Laurel Gabard-Durnam, Department of Psychology, Columbia University; Dylan G. Gee, and Steve S. Lee, Department of Psychology, University of California, Los Angeles; Nim Tottenham, Department of Psychology, Columbia University.

Dylan G. Gee is now at the Sackler Institute for Developmental Psychobiology, Weill Cornell Medical College.

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Correspondence concerning this article should be addressed to Kathryn L. Humphreys, who is now at the Department of Psychology, Bldg. 420, Jordan Hall, Stanford University, Stanford, CA 94305. E-mail: k.humphreys@stanford.edu

ative feedback in the development of risky decision making in a cross-sectional sample of children, adolescents, and adults.

Developmental Changes in Sensitivity to Negative Feedback

The salience of negatively valenced feedback (e.g., loss, punishment) differs across development, though even adults do not engage in purely rational decision making in the context of risk (Kahneman & Tversky, 1979). Numerous cross-sectional studies suggest that young children are particularly sensitive to negative feedback (Levin et al., 2007; Slovic, 1966), showing more reactivity in both behavioral and neural responses to potential loss or punishment (Crone, Bunge, Latenstein, & van der Molen, 2005; van Leijenhorst, Crone, & Bunge, 2006; van Leijenhorst, Westenberg, & Crone, 2008). In addition, children's learning is more likely to be motivated by negative feedback, an effect that diminishes with increasing age (van den Bos, Cohen, Kahnt, & Crone, 2012), as learning from positive feedback becomes more salient. These findings parallel evidence that early life is normatively characterized by higher reactivity to threatening stimuli (Gullone, 2000; Marks, 1987) and negativity biases (Tottenham, Phuong, Flannery, Gabard-Durnam, & Goff, 2013). Behavior influenced by sensitivity to negative feedback is likely to result in more conservative decision making, and this effect on decision making should attenuate with age. In the current study, we examined how negatively valenced feedback influences behavior across development.

Development of Associative Learning

As sensitivity to negative feedback declines across development, the ability to learn associations between stimuli and valenced outcomes increases across development. Learning of stimulus–outcome associations occurs as early as the preschool years (Guo, North, Gorden-Larsen, Bulik, & Choi, 2007; Herbert, Eckerman, & Stanton, 2003), but undergoes significant improvements from childhood into adulthood (Cohen et al., 2010; Dumas, 2005). Successful learning of stimulus–outcome associations is essential for making correct predictions to guide behavior. In the current study, we sought to examine the contributions of both associative learning and sensitivity to negative feedback to risky decision making across development.

Current Study

We used the balloon emotional learning task (BELT; Humphreys, Lee, & Tottenham, 2013) to examine age-related changes (cross-sectional sample from ages 3–26 years) in sensitivity to negative feedback and associative learning as they relate to risky decision making. Participants were presented a series of virtual balloons that they could pump up to earn points. The task involves risky decision making as participants must decide whether to continue pumping or to save their earned points. Balloons explode at an initially unknown point, resulting in the loss of accrued points on that trial. Participants are able to learn through experience which balloons explode after few (quick-to-explode), variable, or many (slow-to-explode) pumps. The BELT was adapted from the balloon analogue risk task (BART; Lejuez et al., 2002). Prior research using the BART has found that pumps made on this task positively correlated with risk-taking behavior in samples of children, adolescents, and adults (Aklin, Lejuez, Zvolensky, Kahler, & Gwadz, 2005; Humphreys & Lee, 2011; Lejuez et al., 2003). Furthermore, recent work indicates that pubertal status is associated with risk taking on the BART, such that adolescents with advanced pubertal status made more pumps on the task, even after accounting for participant age (Collado, MacPherson, Kurdziel, Rosenberg, & Lejuez, 2014). The BELT was designed specifically to modify the BART in important ways. Namely, the BART contains all uncertain conditions (i.e., the participant is unable to learn the optimal point at which to stop pumping up the balloon because all balloon conditions are variable), whereas the BELT provides a variable balloon condition, similar to the BART, in addition to two stable balloon conditions (i.e., the quick-to-explode condition, which has a low-explosion threshold and the slow-to-explode condition which has a high-explosion threshold). The addition of these conditions allows for the ability to learn stimulus–outcome associations to distinguish contexts in which more pumps would likely result in more points (i.e., the slow-to-explode condition) and when this same behavior is more likely to result in the loss of accrued points (i.e., the quick-to-explode condition). The BELT provides the ability to obtain measures of (a) risk taking (i.e., number of pumps), (b) success (i.e., number of points), (c) sensitivity to negatively valenced feedback (i.e., postexplosion pump reduction), and (d) associative learning (i.e., gain in points). The BELT was designed for use across a wide range of ages, allowing for the assessment of a number of aspects of risky decision making from preschool age into adulthood.

Our goal was to examine age-related patterns of risky decision making on the BELT, and whether changes in sensitivity to negative feedback (i.e., postexplosion pump reduction) and learning (i.e., gain in points, which indexes accumulated learning, leading to improvements in task performance) would explain age-related changes on this task. Based on previous work (e.g., Peper, Koolschijn, & Crone, 2013), we anticipated that pumps and points would increase with age. We expected that associative learning would linearly improve with increasing age. We also anticipated that sensitivity to negative feedback would be highest in young children (who would demonstrate a greater decrease in pumping following balloon explosions), and would linearly decrease with age. Last, given that adolescence is developmentally intermediate to these changing processes (i.e., sensitivity to negative feedback and learning), and prior work indicating an adolescent peak in performance due to heightened responsiveness to feedback (van Der Schaaf, Warmerdam, Crone, & Cools, 2011), we expected to find an adolescent-specific peak in both pumps made and points earned on the quick-to-explode balloon condition, as this condition provides the lowest threshold for explosion feedback.

Method

Participants

The youth (children and adolescents) included were part of a larger, ongoing study of emotional development with children and adolescents from a large metropolitan area in the western United States. We included a total of 158 healthy children (46% boys), although 18 were excluded due to invalid responses (e.g., when the participant intentionally exploded all balloons), resulting in a total of 140 valid participants. This sample ranged in age from 3–17 years old ($M = 9.12$, $SD = 4.05$), and parents reported the following racial/ethnic distribution for these youths: 32% European American, 30% African American, 21% other or unknown, 12% Asian American, 12% Hispanic or Latino(a), 4% American Indian or Alaskan Native, 1% Native Hawaiian or Pacific Islander. This sample consisted of never-institutionalized youth (the comparison group) and a portion was previously included in a study examining risky decision making following institutional rearing (Humphreys et al., 2015). The adult sample has been described previously (Humphreys et al., 2013) and consisted of 76 (34% male) participants. This sample ranged in age from 18–36 years old ($M = 20.36$, $SD = 2.48$), and self-endorsed the following racial/ethnic distribution: 45% Asian American, 31% European American, 9% mixed or other, 5% American Indian or Alaskan Native, 4% African American, 4% Native Hawaiian or Pacific Islander, and 1% Hispanic/Latino(a). A total of 216 participants were included in the analyses. Prior studies with these samples included did not explicitly examine age-related changes on the BELT, and by combining existing samples we had the opportunity to examine behavior on this task in a wide age range.

Procedure

Recruitment methods for the youth sample included California birth records, UCLA institutional review board (IRB)-approved local newspaper ads, and online classifieds. To be eligible for the study, all participants were required to be free of psychiatric or neurological illness and major life trauma as determined via phone screening. Exclusionary criteria included an estimated IQ of less than 80 (for participants age 6–17 years) or severe physical handicap (e.g., quadriplegic, blind, or deaf).

Families were then invited to our laboratory for in-person assessments. Following parent consent and child assent, children completed a standardized test of cognitive ability, self-report measures, and computerized tasks. Parents completed rating scales based on their children's behavior and parenting practices. Procedures for the adult sample can be found in Humphreys et al. (2013). The UCLA IRB approved all study procedures.

Measures

Demographic information. Child age and sex were collected via parent report during phone screening. Date of birth was confirmed at the in-person assessment. The adult sample completed this information via self-report at the time of the assessment.

Balloon emotional learning task (BELT). All participants completed the BELT (Humphreys et al., 2013), a computerized risky decision-making task with three different conditions, each with different corresponding explosion points. See Figure 1 for a visual display of the task. For example, pink balloons always exploded at 19 pumps ("slow-to-explode"), orange balloons exploded variably at 7 pumps, 13 pumps, or 19 pumps distributed equally across each third of the task ("variable"), and blue balloons always exploded at 7 pumps ("quick-to-explode"), therefore providing the lowest threshold for feedback. Participants were asked to press a button to "pump up" balloons and earn points based on the number of pumps for each of the 27 balloon trials (i.e., more pumps = more points). Explosions occurred at an initially unknown number of pumps, resulting in the loss of all points for that trial. Balloons color–condition pairings were counterbalanced across participants, and there was an equal number of each balloon condition across each third of the task. Participants were not told that colors signified different response contingencies, but were explicitly told that not all balloons would pop at the same point.

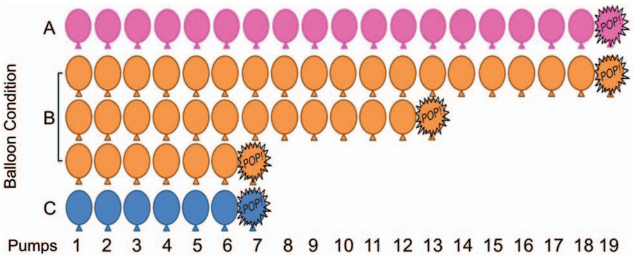

Figure 1. Visual display of the balloon emotional learning task by balloon condition: (A) slow-to-explode, (B) variable, and (C) quick-to-explode. See the online article for the color version of this figure.

Data Analysis

The BELT produces several potential outcome measures of interest: (a) number of pumps made out of number of possible pumps, (b) number of points earned out of number of possible points, (c) postexplosion pump reduction as a measure of sensitivity to negative feedback, and (d) gain in number of points earned from the first third to the second third of the task as a measure of associative learning, given that the most rapid learning occurred during this period of the task, and in concert with other work emphasizing early learning in decision-making tasks (Maddox, Baldwin, & Markman, 2006). Linear mixed models with maximum likelihood estimation were used to accommodate the nested structure of the data (i.e., trials within individuals). Age and age^2 (following Winsorizing of one adult participant's age from 36 years to the next highest value of 26 years, because it fell 3 *SD*s above the mean) were included as predictors to examine potential changes in outcomes by linear and quadratic age. Participant age (centered), age^2, balloon condition (slow-to-explode, quick-to-explode, and variable), and trial were examined as fixed-effects predictors of outcomes, with random slope and intercept within individuals. Balloon condition by age and age^2 interactions were examined. Sex was included as a covariate for all analyses, though was not a significant predictor for any outcome.

To test mediation, per expert recommendations (e.g., Hayes et al., 2009; MacKinnon, Fairchild, & Fritz, 2007), we conducted a single step test of mediation using SPSS PROCESS (Model 4; Hayes, 2013). To assess the indirect effect, a nonparametric bootstrap procedure using sampling with replacement ($n = 5000$) was implemented and 95% bias corrected and accelerated confidence intervals (CI) were calculated for the indirect effect. If the CI did not include zero, the indirect effect was considered statistically significant.

Results

Table 1 provides a correlation matrix and descriptive statistics for the independent variables of interest and outcomes produced by the

Table 1
Correlation Matrix and Descriptive Statistics for Study Variables

Variable	1	2	3	4	5	6	7	8
1. Age	1							
2. Sex (male = 1)	$-.12^{\dagger}$	1						
3. Slow-to-explode pumps	$.40^{***}$	.04	1					
4. Variable pumps	$.39^{***}$	.02	$.79^{***}$	1				
5. Quick-to-explode pumps	$.41^{***}$	$-.02$	$.55^{***}$	$.72^{***}$	1			
6. Slow-to-explode points	$.46^{***}$	.01	$.89^{***}$	$.76^{***}$	$.60^{***}$	1		
7. Variable points	$.32^{***}$	$-.11^{\dagger}$	$.38^{***}$	$.52^{***}$	$.62^{***}$	$.50^{***}$	1	
8. Quick-to-explode points	.10	$-.10$	$-.39^{***}$	$-.41^{***}$	$-.27^{***}$	$-.31^{***}$	$-.02$	1
Mean (*SD*) or %	13.02 (6.32)	42%	.41 (.19)	.51 (.16)	.81 (.14)	.39 (.15)	.40 (.09)	.46 (.19)

† $p < .10$. *** $p < .001$.

BELT. Age was positively correlated with pumps on all three balloon conditions, and points on the slow-to-explode and variable condition. There was no correlation between age and points on the quick-to-explode condition. There was a positive correlation between pumps and points for the slow-to-explode and variable conditions, and a negative correlation between these metrics in the quick-to-explode condition, indicating that these represented separable constructs.

Pumps

The mixed-effects analysis for pumps on the task, which included 27 observed trials for each of the 216 participants, indicated significant effects of balloon condition, $F(1, 5661.71) = 889.53$, $p < .001$, trial, $F(1, 348.46) = 6.02$, $p = .015$, and age, $F(1, 222.07) = 42.13$, $p < .001$ (see Figure 2). On average, the proportion of pumps made was highest on the quick-to-explode condition (.81, 95% CI [.79, .83]), followed by the variable condition (.51, 95% CI [.49, .53]), and the slow-to-explode condition (.41, 95% CI [.39, .43]), all of which significantly differed from each other (*ps* $< .001$). Pumps decreased across the course of the task. Age was associated with more pumps (Estimate = .01 [.001], $p < .001$, 95% CI [.001, .01]), while age^2 was not a significant predictor of overall pumps. However, a significant balloon condition by age^2 interaction was found, $F(1, 5661.71) = 38.50$, $p < .001$. Analyses were then conducted within each balloon condition to determine the shape of age-related change within each condition. For the slow-to-explode condition, there was a linear effect of age, $F(1, 219.01) = 11.21$, $p < .001$, as well as a quadratic effect of age, $F(1, 219.01) = 4.22$, $p = .04$. For the variable condition, there was a linear effect of age, $F(1, 222.76) = 31.46$, $p < .001$; the quadratic effect of age was not significant, $F(1, 222.76) = 2.73$, $p = .10$. For the quick-to-explode condition, there was a significant linear effect, $F(1, 217.65) = 42.35$, $p < .001$, and a significant quadratic effect of age, $F(1, 217.65) = 12.38$, $p < .001$. As can be observed in Figure 2, the age-related pattern of pumps on the slow-to-explode and variable conditions was relatively flat until adolescence, and demonstrated a steep incline from adolescence into adulthood. However, pumps on the quick-to-explode condition increased in early childhood and peaked in late adolescence (age 18). In summary, pumps increased with age, and for the quick-to-explode condition, pumps peaked during adolescence.

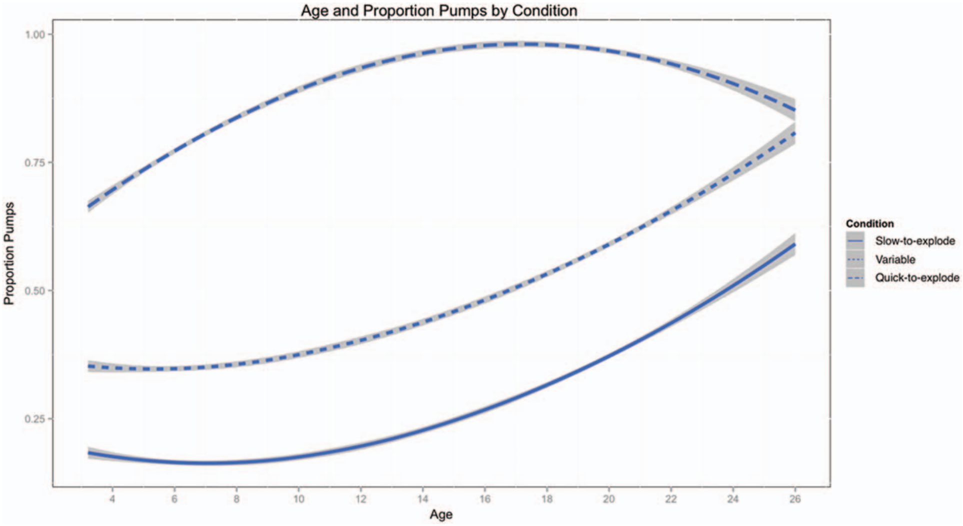

Figure 2. Proportion of number of pumps made out of possible number of pumps across development age by task condition. The gray area represents the 99% CI bounds for the best fit lines. See the online article for the color version of this figure.

Points

The mixed-effects analysis for points on the task indicated significant effects of balloon condition, $F(1, 5804.07) = 194.37$, $p < .001$, trial, $F(1, 678.86) = 30.99$, $p < .001$, and age, $F(1, 222.54) = 58.32$, $p < .001$ (see Figure 3). On average, proportion of points earned was highest on the quick-to-explode condition (.46, 95% CI [.45, .48]), whereas the variable (.39, 95% CI [.38, .41]) and slow-to-explode conditions (.39, 95% CI [.37, .40]) did not significantly differ from one another. Points significantly increased across the task and with age. However, significant balloon condition by age and balloon condition by age^2 interactions were found, $F(1, 5804.07) = 5.27$, $p = .005$ and $F(1, 5804.07) = 26.24$, $p < .001$, respectively. Analyses were conducted within each balloon condition to determine the shape of age-related change within each condition. For the slow-to-explode condition, there was a linear, $F(1, 224.30) = 20.97$, $p < .001$, and quadratic effect of age, $F(1, 224.30) = 4.13$, $p = .04$. For the variable condition, a linear effect of age was found, $F(1, 223.53) = 22.88$, $p < .001$; the quadratic effect was not significant, $F(1, 223.53) = 2.70$, $p = .10$. For the quick-to-explode condition, there was both a significant linear, $F(1, 224.93) = 7.63$, $p = .006$, and quadratic effect of age, $F(1, 224.93) = 14.26$, $p < .001$. As can be seen in Figure 3, proportion points earned on the slow-to-explode and variable conditions were relatively flat until adolescence and inclined steeply from adolescence into adulthood. Proportion points earned on the quick-to-explode condition, however, demonstrated a clear peak in mid-adolescence (age 14). Though adults earned the most points on the slow-to-explode and variable conditions, adolescents earned the most points for the quick-to-explode condition, which had the lowest explosion point and therefore provided feedback regarding its explosion threshold with the fewest number of pumps. We next sought to examine the potential differences in task behavior that resulted in the differing success found in adolescents and adults based on balloon condition.

Learning

To assess associative learning during the task, we examined the change in points earned from the first third to the second third of the task, within each balloon condition. As noted above, the most rapid learning occurred during this period of the task, and early learning in decision-making tasks has been a focus of study (Maddox et al., 2006). Ordinary least squares linear regression was used to examine the impact of age and age^2 on associative learning, statistically controlling for sex and points earned on the first third in each condition. For plotting purposes (see Figure 4) participants were grouped by age (children: ages 3–11; adolescents: ages 12–17; and adults: ages 18 and older). A significant effect was found for linear age on the slow-to-explode condition ($\Delta R^2 = .05$, $\beta = .23$, $p < .001$, 95% CI [–.01, .10]); the quadratic effect was not significant ($\Delta R^2 = .01$, $\beta = .08$, $p = .19$, 95% CI [–.01, .03]). Post hoc pairwise comparisons using the least significant difference test for the age groups described above revealed that adults demonstrated significantly more learning than the adolescent and child groups ($ps < .002$), which did not significantly differ from each other ($p = .86$). For the variable condition, there was a significant effect of linear age ($\Delta R^2 = .02$, $\beta = .16$, $p < .001$, 95% CI [–.02, .06]), and again the quadratic effect was not significant ($\Delta R^2 = .001$, $\beta = –.03$, $p = .48$, 95% CI [–.01, .01]). Post hoc comparisons showed that adults and adolescents did not significantly differ from each other ($p = .87$), and both groups demonstrated significantly more learning than the child group ($ps < .04$). For the quick-to-explode condition, linear age was not a significant predictor of learning ($\Delta R^2 = .001$, $\beta = .04$, $p = .54$, 95% CI [–.01, .01]), though the quadratic effect of age was ($\Delta R^2 = .04$, $\beta = –.19$, $p < .001$, 95% CI [–.01, .08]). Pairwise comparisons demonstrated that adolescents showed significantly more learning than adult and child groups ($ps < .02$), which did not significantly differ from each other ($p = .90$).

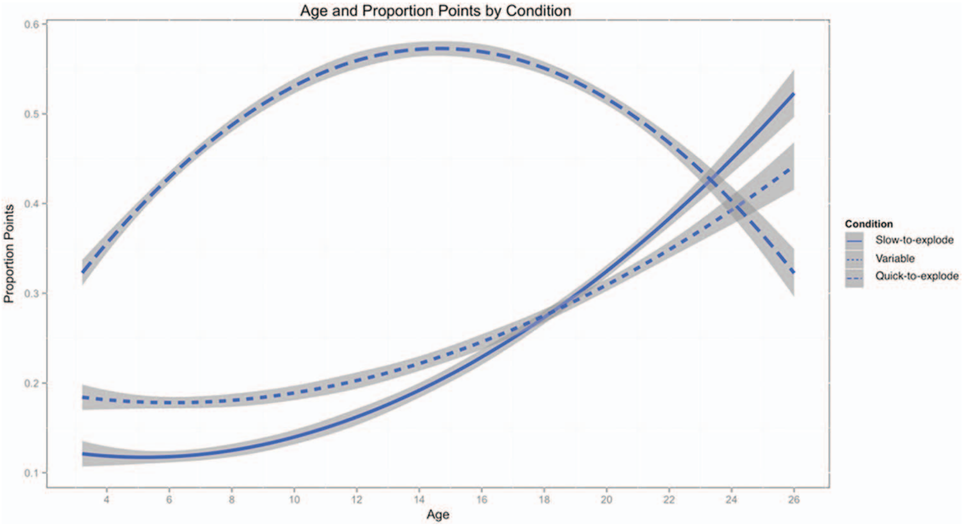

Figure 3. Proportion number of points earned out of possible number of points across development age by task condition. The gray area represents the 99% CI bounds for the best fit lines. See the online article for the color version of this figure.

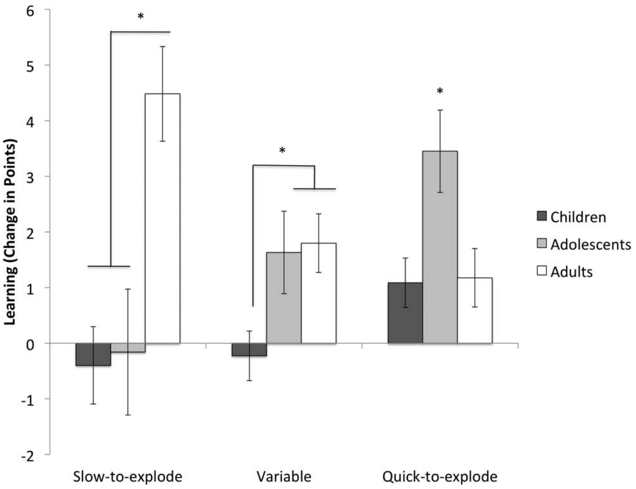

Figure 4. Learning by age group and condition. $^*p < .05$.

Learning as a Mediator of the Association Between Age and Points

We next evaluated whether learning mediated the association between age and total points earned, statistically controlling for sex and points earned on the first third of the task. The 95% CI for the indirect effect of learning did not contain zero (point estimate = .85 [.18], 95% CI [.51, 1.23], thus supporting that a gain in points mediated the association between age and points earned on the task, even after accounting for initial age differences in points earned on the first third of the task.

Postexplosion Behavior

Because decision making had been influenced by negative feedback (i.e., explosions) from previous trials (Humphreys & Lee, 2011; Humphreys et al., 2015), we examined age-related changes in sensitivity to negative feedback using postexplosion reduction in number of pumps on the quick-to-explode condition. This balloon condition had the lowest threshold for explosions and accordingly provided the most opportunity to examine postexplosion reactivity. Postexplosion pump reduction was calculated by taking the mean of the difference in number of pumps made on each explosion trial and the trial immediately following from the same balloon condition. This measured sensitivity to negative feedback, positive values of which indicated fewer pumps on the subsequent balloon, whereas a value of zero indicated no change in pump number following the balloon explosion. Thirteen individuals did not explode a balloon, and were therefore not included in this analysis. The mean for postexplosion pump reduction was .21 ($SD = .14$), and a one-sample t test demonstrated that it significantly differed from zero ($p < .001$) such that, on average, individuals pumped less following an exploded balloon. There was a linear effect of age on postexplosion pump reduction, $t(200) = -4.32$, $B = -.01$ [.002], $p < .001$, 95% CI [$-.01$, $-.004$], but no quadratic effect. For graphing purposes, we plotted standardized (z-score) sensitivity to negative feedback for all of the age groups (i.e., children, adolescents, and adults) against standardized associative learning (see Figure 5). This figure indicates that while learning increased across developmental periods, sensitivity to negative feedback decreased. Whereas children and adults were high on at least one of these scores, adolescents were intermediate on both.

Sensitivity to Negative Feedback as a Mediator of the Association Between Age and Points

We conducted another mediation analysis to examine whether sensitivity to negative feedback mediated the association between age and total points earned, with sex as a covariate. The 95% CI for the indirect effect of sensitivity to negative feedback did not contain zero, point estimate = .16 [.09], 95% CI [.02, .36], thus, sensitivity to negative feedback also mediated the association between age and points earned on the task.

Discussion

In a cross-sectional sample of individuals from preschool age to early adulthood we observed linear age-related changes in learning (gain in points) and sensitivity to negative feedback (postexplosion pump-number reduction) that were associated with nonlinear changes in both behavior and outcome on a risky decision-making task. Results indicated that age-related patterns in pumps made and points earned varied by task condition. Conditions with higher thresholds for negative feedback (i.e., slow-to-explode, variable) exhibited positive age-related increases in points, whereas an adolescent peak in points was found on the condition with the lowest threshold for negative feedback (i.e., quick-to-explode).

The Role of Learning During Risky Decision Making

Learning from experience is clearly important to successful decision making, and sequential tasks test the ability to demonstrate how learning affects subsequent behavior. Older age is associated with greater use of feedback to guide behavior (Byrnes & Beilin, 1991; Byrnes & Overton, 1986). Byrnes and colleagues found that adults not only made better choices at the beginning of a decision-making task compared with adolescents, they also learned more through task experience (Byrnes, Miller, & Reynolds, 1999). This is in concert with our findings that adults dem-

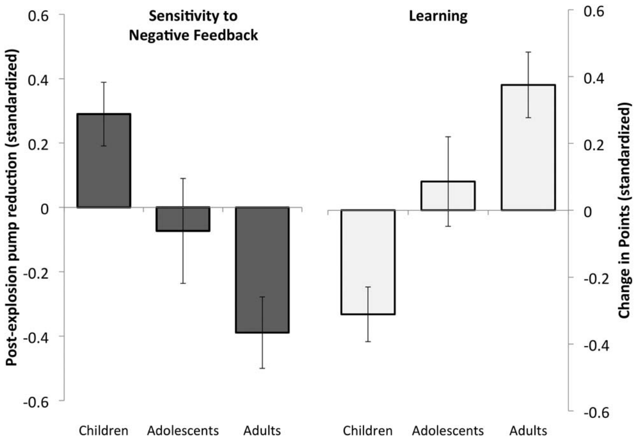

Figure 5. Postexplosion pump-number reduction on the quick-to-explode balloon condition and learning by age group.

onstrated the greatest learning on the BELT. Learning mediated the association between age and total points earned on the task, which supports other work that revealed age-related increases in successful risky decision making (Cassotti et al., 2014). Adults are able to distinguish between balloon conditions from experience (Humphreys et al., 2013), learning that the slow-to-explode balloons would explode after a greater number of pumps and the quick-to-explode balloons would explode after a smaller number of pumps.

It is important to note that learning was observed across all age groups, indicating that the task was likely understood even by young participants. Work from other implicit learning tasks has indicated that this learning may have first occurred at an emotional, rather than strictly cognitive level. The somatic marker hypothesis (Bechara, Damasio, & Damasio, 2000; Bechara, Damasio, Damasio, & Lee, 1999; Damasio, 1994), posits that emotions play a crucial role in learning and decision making, as the feelings experienced after making decisions result in learning that enables better subsequent decisions.

The Role of Sensitivity to Negative Feedback During Risky Decision Making

Considering the results from an affective development perspective, this work is consistent with evidence of a normative, increased negativity bias in childhood (Tottenham et al., 2013), when children seem particularly susceptible to potentially negative information (van den Bos et al., 2012). This negativity bias is consistent with the heightened amygdala reactivity commonly observed in childhood, a marker of emotional reactivity at the neural level (Decety, Michalska, & Kinzler, 2012; Decety & Michalska, 2010; Gee et al., 2013; Swartz, Carrasco, Wiggins, Thomason, & Monk, 2014; Vink, Derks, Hoogendam, Hillegers, & Kahn, 2014) paired with immature top-down regulation from the prefrontal cortex (Decety et al., 2012; Gabard-Durnam et al., 2014; Gee et al., 2013; Perlman & Pelphrey, 2011), which is a neural phenotype linked to negative emotionality (Goldin, McRae, Ramel, & Gross, 2008). We found that the youngest participants were characterized by high sensitivity to negative feedback and the oldest participants demonstrated low sensitivity to negative feedback; adolescents were intermediate in this behavior. That is, younger age was associated with a greater behavioral reaction (reduced pump numbers on subsequent trials) to an explosion. An intermediate level of sensitivity to negative feedback appeared to result in better outcomes for adolescents on the quick-to-explode condition, whereas the same advantage was not found in conditions with a higher threshold for negative feedback. Thus, for the quick-to-explode condition, the adolescents' intermediate level of loss sensitivity resulted in a "sweet spot," allowing this group to outperform both younger and older participants, as well as providing evidence that adolescents were invested in performing well on the task. A similar adolescent peak in performance (compared with both younger children and adults) was found in a study of reversal learning (Van Der Schaaf et al., 2011). The authors also pointed to adolescents' intermediate level of punishment learning, relative to younger children and adults, for their success on this task and ruled out age-related differences in motivation and arousal for the observed inverted U-shaped pattern across development. The BELT, unlike some other implicit decision-making tasks (see Bechara, Damasio, Tranel, & Damasio, 1997), allowed for probing that revealed that increased sensitivity to negative feedback may be advantageous only under certain conditions.

Several converging studies have provided evidence that younger children and adolescents' heightened sensitivity to negative feedback can impair decision making in the context of risk (Aïte et al., 2012; Cassotti, Houdé, & Moutier, 2011; Huizenga, Crone, & Jansen, 2007). For example, children and adolescents are more likely to shift from an advantageous choice following negative feedback compared with adults (van den Bos, Güroğlu, van den Bulk, Rombouts, & Crone, 2009), which can result in less adaptive outcomes. On the BELT, this heightened sensitivity likely hampered exploration that would have allowed these younger participants to earn more points on the slow-to-explode balloon condition.

Taken together, the decreased sensitivity to negative feedback found in adults, in combination with predictive error learning, led to successful decision making under risk in most circumstances. Detecting errors facilitates learning, and so does the ability to tolerate some negative feedback (Cassotti et al., 2014). Adults were willing to tolerate more exploded balloons to learn more about the task parameters, enabling them to earn more points on balloon conditions with higher explosion thresholds; yet each balloon exploded resulted in a loss of all points on that trial. Thus, this ability to tolerate loss comes with a cost. The adults' relative insensitivity to balloon explosions appeared to result in slower learning of the quick-to-explode threshold and fewer points earned on this condition than adolescents.

There are several limitations to this study that should be noted. Although we treated age as a continuous variable in initial analyses, we defined adolescence broadly in the grouped analyses, and therefore these findings may not be directly comparable to studies using alternative age cut-off points. Related to this point, our analyses were based on age in years, rather than pubertal status, which may be an important predictor in understanding developmental shifts in emotional processing in adolescence (Steinberg, 2007). In addition, though our wide age range allowed us to consider age-related changes, the cross-sectional nature of the sample precluded us from studying intraindividual change. It is also possible that, given the large range of ages included, understanding of the BELT may have varied based on developmental level, because the task involved multiple decisions to be made. Future work may lead to benefits by obtaining participants' perceived strategies during and/or after the task. Whereas the BELT provides some distinct advantages over more simplistic tasks, more complex tasks tend to have better ecological validity (Schonberg, Fox, & Poldrack, 2011). It is unclear how outcomes from the BELT align with real-world behavior, though there is evidence that behavior on the BART is associated with real-world risk-taking behavior (Lejuez et al., 2002, 2007). Previous work has linked responses to the BELT to personality traits (e.g., sensation seeking and associative sensitivity; Humphreys et al., 2013), as well as separation anxiety (e.g., Humphreys et al., 2015). Some have recommended separation of the study of risky choice and sensitivity to gains and losses (van Duijvenvoorde & Crone, 2013), which were combined in the present task. As with Cohen et al. (2010), our task allowed for the decomposition of stimulus, choice, and feedback, but also differed from other risky decision-making tasks in that the parameters were fixed but unknown to participants, who may or may not have determined the explosion thresholds during the 27 trials. Future research will need to address these methodological issues with longer tasks and more varied rewards and losses.

In conclusion, we found overall age-related increases in learning on a risky decision-making task, as well as overall age-related decreases in sensitivity to negative feedback. Both factors predicted changes in successful, risky decision making. Examiners of developmental changes in risky decision making and the results of this behavior should take into account these two changing systems. The use of instrumental learning tasks, in which participants choose the degree to which they explore the environment, provides a useful addition to traditional associative learning and risky decision-making tasks.

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