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SHORT REPORT

Eye blink rate predicts reward decisions in adolescents

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Abstract

The ventral striatum displays hyper-responsiveness to reward in adolescents relative to other age groups, and animal research on the developmental trajectory of the dopaminergic system suggests that dopamine may underlie adolescent sensitivity to reward. However, practical limitations prevent the direct measurement of dopamine in healthy adolescents. Eye blink rate (EBR) shows promise as a proxy measure of striatal dopamine D2 receptor function. We investigated developmental differences in the relationship between EBR and reward-seeking behavior on a risky decision-making task. Increasing EBR was associated with greater reward maximization on the task for adolescent but not adult participants. Furthermore, adolescents demonstrated greater sensitivity to reward value than adults, as evinced by shifts in decision patterns based on increasing potential reward. These findings suggest that previously observed adolescent behavioral and neural hypersensitivity to reward may in fact be due to greater dopamine receptor activity, as represented by the relationship of blink rate and reward-seeking behavior. They also demonstrate the feasibility and utility of using EBR as a proxy for dopamine in healthy youth in whom direct measurements of dopamine are prohibitively invasive.

Research highlights

- Study demonstrates the feasibility and utility of using eye blink rate (EBR) as a proxy for dopamine in healthy youth in whom direct measurements of dopamine are prohibitively invasive.
- EBR was associated with reward-seeking behavior in adolescents but not adults
- Adolescents show more value sensitivity than adults.

Introduction

Adolescents exhibit high sensitivity to rewards. Functional magnetic resonance imaging (fMRI) has been used to investigate the neural substrates of adolescent responsiveness to reward, and evidence generally demonstrates that the ventral striatum (VS) is hyper-responsive to the anticipation and experience of reward (May, Delgado, Dahl, Stenger, Ryan *et al.*, 2004; Ernst, Nelson, Jazbec, McClure, Monk *et al.*, 2005; Galván, Hare, Parra, Penn, Voss *et al.*, 2006; Cohen, Asarnow, Sabb, Bilder,

Bookheimer *et al.*, 2010; Geier, Terwilliger, Teslovich, Velanova & Luna, 2010; van Leijenhorst, Zanolie, Van Meel, Westenberg, Rombouts *et al.*, 2010) and to value more generally (Barkley-Levenson & Galván, 2014) in adolescents relative to other age groups, although such findings are not universal (e.g. Bjork, Knutson, Fong, Caggiano, Bennett *et al.*, 2004; Bjork, Smith, Chen & Hommer, 2010 and Bjork & Pardini, 2015, who suggest that their divergent results may be due to task-specific characteristics such as motor preparation and attentional demands and individual differences among adolescents on traits such as behavioral disinhibition). While fMRI has been key in elucidating the importance of the VS in adolescent reward responsiveness, complementary techniques are required to explore the neurochemical mechanisms underlying value processing in adolescents. Of particular interest is striatal dopamine, which is associated with the experience and expectation of reward (e.g. Schultz, Apicella & Ljungberg, 1993; Schultz, Dayan & Montague, 1997; Ikemoto & Panksepp, 1999).

Aspects of the dopamine system differ in adolescence relative to childhood or adulthood. The number of D1

and D2 dopamine receptors in the rat striatum peaks during adolescence before undergoing pruning (Teicher, Andersen & Hostetter, 1995), and adolescent rat dopaminergic neurons release more dopamine in response to environmental or pharmacological stimulation than adult neurons do (Laviola, Pascucci & Pieretti, 2001; Laviola, Macrì, Morley-Fletcher, and Adriani, 2003). However, direct investigation of dopamine in the human adolescent brain poses a methodological challenge. Invasive electrode recordings of the human basal ganglia are rare and are only conducted on patients with severe neurological conditions such as Parkinson's Disease or obsessive-compulsive disorder (Engel, Moll, Fried & Ojermann, 2005; Münte, Heldmann, Hinrichs, Marco-Pallares, Krämer *et al.*, 2007; Münte, Heldmann, Hinrichs, Marco-Pallares, Krämer *et al.*, 2008). Positron emission tomography (PET) allows for the measurement of components of the dopamine system in healthy and clinical human populations through the injection of radioactive ligands (Volkow, Fowler, Gatley, Logan, Wang *et al.*, 1996), but this technique remains prohibitively invasive for use in non-medical developmental research.

One technique that captures aspects of dopaminergic functioning without the injection and radiation exposure of PET is the measurement of eye blinks (Karson, 1983). Spontaneous eye blink rate (EBR) in primates correlates positively with D2-like receptor availability in the striatum (Taylor, Elsworth, Lawrence, Sladek, Roth *et al.*, 1999; Groman, James, Seu, Tran, Clark *et al.*, 2014) and performance of a dopamine-driven learning task (Groman *et al.*, 2014). Human clinical research supports this, demonstrating that EBR is suppressed in individuals with Parkinson's disease (Karson, Lewitt, Calne & Wyatt, 1982) and elevated in unmedicated patients with schizophrenia (Karson, 1983), disorders with known dopaminergic dysfunction. Similarly, higher EBR correlates with impaired motor response inhibition (Colzato, van den Wildenberg, van Wouwe, Pannebakker & Hommel, 2009), consistent with the role of dopamine in impulsivity (Frank, Samanta, Moustafa & Sherman, 2007), and lower EBR correlates with greater learning from negative outcomes, consistent with the role of the dopamine D2 pathway in avoidance learning (Slagter, Georgopoulou & Frank, 2015). The relationship between dopamine and EBR appears to be striatum-specific: The positive relationship between EBR and schizophrenia is consistent with that disorder's hyperactive mesolimbic dopamine activity but not its hypoactive prefrontal cortical dopamine activity (Brisch, Saniotis, Wolf, Biellau, Bernstein *et al.*, 2014), while in primates EBR has been shown to correlate with dopamine levels specifically in the rostral body of the ventromedial caudate, but not with other nigrostriatal regions (Taylor *et al.*, 1999). Given the

converging findings from primate (Groman *et al.*, 2014) and human (Slagter *et al.*, 2015) research, EBR appears to specifically reflect striatal dopamine D2 receptor availability or function, although this relationship has not yet been directly observed in humans using PET. In addition, clinical studies show that EBR increases when children and adolescents are administered ziprasidone, an indirect dopamine agonist (Sallee, Gilbert, Vinks, Miceli, Robarge *et al.*, 2003), suggesting that EBR is an effective proxy for direct dopamine measurement in adolescents as well as in adults.

The present study aims to leverage the well-established finding from animals and adult humans that EBR is a behavioral biomarker of striatal dopamine activity and use it as a proxy for dopamine in the healthy adolescent brain. Our goal is to investigate developmental differences in the relationship between dopamine and reward sensitivity using a risky decision-making task and the measurement of baseline EBR in adolescent and adult participants. We focus on decision-making under risk for three reasons. First, risky behavior is associated with increased dopamine levels (Riba, Krämer, Heldmann, Richter & Münte, 2008; Zald, Cowan, Riccardi, Baldwin, Ansari *et al.*, 2008). Second, adolescents exhibit high risky behavior in the real world. Third, risk-taking tasks provide an easily understandable paradigm in which to introduce the potential for losses as well as gains, allowing us to explore the extent to which adolescent sensitivity to reward is actually reflective of overall sensitivity to value. The task employed here allows for three different decision strategies: probability-maximizing, gain-maximizing, and loss-minimizing. We hypothesized that if dopamine is driving reward-seeking behavior, participants with higher EBR would more frequently select the gain-maximizing strategy. Furthermore, if adolescent neurobiological conditions produce heightened dopamine-related reward sensitivity, we would expect a stronger relationship between EBR and gain-maximizing for adolescents versus adults.

Methods

Participants

Twenty-five middle and high school-aged adolescent participants (age range 13,3–18,5, $M = 15.7$, $SD = 1.6$, 13 female) were recruited from the community. An additional 26 adult participants (age range 18,11–22,5, $M = 20.4$, $SD = 0.9$, 16 female) were recruited from the university undergraduate population. All participants were fluent in English. Adult participants self-reported that they had no history of psychiatric diagnoses and

were not currently taking any psychoactive medications; the parents/guardians of adolescent participants reported the same information.

Materials

Baseline eye blink rate

Participants completed two 5-minute video recording sessions for the purpose of measuring spontaneous eye blink rate. Videos were collected using the Apple iSight camera and PhotoBooth program. Participants were seated approximately 25 inches from the camera during recording. Participants were instructed to face a black screen with a fixation cross and to remain awake while behaving normally during the 5-minute period. Participants with corrected vision were allowed to wear either glasses or contact lenses based on their preference, in the interest of capturing naturalistic data.

Survey measures

Because sleepiness has been related to EBR (Barbato, Ficca, Muscettola, Fichelle, Beatrice *et al.*, 2000) and

sleep-deprivation has previously been shown to affect performance on the task used in this study (Venkatraman, Huettel, Chuah, Payne & Chee, 2011), we collected self-reported sleepiness data from participants using the Stanford Sleepiness Scale (SSS; Hoddes, Zarcone, Smythe, Phillips & Dement, 1973), a measure of sleepiness/alertness at the time of assessment.

Roulette Game

Participants completed a total of two runs of the Roulette Game (RG; Figure 1), a novel version of a task originally designed by Payne (2005) to assess probability sensitivity in risky choice. In this task, participants were presented with a series of 'wheel' gambles with a 1/3 probability of gaining money (ranging from +\$3.50 to +\$8), a 1/3 probability of losing money (ranging from −\$4 to −\$8.50) and a 1/3 probability of receiving \$0. A total of 400 trials were created and divided among five runs of 80 trials each; the run number and order were counterbalanced across participants, and each participant completed two runs for a total of 160 trials. After viewing the gamble for 1000 ms, participants were presented with an amount of money

Figure 1 Example of a trial from the Roulette Game. Participants view a gamble for 1000 ms. Participants are then shown an amount of money and are asked to select the space on the wheel to which they wish to add that amount. The decision phase is self-paced. After making a selection, participants experience a 500 ms inter-trial interval before viewing the next gamble.

(ranging from \$1 to \$2.50) and instructed to add that amount of money to one of the three spaces on the 'wheel', changing the value of that gamble. Thus, on each trial the participant made a decision employing one of three strategies. A gain-maximizing (GMax) decision was one where the participant chose to add money to the positive-value space on the 'wheel', increasing the maximum possible amount they could win without altering outcome probabilities. A probability-maximizing (PMax) decision was one where the participant added money to the reference (\$0) space, increasing the probability from 1/3 to 2/3 chance of winning some amount of money without altering the range of values. Finally, a loss-minimizing (LMin) decision was one where the participant added money to the negative-value space, reducing the value of the potential loss without altering outcome probabilities. Because the probabilities of each space are equal, the expected value of a given value-added gamble is equal for each of the three decision strategies. For example, the gamble [+/\$8, \$0, −\$6.50] shown in Figure 1 has an initial expected value of \$0.50. After participants add \$1 to any of the three spaces, the expected value is \$0.83. Therefore, no one strategy can be considered optimal because no one strategy maximizes expected value, and different strategies may be seen as reflecting different but equally valid approaches to risk-taking. Across all trials, initial expected values ranged from −\$1.67 to \$1.33, and value-added expected values ranged from −\$0.67 to \$2.17. Participants were informed that one trial (including the money added by the participant to the chosen space) would be selected at random at the end of the study and its outcome would be resolved for real money, with any gain or loss being added to or subtracted from their \$15 base pay for the session. This design incentivized participants to respond based on their actual preferences for every trial. In actuality, each trial was resolved such that either the reference or gain amount was selected at random, ensuring that all participants received at least \$15 for the testing session.

Procedure

All participants under the age of 18 completed informed assent while their parents or guardians provided informed consent; participants over the age of 18 provided informed consent. During testing, participants completed baseline eye blink recording, surveys, and the RG. Adolescent participants completed their testing in two separate sessions (with one EBR recording and one run of RG at each session) while adult participants completed two EBR recordings and two runs of RG in a single session. Adolescent EBR recordings were

separated by approximately one week and adult EBR recordings were separated by approximately one hour. No significant differences were observed within either the adolescent sample or the adult sample when comparing the two measurements of EBR, the number of GMax trials selected in each run, the number of PMax trials selected in each run, and the number of LMin trials selected in each run ($p > .05$ for all paired t -tests). Furthermore, correlations between each of these pairs were highly significant ($p < .01$ and $r > .5$ for all correlations), suggesting that the procedural difference does not explain our findings.

Eye blink rate analysis

Three independent raters counted the total number of blinks captured in each recording using a computerized scoring program described by Groman et al. (2014). Times during which participants' eyes were not visible were removed from the recorded total time, and eye blink rate (EBR), measured as blinks per visible minute (BPVM), was calculated for each recording. The intra-class correlation coefficient between the three raters was .988 ($p < .001$) for the first recording session and .986 ($p < .001$) for the second recording session; with satisfactory inter-rater reliability, the raters' scores were averaged for each recording.

Generalized linear mixed models

To assess the relationships among decision strategy selection, EBR, sleepiness, and task gain and loss values, we used generalized linear mixed models (Baayen, Davidson & Bates, 2008; Bolker, Brooks, Clark, Geange, Poulsen *et al.*, 2009), which incorporate both random effects (in this dataset, multiple trials and experimental runs for each participant) and non-normally distributed variables (in this dataset, binary 'yes' or 'no' responses for the selection of each decision strategy on each trial). Models were fitted by maximum likelihood using a Laplace approximation and all analyses were carried out with the 'lme4' package (Bates, Maechler, Bolker & Walker, 2014) in *R* (R Core Team, 2015).

Results

EBR results

Spontaneous eye blink rates recorded during two 5-minute baseline measurements demonstrated adequate test–retest reliability, $r(49) = .87$, $p < .001$, and were averaged for subsequent analyses. EBR ranged from 3.05

to 47.37 blinks per visible minute (BPM), with a mean of 20.04 BPM ($SD = 11.69$). Blink rate did not differ significantly between adolescent and adult participants, although the data trend toward adults having a higher average blink rate, $t(49) = -1.979$, $p = .053$.

Roulette Game results

Mean reaction times (GMax $M = 3678$ ms, $SD = 2763$ ms, PMax $M = 3589$ ms, $SD = 2178$ ms, LMin $M = 3204$ ms, $SD = 2160$ ms) did not differ between any of the decision strategies for the sample as a whole or for adolescent and adult participants analyzed separately. Adults responded significantly faster than adolescents for all decision strategies ($t(45) = 3.571$, $p < .001$ for GMax, $t(44) = 3.569$, $p < .001$ for PMax, $t(47) = 3.836$, $p < .001$ for LMin).

On average, adolescents employed the gain-maximizing (GMax) decision strategy on 22.9% of trials, the probability-maximizing (PMax) decision strategy on 33.1% of trials, and the loss-minimizing (LMin) decision strategy on 44.0% of trials. Adults employed the GMax strategy on 24.9% of trials, the PMax strategy on 26.6% of trials, and the LMin strategy on 48.5% of trials. Adolescents and adults did not differ significantly in the number of trials for which they employed the GMax strategy ($t(49) = -.265$, $p = .792$), the PMax strategy ($t(49) = .876$, $p = .385$), or the LMin strategy ($t(49) = -.551$, $p = .584$) (Figure 2).

Paired-samples t -tests revealed that, overall, participants employed the LMin strategy significantly more than the GMax strategy ($t(50) = -3.314$, $p = .002$) and significantly more than the PMax strategy

Figure 2 Percentage of trials employing each decision strategy for adolescent and adult participants. ** $p < .01$; * $p < .05$. Error bars represent standard error of the mean.

($t(50) = -2.401$, $p = .020$). The frequencies of the GMax and PMax strategies did not differ significantly from one another, $t(50) = -.956$, $p = .344$.

Effects of sleepiness

We investigated the effect of self-reported sleepiness on decision strategy selection using a generalized linear mixed model, with sleepiness as a fixed effect and participant and run number as random effects. The results of this model are shown in Table 1. This model demonstrated that sleepiness significantly increased the selection of the GMax strategy and significantly decreased the selection of the LMin strategy, consistent with prior research (Venkatraman *et al.*, 2011). A separate generalized linear mixed model revealed no significant effect of the interaction of sleepiness and age group on any of the decision strategies (GMax $B = -0.048$, $p = .954$, PMax $B = 1.132$, $p = .085$, LMin $B = -0.128$, $p = .856$), suggesting that this pattern does not differ between adolescents and adults. We did not observe a significant correlation between EBR and reported sleepiness, $r(74) = .128$, $p = .28$.

EBR and decision strategy

To investigate the effects of EBR on decision strategy, we conducted a generalized linear mixed model with blink rate as a fixed effect and participant and run number as random effects. The results of this model are shown in Table 2. This model demonstrated that increased blink rate was significantly associated with increased selection of the GMax strategy and decreased selection of the PMax strategy (Figure 3).

Effect of age on EBR and decision strategy

To explore whether the relationship between blink rate and decision strategy selection differed as a function of age, we conducted a generalized linear mixed model with the interaction term of blink rate by age group

Table 1 Effect of sleepiness on decision strategy selection

Decision strategy	Estimate	SE	p-value
GMax	0.261	0.059	<0.001
PMax	-0.032	0.053	0.553
LMin	-0.182	0.052	<0.001

GMax = gain-maximizing; PMax = probability-maximizing; LMin = loss-minimizing. Significant effects are in bold. Example of full model in R: GMax ~ sleepiness + (1 | participant) + (1 | run number), family = binomial

Table 2 Effect of EBR on decision strategy selection, combined and by age group

Decision strategy	All participants			Adolescents only			Adults only		
	Est.	SE	p	Est.	SE	p	Est.	SE	p
GMax	0.023	0.010	0.020	0.050	0.012	<0.001	−0.040	0.019	0.033
PMax	−0.024	0.011	0.023	−0.055	0.013	<0.001	0.029	0.017	0.102
LMin	−0.004	0.009	0.633	−0.011	0.012	0.363	0.006	0.015	0.688

GMax = gain-maximizing; PMax = probability-maximizing; LMin = loss-minimizing. Significant effects are in bold. Example of full model in R: GMax ~ baselineEBR + (1 | participant) + (1 | run number), family = binomial

Figure 3 Effect of blink rate on selection of decision strategies.**Table 3** Interaction of EBR and age group on decision strategy selection

Decision strategy	Estimate	SE	p-value
GMax	−0.093	0.022	<0.001
PMax	0.082	0.022	<0.001
LMin	0.017	0.018	0.355

GMax = gain-maximizing; PMax = probability-maximizing; LMin = loss-minimizing. Significant effects are in bold. Example of full model in R: GMax ~ baselineEBR * age group + (1 | participant) + (1 | run number), family = binomial

(adolescent or adult) as a fixed effect and participant and run number as random effects (Table 3). This analysis demonstrated a significant interaction of age group with blink rate for the GMax strategy, with increasing blink rate predicting increased gain-maximizing for adolescents but not for adults; in adults, increasing blink rate predicted decreased gain-maximizing (Figure 4A). Similarly, increasing blink rate predicted decreased probability-maximizing for adolescents but not for adults (Figure 4B). No significant interaction was observed for the LMin strategy (Figure 4C). These observations were confirmed by running the model of EBR on decision

strategy separately for the adolescent sample and the adult sample (Table 2).

Effects of changing values on decision strategy

We explored the extent to which changes in the potential gain and loss amounts presented in each gamble influenced participants' selection of decision strategies, as well as whether age group and EBR altered this sensitivity to value. For this analysis, we conducted generalized linear models predicting each of the three decision strategies, with gain amount and loss amount separately as fixed effects, for a total of six models (Table 4). For each model we included the interaction between age group and EBR, and included participant and run number as random effects. These analyses suggest that decision strategy selection is sensitive to monetary value; for example, increasing gain amounts are associated with reduced selection of the LMin strategy and increased selection of PMax and GMax strategies. Furthermore, age appears to affect value sensitivity in some instances. Adolescents show more value sensitivity than adults both in terms of the extent to which increasing gain amounts reduce LMin strategy

Figure 4 The relationship between blink rate and GMax strategy selection (A) changes as a function of age group, as does the relationship between blink rate and PMax strategy selection (B). The relationship between blink rate and LMin strategy selection (C) does not change as a function of age group. Gray areas represent 95% confidence intervals.

Table 4 Effects of increasing gain amount, loss amount, and interactions with age group and EBR on decision strategy selection

	GMax selection			PMax selection			LMin selection		
	Est.	SE	p	Est.	SE	p	Est.	SE	p
Gain Amount	0.231	0.074	0.002	0.278	0.067	<.001	-0.510	0.065	<.001
Gain Amt * Age	-0.033	0.047	0.471	-0.118	0.043	0.006	0.179	0.039	<.001
Gain Amt * EBR	-0.001	0.002	0.552	-0.001	0.002	0.587	0.003	0.002	0.104
Loss Amount	0.160	0.076	0.035	-0.109	0.071	0.123	0.175	0.070	0.012
Loss Amt * Age	-0.249	0.049	<.001	-0.161	0.047	<.001	0.191	0.043	<.001
Loss Amt * EBR	-0.004	0.002	0.047	-0.002	0.002	0.289	0.005	0.002	0.154

GMax = gain-maximizing; PMax = probability-maximizing; LMin = loss-minimizing. Significant effects are in bold. Example of full model in R: GMax ~ gain amount + gain amount * baselineEBR + gain amount * age_group + (1 | participant) + (1 | run number), family = binomial

selection (Figure 5A) and increase PMax strategy selection (Figure 5B).

Discussion

In this study, we observe a positive relationship between EBR and reward-seeking behavior, consistent with the role of striatal dopamine in reward-seeking and further supporting the use of EBR as a dopamine proxy measure in healthy youth. The positive relationship between EBR and reward-seeking was driven by adolescents (and indeed the effect appears to be reversed for adults). One interpretation is that a stronger relationship between dopamine and reward sensitivity exists in adolescents than in adults, consistent with the adolescent ventral striatum's hypersensitivity to reward frequently observed with neuroimaging. Furthermore, we demonstrate that EBR can be measured inexpensively, reliably and non-invasively in adolescents and adults.

Figure 5 Small increases in gain amount are more strongly associated with decreased selection of the LMin strategy for adolescents than for adults (A), and are more strongly associated with increased selection of the PMax strategy for adolescents than for adults (B). Gray areas represent 95% confidence intervals.

The trend in our data toward adults having higher average EBR than adolescents, though initially appearing to be at odds with adolescent dopaminergic hyper-responsiveness, is in fact consistent with the observation of lower basal levels of dopamine for periadolescent versus adult rats in the synaptic cleft of the striatum (Andersen & Gazzara, 1993). Despite lower basal dopamine levels, adolescent rats actually release more dopamine than adults when highly stimulated by environmental or pharmacological challenges (Laviola *et al.*, 2003). Our findings are consistent with a potentially similar dopaminergic profile in human development, wherein adolescents have lower baseline dopamine measurements but greater sensitivity to motivationally relevant stimuli. Because our adult sample consisted of young adults, many of whose neurochemical functioning may still be similar to their adolescent counterparts, investigating this effect with the inclusion of an older adult sample would help understand the developmental trajectory of human dopamine.

Our findings can be interpreted in the context of two of the major developmental models of adolescent risky decision making: the neurodevelopmental imbalance model (e.g. Casey, Jones & Hare, 2008; Steinberg, 2007), which proposes that under certain conditions adolescents' hypersensitive motivational systems and maturing cognitive control systems interact to produce risk-taking behavior, and fuzzy-trace theory (Reyna, 2004; Reyna & Rivers, 2008), which proposes that verbatim-based processing (reasoning based on costs, benefits and probabilities) is more prevalent early in life and that gist-based processing (rapid reasoning based on heuristics formed through experience) increases from childhood to adulthood (see Defoe, Dubas, Figner & van Aken, 2015, for a meta-analysis incorporating both models). Notably, both theories predict that adolescents will be more sensitive than adults to changes in reward magnitude, as we observe here. Under the neurodevelopmental imbalance model, this is due to heightened value sensitivity in the adolescent ventral striatum (e.g. Barkley-Levenson & Galván, 2014). Under fuzzy-trace theory, adolescents' greater reliance on verbatim-based analysis leads to increased focus on reward magnitudes, with heightened risk-taking in gain frames (Reyna, Estrada, DeMarinis, Myers, Stanisiz *et al.*, 2011). The relationship between EBR and increased reward-seeking shown here in adolescents suggests the possibility of dopamine playing a role in both of these theoretical models. If striatal dopamine receptor availability contributes to heightened reward sensitivity in the striatum, we would expect to see EBR correlate with reward sensitivity, as it does here. Similarly, dopamine's role in encoding value (e.g. Schultz, 2010) suggests that it may

provide cost and benefit signals necessary for verbatim-based processing engaged more heavily in adolescence; greater EBR in this model could reflect greater reliance on verbatim-based relative to gist-based processing, and would therefore correlate with increased focus on reward magnitude (as seen in increased reward-seeking responses on the RG).

Behaviorally, both adolescents and adults exhibited loss aversion on the RG, demonstrating a preference for avoiding losses over seeking gains or maximizing the probability of winning. Although adolescents appear to have a stronger relationship between dopamine and reward-seeking, they did not actually differ from adult participants in the proportion of trials in which they chose the GMax strategy, nor did they differ on the selection of the other strategies. A possible explanation is that different underlying cognitive (and neurobiological) processes lead participants to similar behavioral outcomes. For example, in keeping with fuzzy-trace theory, adolescents may rely more heavily on dopamine-driven value signals to engage in deliberative (verbatim-based) processing of risky decisions, leading to greater value sensitivity (as discussed previously), while adults engage in more rapid heuristic (gist-based) processing. Such a distinction would be consistent with faster response times for adults, which we observed on all trial types of the RG.

Consistent with our previous work (Barkley-Levenson & Galván, 2014), adolescents in this study exhibited greater value sensitivity than adults. Adolescents were more likely to increasingly select the probability-maximizing decision and to reduce selection of the loss-minimizing decision as the amount of the potential gain increased. This decision suggests that relatively small increases in monetary value held greater significance for the adolescents versus adults.

One shortcoming of the decision-making task we employed is the non-independence of the three decision strategies (i.e. if selection of one strategy increases then selection of the other two must necessarily decrease), making the interpretation of correlations between EBR and decision strategy selection more complicated than for a binary choice task. However, the fact that only GMax shows a positive relationship with EBR suggests that this effect is genuine, rather than the less parsimonious explanation that it is a byproduct of EBR independently suppressing both PMax and LMin strategies. Recent decision-making research has investigated the process of trinary choice by applying a multi-attribute drift diffusion model to behavioral and eye-tracking data (Krajbich & Rangel, 2011). In future studies a similar approach using a modified version of the Roulette Game could more precisely characterize

participant decision strategy selection on this trinary choice task. Another shortcoming of the trinary choice task, rather than the original design (a five-outcome mixed gamble), is that we are unable to dissociate loss aversion from risk aversion or to investigate framing effects in risk attitudes that have been shown to differ developmentally (Reyna & Ellis, 1994; Reyna *et al.*, 2011). This may explain why we did not observe in our adult participants the bias towards the PMax strategy reported elsewhere (Payne, 2005; Venkatraman, Payne, Bettman, Luce & Huettel, 2009; Venkatraman *et al.*, 2011) and consistent with greater gist-based processing as predicted by fuzzy-trace theory (Reyna & Farley, 2006). The binary and trinary versions of the task address different questions but do not lend themselves to direct comparison.

While the use of EBR to characterize dopamine functioning in developmental research is promising, it remains an indirect measure, with the limitations that entails. Human research directly comparing EBR and PET will be necessary to confirm the relationship between blink rate and dopamine that has been conclusively demonstrated in primates (Groman *et al.*, 2014). Slower event-related task designs (or blocked designs) are required to observe phasic changes in EBR in response to changes in stimulus value. Understanding the extent to which environmental conditions affect blink rate independently of dopamine (e.g. testing room luminance, viewing screens versus physical stimuli) will also be crucial in standardizing EBR collection protocols to minimize noise. Furthermore, in the current study we did not collect data on individual differences in the sensitivity of participants' eyes (e.g. seasonal allergies, contact lenses, or chronically dry eyes). We recommend that subsequent research measuring adolescent and adult EBR should investigate whether any such conditions systematically influence an individual's blink rate. Nonetheless, EBR provides an opportunity for researchers of vulnerable populations, those with metal in the body (including braces, a common limitation in human adolescent research) or other contraindications for fMRI, or without access to PET to readily explore the dopaminergic underpinnings of behavior.

These findings suggest that previously observed adolescent behavioral and neural hypersensitivity to reward may in fact be due to heightened sensitivity to dopamine, as represented by the relationship of blink rate and reward-seeking behavior. This technique opens the door for considering adolescent individual differences at the neurochemical as well as the behavioral level when exploring responses to reward, value and risk.

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Graphical Abstract

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Measurement of spontaneous eye blink rate (EBR) can be used as a proxy for dopamine in healthy adolescents in whom direct measurements of dopamine are prohibitively invasive. EBR correlates with reward-seeking decisions in adolescents but not adults, suggesting a role for dopamine receptor availability in previously observed adolescent behavioral and neural hypersensitivity to reward.