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Alterations in adolescent dopaminergic systems as a function of early mother-toddler attachment: A prospective longitudinal examination

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ABSTRACT

Early experiences have the potential for outsized influence on neural development across a wide number of domains. In humans, many of the most important such experiences take place in the context of the mother-child attachment relationship. Work from animal models has highlighted neural changes in dopaminergic systems as a function of early care experiences, but translational research in humans has been limited. Our goal was to fill this gap by examining the longitudinal associations between early attachment experiences (assessed at 2.5 years) and neural responses to risk and rewards during adolescence (assessed at 13 years). Adolescence is a developmental period where sensitivity to rewards has important implications for behavior and long-term outcomes, providing an important window to study potential influences of early attachment experiences on reward processing. In order to address this question, 50 adolescents completed a risk and reward task during an fMRI scan, allowing us to assess differences in neural sensitivity to changes in risk level and reward amount as a function of early attachment experiences. Adolescents with insecure attachment histories showed *blunted* sensitivity to increasing risk levels in regions of the dorsal striatum, while also showing *heightened* sensitivity to increasing reward levels in the same region. These results highlight the importance of early attachment experiences for long-term neural development. Specifically, early exposure to more maladaptive relationships with caregivers may confer dual risks prospectively for adolescents, sensitizing them to rewarding outcomes while de-sensitizing them to potential risks associated with those behaviors, perhaps due to stress-related dopaminergic changes early in development.

1. Introduction

The caregiver-offspring relationship is one of the most important influences early in life. Not only does the young organism depend on the caregiver (primarily the mother across the majority of species) for survival, including food and protection from threats, but interactions between mother and offspring also shape developing neurobiological circuits, resulting in changes in neural processing and behavior later in life (Meaney, 2001). The system of safety-regulating behavioral patterns between mother and offspring (e.g., proximity maintenance), termed attachment, has been the subject of extensive theory (Bowlby, 1969,1982; 1973) and empirical research in humans (see Cassidy and Shaver, 2008). Attachment is the result of strong evolutionary pressures predicated on the dependence of the infant on the mother for basic care and survival (Bowlby, 1969,1982; Bennett et al., 2017). As such, the attachment relationship consists of a complex system of inter-individual behavioral patterns that form the basis for how infants respond to stress both within the relationship, and when they are threatened, either by an external stimulus or through separation from their caregiver (Ainsworth et al., 1978). Attachment captures a large set of maternal and child behaviors which help infants to construct an internal working model of the world based on interactions with the caregiver (Bowlby, 1969; Bretherton, and Munholland, 1999; Schore, 2000). Highlighting its importance, the quality of attachment in early life predicts a variety of behavior outcomes later in life, including internalizing (Madigan et al., 2013) and externalizing (Fearon et al., 2010) symptoms, as well as social competence (Groh et al., 2014). However, to date, studies of how early infant-caregiver attachment shapes neural responsivity later in life have largely been restricted to rodent models. Research in humans generally involves either concurrent or retrospective designs or focuses on severe adverse caregiving (e.g., child maltreatment, trauma) rather than normative variation in attachment. Based on findings in

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rodent models, which indicate alterations in reward neural circuitry as a function of early care experiences, we focused on neurodevelopmental outcomes in adolescence, a period characterized by heightened sensitivity to rewards (e.g., Casey, 2015; Telzer, 2016). Specifically, we utilized a prospective longitudinal design to examine how early mother-child attachment security is associated with alterations in neural processing of risk and reward during adolescence.

The study of early attachment and neural and behavioral functioning later in life has a rich history in rodent models (for reviews, see Meaney, 2001; Curley and Champagne, 2016). Much of the early work in rodents focused on the effects of maternal care on stress reactivity or on intergenerational transmission of maternal behavior (e.g., Francis et al., 1999; Champagne et al., 2003), however, more recent work has broadened the scope to include research on other systems which are impacted by stress, and how early experience shapes long-term function in these neural networks. One key system is the dopaminergic network, including regions of the ventral tegmental area (VTA), nucleus accumbens and other mid-brain striatum regions, as well as the medial prefrontal cortex (Wise, 2004). While classically associated with reward (Schultz, 1998; Wise, 2004), dopamine (DA) is also released in response to stress (Alonso et al., 1993; Ortiz et al., 1996; Saal et al., 2003), forming a candidate link between early life experiences and alterations in reward sensitivity, motivated behavior, and learning that are supported by the dopaminergic system (Champagne et al., 2004). In rodents, the DA system continues to mature for several weeks postnatally (Voorn et al., 1988), rendering the system susceptible to environmental influences, including variations in maternal care and stress (Barros et al., 2004; Jahng et al., 2010). Work with rodent models suggests that reductions in maternal care (through deprivation or natural instability) leads to increases in DA availability in mid-brain reward structures (Afonso et al., 2011). Behaviorally, this poor maternal care has some disparate results: reducing drive towards naturally rewarding stimuli (e.g., fatty foods: Ventura et al., 2012; Peña et al., 2014), but increasing susceptibility to addictive drugs such as cocaine (Francis and Kuhar, 2008) and heightening preference for social interactions (Peña et al., 2014). Taken together, these results suggest a role of maternal behavior in mediating the programming of dopaminergic systems in the developing offspring, with life-long consequences for reward processing and motivated behavior.

Parallel neurobiological research in humans has been relatively sparse. Studies of the neurobiological correlates of adult attachment (Lemche et al., 2006; Karremans et al., 2011; DeWall et al., 2011) do not take into account early attachment relationships. The one study to combine measures of both early maternal behavior and dopaminergic function (Pruessner et al., 2004) utilized positron emission tomography (PET) to characterize adult dopamine release in response to a psychological stressor as a function of the quality of early life care. Individuals reporting low early maternal care quality showed heightened striatal dopamine responses during the stressor, providing a link between stress and dopamine reactivity, moderated by the quality of early maternal care (Pruessner et al., 2004). Although, no previous study has investigated alterations of reward processing in adolescents as a function of *early* attachment, there are several reasons such an investigation is theoretically motivated. First, the quality of attachment relationships has implications for motivational processes (Coan, 2016). Given absolute dependence of the offspring on the caregiver during early life, there are imperative biological motivations for the child to seek comfort and security from the caregiver, regardless (to a large extent) of the quality of care actually provided. Negative or inconsistent feedback from the caregiver in response to these attachment-related behaviors – and particularly caregiver responses to child distress (McElwain and Booth-LaForce, 2006) – can impact motivational (i.e., dopamine) systems either directly (Hall et al., 1999) or indirectly through alterations in the stress-response system (Ladd et al., 1996; Loman and Gunnar, 2010). Second and relatedly, the release of dopamine during stressful experiences (Alonso et al., 1993; Saal et al., 2003), including during separation from caregivers, offers a plausible mechanistic pathway for the alteration of reward-processing via early care-giving experiences. Finally, our assessment protocol of attachment (described in detail later) shares features of experimental procedures (i.e., maternal separation, variation in care quality) that are utilized in animal models. Taken together, the attachment relationship offers a useful translational measure for investigating the impact of early caregiving experiences in humans on neural reward sensitivity later in life.

In the current study, we examined the prospective association between mother-child attachment security measured during early life and dopaminergic processing of risks and rewards during adolescence. Since adolescence is a period of development characterized by heightened responsivity to rewarding stimuli (Casey, 2015; Telzer, 2016; van Duijvenvoorde et al., 2016), understanding how early experiences shape that responsivity is particularly important. The quality of mother-child attachment security was assessed at 2.5 years using a modified Strange Situation procedure (Cassidy et al., 1992). Almost a decade later, adolescents (aged 12–14) who participated in the original study (McElwain et al., 2016) returned to the lab and completed the Balloon Analogue Risk Task (BART; Lejuez et al., 2002; McCormick and Telzer, 2017a) during a functional MRI scan. The BART is a risky decision-making task where adolescents balance the potential for rewards against the relative risk of each decision. Participants choose to pump a virtual balloon for points, with each pump associated with increasing points, but they risk the balloon exploding if they pump too much, in which case they lose all points. As such, risk levels increase parametrically across each pump decision, allowing us to measure neural responses to increasing risk. In addition, reward value varies across balloons depending on when the participant chooses to cash-out, allowing us to examine neural responses to the receipt of increasing reward. The BART elicits robust activation of dopamine-rich regions in response to both components of risk and reward (Telzer et al., 2013; McCormick and Telzer, 2017a; 2017b), and importantly both behavior and neural activation on the BART has been shown to vary as a function of the quality of social relationships, both currently (Telzer et al., 2013, 2015) and longitudinally over a few years (Qu et al., 2015b). For example, negative social relationships with peers (Telzer et al., 2015) and parents (Telzer et al., 2013; Qu et al., 2015b) during adolescence are related to heightened striatal responses in response to both risk and reward on the BART. As such, the BART provides two contexts (i.e., risk and reward) in which to explore the relation between early attachment experiences and dopaminergic function in adolescence. Based on previous findings in rodents and humans, we hypothesized that adolescents classified with an insecure attachment at age 2.5 years would show heightened dopaminergic responses, indexed by heighted neural tracking in dopamine-rich regions (e.g., the striatum) to increasing levels of risk and reward, compared with their securely attached counterparts.

2. Methods

2.1. Participants

One-hundred and twenty-eight 2.5-year-old children (66 girls, M_{age} = 32.7 months, SD = .76) and their parents participated. Families were recruited via birth announcements and flyers distributed to community organizations and daycare centers. At wave 1, toddlers and their primary caregiver came into the laboratory to complete a series of behavioral assessments, including a modified Strange Situation protocol to assess mother-child attachment security. Approximately 10 years later, families were contacted to participate in a follow-up neuroimaging study. Attempts were made to contact all original families, and 67 adolescents and their parents agreed to participate in the follow-up study. Of the 67 families, 50 adolescents completed the scanning session (M_{age} = 13.27 years, SD = .605, *range* = 12.50–14.83 years; 16 female). Reasons for not completing the scan included claustrophobia

(n = 4), a history of metal work (n = 1), braces (n = 7), and declining to complete the scan session (n = 5). Among included participants, mothers averaged 16.2 (SD = 1.86) years of education, and fathers averaged 15.5 (SD = 2.31) years. The final sample consisted of a greater proportion of males (Z = 2.35, p = 0.02), but did not differ in terms of maternal ($t_{(176)}$ = 0.814, p = 0.417) or paternal ($t_{(176)}$ = 1.26, p = 0.211) education relative to the original sample. Adolescents primarily identified as European-American (90%), with 4% identifying as African-American, and 6% as mixed/multiple-ethnicities. Written informed assent was obtained for all adolescent participant, as well as written informed consent from their primary legal caregivers. All methods were carried out in accordance with the relevant guidelines and regulations outlined by the Declaration of Helsinki and experimental protocols were approved by the Institutional Review Board.

2.2. Early mother-child attachment security

At wave 1, families completed a modified version of the Strange Situation, a widely-used and validated task used to assess the quality of the attachment relationship between caregivers and their children (Cassidy et al., 1992). This version of the Strange Situation consisted of a standardized protocol, including 5 episodes: 3-min of warm up; 3 min of mother-child separation; 3 min of mother-child reunion; a second 5-min mother-child separation; and a second 3 min mother-child reunion. Unlike previous versions of the protocol, separation events did not include the presence of a "stranger" preceding or during the separation events. Mothers received no instruction as to what to say to their toddlers when initiating the separation episodes. The attachment style of each toddler was coded by two independent, trained coders, and 20% of protocols were double-coded and disagreements between coders were resolved by consensus (see McElwain et al., 2016 for further details). The security of the mother-child attachment relationship was quantified in two ways: 1) discrete categories of attachment, and 2) a continuous score of attachment security (1–9; where higher scores indicated a more-secure relationship). For the 4-way categorial classification, interobserver agreement (before consensus) was 88% (κ = .77), and the interclass correlation for the continuous scale was .82 (as reported in McElwain et al., 2016). Previous work using the modified Strange Situation Procedure shows that attachment is related in the expected direction with concurrent maternal and child characteristics (e.g., Moss et al., 2004; McElwain et al., 2012).

At wave 1, raters categorized children as secure (n = 86), avoidant (n = 6), dependent/resistant (n = 15), controlling/insecure other (n = 20), or uncodeable (n = 1). Given the relatively low frequency of different insecure attachment styles, we dichotomized the categorical approach into secure (n = 86) and insecure (n = 41) attachment. Participants completing the neuroimaging session showed comparable proportions of secure (n = 32) and insecure (n = 19) attachment (as measured at 33 months) to the original sample (Z = 0.57, p = .569).

2.3. Self-reported risk taking

To examine real-world risk-taking behaviors, adolescents completed a modified version of the Adolescent Risk-Taking Scale (Alexander et al., 1990; Telzer et al., 2013). Participants rated 12 items indicating how frequently (0 = *Never* to 3 = *Many Times*) they engaged in a variety of risky behaviors (e.g., "I have gotten high or drunk at a party," and "I have slipped out at night while my parents thought I was asleep."). Overall scores on the scale are calculated by taking the mean of all items, with higher scores reflecting engaging in risky behaviors more frequently. The scale had good reliability (α = .86).

2.4. Risk and reward task

Adolescent participants completed a version of the Balloon Analogue Risk Task (BART), a well-validated experimental paradigm (Lejuez et al., 2002; Wallsten et al., 2005) that has been adapted for fMRI in developmental populations (Telzer et al., 2015; McCormick and Telzer, 2017a). The BART measures participants' willingness to engage in risky behavior in order to earn rewards and is associated with real-life risk taking in adolescents (Qu et al., 2015a; McCormick and Telzer, 2017b) and adults (Lejuez et al., 2002; Wallsten et al., 2005). During the scan session, participants were presented with a sequence of 24 balloons that they could pump up to earn points. Each pump decision was associated with earning one point but increased the risk that a balloon would explode. If participants pumped too many times on a balloon, the balloon would explode and participants would lose all the points they had earned for that balloon. However, if participants chose to cash out before the balloon exploded, the points they earned would be added to the running total of points, which was presented on the screen as a points meter. Participants were instructed that their goal was to earn as many points as possible during the task. Each event (e.g., larger balloon following a pump, new balloon following cashed or explosion outcomes) was separated with a random jitter (500–4000 ms). Balloons exploded between 4 and 10 pumps, and the order of balloons was presented in a fixed order (after being pseudo-randomly ordered prior to data collection), although none of this information was made available to participants. The BART was self-paced and would not advance unless the participant made the choice to either pump or cash out. Participants were told that they could win a $10 gift card at the end of the neuroimaging session if they earned enough points during the task. The point threshold for winning this prize was intentionally left ambiguous so that participants were motivated to continue earning points throughout the task. In reality, all participants were given a $10 gift card after completing the scan session.

2.4.1. Modeling sensitivity to increasing risk and reward in the BART

The BART dynamically varies the levels of potential risk and reward across participant decisions. For each pump decision on a given balloon, the risk that the subsequent pump decision will result in an explosion (and loss of points) increases parametrically. As such, we can model how neural activation changes across pump decisions within a balloon (i.e., across increasing risk) to understand how the level of risk at each decision tunes neural responses. The trade-off for this increasing level of risk is that participants can also gain more points if they are able to cash out before the balloon explodes. Since the level at which participants cash-out varies across balloons, we can model how neural regions track the reward value of cash-out decisions. This feature of the task and participant behavior allows us to assess how the brain responds to risk or reward generally, as well as those responses are moderated by the relative risk or reward of each decision in the task.

2.5. fMRI data acquisition and processing

2.5.1. fMRI data acquisition

Imaging data were collected utilizing a 3 T Trio MRI scanner. The BART included T2*-weighted echoplanar images (EPI; slice thickness = 3 mm; 38 slices; TR = 2 s; TE = 25 ms; matrix = 92 × 92; FOV = 230 mm; voxel size = 2.5 × 2.5 × 3mm^3). Additionally, structural scans were acquired, including a T1* magnetization-prepared rapid-acquisition gradient echo (MPRAGE; slice thickness = 0.9 mm; 192 slices; TR = 1.9 s; TE = 2.32 ms; matrix = 256 × 256; FOV = 230 mm; voxel size = 0.9 × 0.9 × 0.9 mm^3; sagittal plane) and a T2*-weighted, matched-bandwidth (MBW), high resolution, anatomical scan (slice thickness = 3 mm; 192 slices; TR = 4 s; TE = 64 ms; matrix = 192 × 192; FOV = 230 mm; voxel size = 1.2 × 1.2 × 3mm^3). EPI and MBW scans were obtained at an oblique axial orientation in order to maximize brain coverage and minimize dropout in orbital regions.

2.5.2. fMRI data preprocessing and analysis

Preprocessing utilized FSL FMRIBs Software Library (FSL v6.0; https://fsl.fmrib.ox.ac.uk/fsl/). Steps taken during preprocessing

included: skull stripping of all images with BET; correction for slice-to-slice head motion using MCFLIRT; and high-pass temporal filtering with a 128 s cutoff to remove low frequency drift across the time-series. Functional images were re-sampled to a 2 × 2 × 2 mm space and co-registered in a two-step sequence to the MBW and the MPRAGE images using FLIRT in order to warp them into the standard stereotactic space defined by the Montreal Neurological Institute (MNI) and the International Consortium for Brain Mapping. Spatial smoothing utilized a 6 mm Guassian kernel, full-width-at-half maximum. Preprocessing was completed utilizing individual-level independent component analysis (ICA) with MELODIC combined with an automated component classifier (Tohka et al., 2008; Neyman-Pearson threshold = 0.3), which was applied to filter signal originating from noise sources (e.g., motion, physiological rhythms).

The BART was modeled using an event-related design using the GLM within SPM8. Fixed-effects models included a general linear model for each condition of interest, which included pump decisions, cash-out decisions, and explosion events, using the trial duration corresponding to participant response time on a given pump or cash-out, or using the average RT across the task on explosions. As we were interested in how early mother-child attachment history (secure vs insecure) was associated with risk and reward sensitivity, we focused our analyses on the pump and cash-out decisions. The jittered inter-trial periods were not modeled and served as the implicit baseline for the task. A parametric modulator (PM) was included for each of the conditions of interest, and represents the pump number for a balloon at each pump or cash-out decision. The parametric modulator contrast for pump decisions was used to measure neural sensitivity to increasing risk level. The PM values were centered on the first pump within a balloon and increased linearly with each pump decision (0, 1, etc.). This linearly increasing parameter highlights regions that show strong tracking of increasing levels of risk. Put another way, activated regions show a differential (i.e., linearly increasing or decreasing) response depending on the level of risk. Similarly, the PM contrast for cash-out decisions was used to measure neural sensitivity to increasing reward value. PM values for reward outcomes were centered within individuals at the average reward level for that participant. As such, regions which show a significant effect of the PM are those that scale (i.e., increase or decrease) their neural response according to the value of the cash-out decision being made. Contrasts were then computed at the individual level for each condition of interest.

Random effects, group-level analyses were run for all contrasts using GLMFlex (http://mrtools.mgh.harvard.edu/index.php/GLM_Flex), which offers several advantages, including removing outliers and sudden activation changes in brain, correcting for variance-covariance inequality, partitioning error terms, and analyzing all voxels containing data. Group level analyses focused on pump and cash-out decisions because not all participant had enough explosion events to model appropriately. Correction for multiple comparisons was run using a Monte Carlo simulation through the updated version (April, 2016) 3dFWHMx and 3dClustSim programs from the AFNI software package (Ward, 2000) using the group-level brain mask. The simulation resulted in a voxel-wise threshold of $p < .005$ and a minimum cluster size of 68 voxels for the whole brain, corresponding to $p < .05$, Family-Wise Error (FWE) corrected. All results are available on Neurovault (https://neurovault.org/collections/TJISXZPD/; Gorgolewski et al., 2015).

3. Results

3.1. Behavioral results

We first investigated associations between early attachment and real-world risk-taking behavior (for summary statistics and zero-order correlations, see Table 1). Adolescents in the insecure group reported higher ($M = 0.317$, $SD = .286$) risk behavior than adolescents in the secure group ($M = 0.158$, $SD = .148$; $t_{(48)} = 2.58$, $p = 0.012$), suggesting that early life experiences are associated with adolescents' risk behavior in their daily life.

Table 1
Summary Statistics and Zero-Order Correlations for Variables of Interest.

	Variable	*M*	*SD*	*range*	1	2	3
1.	Attachment Security	0.640	.485	coded 0, 1	–	.077	-.351*
2.	Average Pumps	4.790	.900	3.04-6.56		–	−.018
3.	Risk Behavior	0.214	.220	0.00-0.86			–

* $p < .05$.

Next, we examined behavior on the BART. Consistent with previous research (Rao et al., 2008; Telzer et al., 2015; McCormick and Telzer, 2017a; b), adolescents pumped approximately five times on average across all balloons ($M = 4.79$, $SD = .90$, *range* = 3.04–6.56), and cashed-out on the majority of balloons ($M = 17.06$ out of 24 balloons, $SD = 3.07$, *range* = 9–24). Adolescents in the secure and insecure groups did not differ in terms of average number of pumps ($t_{(48)} = .537$, $p = .594$) or number of cash-out decisions ($t_{(48)} = .373$, $p = .711$). Average number of pumps on the BART were not correlated with self-reported risk behavior ($r = -.018$, $p = .900$).

3.2. fMRI results

At the neural level, we examined the association between attachment security measured at age 33 months and neural activation in adolescence to increasing risk level during pumps and increasing reward value during cash-out decisions (for Main Effects on task, see Table 1 and NeuroVault: https://neurovault.org/collections/TJISXZPD/).

3.2.1. Attachment insecurity associated with blunted sensitivity to increasing risk

We first examined neural sensitivity to increasing risk during pump decisions based on early attachment. To do so, we conducted a whole-brain independent-samples *t*-test (0 = insecure, 1 = secure) when taking increasing risks (i.e., pump decisions). Relative to adolescents with secure attachment histories, adolescents with insecure histories showed blunted tracking of risk in the bilateral dorsal striatum, bilateral DLPFC, right VLPFC, precuneus, and bilateral posterior insula (Fig. 1a), regions involved in reward processing, cognitive control and salience detection, respectively. For descriptive purposes we extracted parameter estimates of neural tracking of increasing risk and plotted the linear tracking of risk levels in the dorsal striatum by attachment group. As shown in Fig. 1b, adolescents in the secure and insecure groups do not show differential responsivity to risk in these regions at early pump decisions, and instead differed in how that response scaled to the level of risk at each subsequent decision. Specifically, adolescents classified as insecure at 2.5 years showed relative insensitivity to increasing risk at the neural level, whereas adolescents in the secure group showed increasing sensitivity in the dorsal striatum as risk level increased (Table 2 and 3).

3.2.2. Attachment insecurity associated with enhanced sensitivity to increasing reward

Next, we examined differential neural sensitivity to increasing reward receipt on the cash-outs based on early attachment. We ran similar whole-brain independent-samples *t*-tests. In contrast to results examining risk, adolescents in the insecure group showed enhanced tracking of increasing reward value in the bilateral dorsal striatum, bilateral anterior insula, anterior cingulate cortex, and left VLPFC (Fig. 2a). We extracted parameter estimates of neural tracking of reward value from the dorsal striatum to plot reward sensitivity for secure and insecure groups separately. Similar to findings with risk, adolescents with a secure versus insecure attachment history showed similar

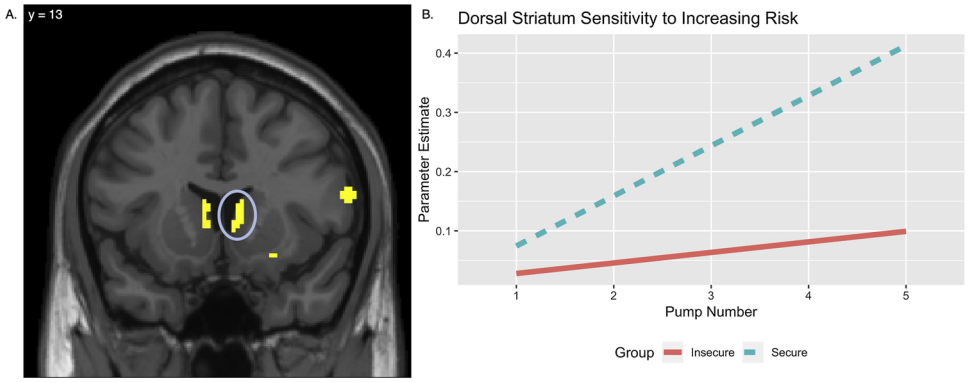

Fig. 1. Compared with adolescents in the securely-attached group (dashed teal), adolescents in the insecurely-attached group (solid red) show blunted sensitivity to increasing risk level in the dorsal striatum.

Table 2
Neural Regions Showing Significant Main Effect Tracking of Neural Activation.

Anatomical Region	+/-	BA	x	y	z	t	k
Main Effect of Increasing Risk							
R VS[a]	+		10	10	−4	12.49	3466
L VS[a]	+		−8	6	−2	10.19	
VTA[a]	+		6	−30	−6	9.95	
R Anterior Insula[b]	+		34	26	2	10.81	2046
R IFG[b]	+	45	38	28	−2	9.73	
L IFG[c]	+	45	−30	25	−2	10.71	1367
L Anterior Insula[c]	+		−34	18	8	9.21	
R Motor Cortex[d]	+	4	44	−16	56	8.52	6415
R MCC[d]	+	31	10	10	40	8.43	
R MOG	+	18/19	22	−94	10	6.26	432
L MOG	+	18/19	−22	−96	12	7.73	374
L Motor Cortex	+	4	−16	−6	64	5.96	208
R Cuneus	+	17	16	−72	36	5.39	129
R Posterior Insula	+		40	−22	18	4.72	465
L Angular Gyrus[e]	–	39/40	−38	−70	38	−10.58	40174
PCC[e]	–	23/31	0	−46	32	−10.02	
L Motor Cortex[e]	–	4	−34	−26	60	−9.47	
L ITG[e]	–	20	−60	−52	−8	−9.45	
R ITG[e]	–	20	64	−50	−8	−9.29	
R Angular Gyrus[e]	–	39/40	52	−66	28	−8.18	
R ATC[e]	–	38	66	−14	−22	8.23	
L ATC[e]	–	38	−62	−20	−24	5.94	
R Hippocampus[e]	–		22	−22	−14	7.70	
L Hippocampus[e]	–		−20	−24	−12	6.52	
mPFC[f]	–	8/9	2	60	−6	9.36	14873
R SFG[f]	–	46	30	24	52	9.21	
L SFG[f]	–	46	−22	26	52	8.95	
vmPFC[f]	–	10/11	4	46	−10	8.74	
Medial OFC[f]	–	11	2	38	−26	8.00	
L DLFPC[f]	–	46	−52	30	26	7.79	
Main Effect of Increasing Reward							
R IOG	+	19	30	−88	−2	4.92	6621
R Cerebellum	+		28	−58	−30	4.57	
R Parahippocampus	+		24	6	−22	4.43	
R vmPFC	+	10/11	−4	34	−6	4.58	540
L Parahippocampus	+		−24	−22	−20	4.08	887
R OFC	+	11	26	56	−2	3.30	287

Note: L and R refer to left and right hemispheres; + and – refer to positive or negative activation; BA refers to Brodmann Area of peak voxel; k refers to the number of voxels in each significant cluster; t refers to peak activation level in each cluster; x, y, and z refer to MNI coordinates. Superscripts (e.g. a, b, etc.) indicate that peak voxels are part of a contiguous cluster. VS = Ventral Striatum; VTA = Ventral Tegmental Area; IFG = Inferior Frontal Gyrus; MCC = Mid-cingulate Cortex; MOG = Middle Occipital Gyrus; PCC = Posterior Cingulate Cortex; ITG = Inferior Temporal Gyrus; ATC = Anterior Temporal Cortex; mPFC = Medial Prefrontal Cortex; SFG = Superior Frontal Gyrus; vmPFC = Ventromedial Prefrontal Cortex; OFC = Orbitofrontal Cortex; DLPFC = Dorsolateral Prefrontal Cortex.

Table 3
Adolescents' Neural Regions Showing Significant Differences by Attachment Classification (Secure versus Insecure) at 2.5 Years.

Anatomical Region	+/-	BA	x	y	z	t	k
Increasing Risk							
R Posterior DS	–		8	−2	6	−3.68	187
R Anterior DS	–		6	12	2	−3.55	
L DS	–		−6	10	14	−3.23	55
L Posterior Insula	–		−44	−6	10	−3.86	153
R MFG	–		24	40	38	−3.85	183
L MFG	–		−18	46	28	−3.20	68
R Lateral OFC	–		34	44	−14	−3.64	104
R IFG	–		34	24	−14	−4.54	81
Increasing Reward							
R Posterior DS	+		8	−2	8	3.69	648
R Anterior DS	+		12	8	6	3.53	
R Putamen	+		24	18	0	3.93	
R Insula	+		32	20	−6	4.22	
R Thalamus	+		−8	−8	4	3.22	75
L Putamen	+		−28	−4	2	3.99	300
L Posterior Insula	+		−38	14	6	3.78	291
L Motor Cortex	+		−28	−24	70	3.64	142
ACC	+		−6	20	36	2.61	312
L IFG	+		−44	36	−10	3.41	112

Note: L and R refer to left and right hemispheres; + indicates that adolescents in the insecurely-attached group show enhanced tracking and - indicates that adolescents in the insecurely-attached group show blunted tracking relative to adolescents in the securely attached group; BA refers to Brodmann Area of peak voxel; k refers to the number of voxels in each significant cluster; t refers to peak activation level in each cluster; x, y, and z refer to MNI coordinates. Superscripts (e.g. a, b, etc.) indicate that peak voxels are part of a contiguous cluster. DS = Dorsal Striatum; MFG = Middle Frontal Gyrus; OFC = Orbitofrontal Cortex; IFG = Inferior Frontal Gyrus; ACC = Anterior Cingulate Cortex.

responsivity to reward at average reward values (i.e., cashing out after 5 pumps), but that response scaled differentially to higher levels of the reward outcome. In contrast to findings for increasing risk, adolescents classified as insecure showed neural hyper-sensitivity to increasing reward value (Fig. 2b). These results show that adolescents in the insecure group display heightened sensitivity to increasingly rewarding outcomes in many of the same regions that they show *blunted* sensitivity to increasing risk levels (i.e., dorsal striatum).

4. Discussion

A rich tradition of research has highlighted the importance of early life experiences in shaping neural circuits throughout the lifespan (Meaney, 2001; Curley and Champagne, 2016). Given the dependence of young offspring on their caregiver (most often their mothers), many

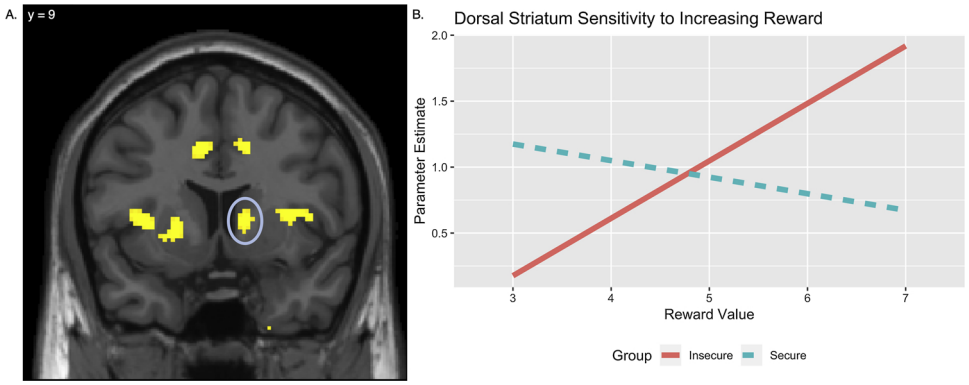

Fig. 2. Compared with adolescents in the securely-attached group (dashed teal), adolescents in the insecurely-attached group (solid red) show heightened sensitivity to increasing reward value in the dorsal striatum.

of these early experiences take place in the context of the mother-child attachment relationship. As such, the behaviors and expectations that constitute the attachment system have the potential to shape neural systems across development (Voorn et al., 1988; Barros et al., 2004; Jahng et al., 2010; Peña et al., 2014). Previous work in animal models has suggested that one of the key neurobiological impacts of maternal care involves dopaminergic reactivity to stress and reward (Ortiz et al., 1996; Saal et al., 2003; Afonso et al., 2011), which may have important consequences for motivated behavior later in life (Ventura et al., 2012; Francis and Kuhar, 2008). In the present study, we focus on adolescence, a period of development characterized by sensitivity to rewards (Steinberg et al., 2008; Casey, 2015; Telzer, 2016), where early tuning of dopamine activity may be particularly important for neural function. Participants' early attachment to their mother was assessed at 2.5 years, and then neural reactivity to risks and reward was measured a decade later during adolescence. We found that adolescents with an insecure attachment history (compared with their securely-attached peers) reported higher levels of real-world risk behavior. These same adolescents further showed both a blunted sensitivity to increasing risks as well as heightened sensitivity to increasing rewards. These results suggest that early exposure to more maladaptive relationships with caregivers confers dual risks prospectively for adolescents, potentially sensitizing them to rewarding outcomes while de-sensitizing them to potential risks associated with those behaviors.

The findings in the current study offer an exciting, initial parallel with work in animal models showing the link between early caregiving experiences and dopaminergic function later in development. Similar to work with rodent models (e.g., Ventura et al., 2012; Peña et al., 2014), early experiences prospectively predicted alterations to dopamine-rich areas of the striatum, however, several key differences also emerged. The majority of rodent models target the nucleus accumbens/ventral striatum, as this region is a major target of dopaminergic projections from the VTA (Wise, 2004), and signals reward anticipation (Schultz, 1998; Knutson et al., 2001). However, one of the main regions in the current study which showed differential tracking of risk and reward as a function of early-life attachment in the current study was more-dorsal regions of the striatum. Several explanations may account for this cross-species difference, however, one likely candidate is the nature of the task we used to investigate neural sensitivity to risk and reward in adolescents. Like its ventral counterpart, the dorsal striatum is highly innervated by dopamine (DA) projections from the VTA, however, previous work has highlighted dissociable functions for the ventral and dorsal striatum. The dorsal striatum appears to play an important role in learning and decision-making by integrating motivational, sensory, and cognitive information in the service of action implementation (O'Doherty et al., 2004; Balleine et al., 2007). This role may be particularly highlighted in the BART, as the task structure provides opportunities for learning and the implementation of new behavior based on information gathered previously. In fact, previous work on the BART has shown that participants adjust their behavior based on the feedback information they receive from the task (McCormick and Telzer, 2017a, b; McCormick & Telzer, 2018) and beliefs about the task structure (Wallsten et al., 2005). This contrasts with rodent models where reward sensitivity is typically measured through direct delivery of reinforcers (e.g., palatable food, drugs, social reinforcement;), which typically evokes dopamine signaling in the accumbens (Knutson et al., 2001). This difference in procedure may highlight different regions of the striatum, but is consistent with the idea that early caregiving experiences shape dopaminergic pathways in the developing brain.

Understanding the dopaminergic programming effects of early attachment as alterations in how adolescents learn from and adapt to their environment is consistent with the idea of attachment shaping neural pathways involved in stress responsivity and motivational signaling (Hall et al., 1999), and the fact that the same region (i.e., the dorsal striatum) shows divergent patterns based on attachment classification at 2.5 years in both risk and reward contexts on the BART. While increased tracking of increasing reward value in adolescents with an insecure attachment history might be explicable within a pure reward sensitivity framework, that explanation seems less well suited to explaining the *blunted sensitivity* to increasing risk levels. However, a learning and information integration account would suggest that adolescents with an insecure attachment history may show a bias towards incorporating reward (i.e., positive) information while discounting risk (i.e., potentially negative) information during decision-making. This bias of information processing and implementation could serve as a hypothesized mechanism underlying heightened risk-taking and antisocial behavior in insecurely attached individuals (Cooper et al., 1998; Burgess et al., 2003; Fearon et al., 2010), and would posit that these individuals both over-weight the potential benefits of such behavior while discounting the potential ramifications.

While the current results are an exciting translational extension of animal models of the role of early experiences in shaping dopaminergic systems, more work is needed to fully understand the relationship between attachment and neural sensitivity to risk and reward. First, investigating dopaminergic function across a range of contexts might help elucidate the specificity of the task environment for highlighting attachment-related differences in the dorsal versus ventral striatum. It could be that insecure forms of attachment specifically tune the dorsal striatum, or more likely, early experiences tune the entire DA system but manifests differently depending on the demands of the environment. Secondly, the current results highlight differences in sensitivity to levels of risk and reward in insecurely-, compared with securely-attached, adolescents; however, these neural differences are not linked with overt behavioral differences in adolescent performance on the BART (i.e., number of risk decisions), despite heightened levels of self-reported risk-taking behavior by adolescents classified as insecure early

in development. This feature of the results has certain advantages, but also theoretical limitations. On the one hand, this behavioral parity allows for greater confidence that the neural findings are not simply driven by asymmetrical amounts of data between securely- and insecurely-attached adolescents. Furthermore, the results suggest that while the emergent behavior may be the same, early attachment security nevertheless alters how adolescents process and interact with information in their environment. While direct parallels are tentative, this view is consistent with findings from investigations of the long-term neural impacts of early temperament. Temperament consists of early emerging, biologically-based mood and behavioral differences, especially in response to external stimuli that tend to persist across development (Kagan et al., 1998), and as such, shares some similarities with attachment as an early predictor of later behavior. Results from studies involving temperament (outside of the context of risk-taking) have also shown neural differences in the absences of overt behavioral differences (Schwartz et al., 2003; Bar-Haim et al., 2009; Fu et al., 2017). The absence of direct effects might reflect the presence of intervening effects that change overt behavior, while the underlying neural tuning driven by these early predictors remain. A few studies using behavioral versions of the BART have shown that direct relationships between temperament and behavior on the task, even over shorter developmental periods (e.g., 2–3 years), are rare, and instead there are important interactions with other variables including attentional biases (Lahat et al., 2012) and behavioral inhibition (Williams et al., 2010). Future research would be well-served to explore different moderating contexts where these underlying neural differences do result in manifestations of different behaviors. In the contexts of adolescents, contextual exacerbations of these differences might include peer influence (e.g., Chein et al., 2011) or exposure to highly hedonic stimuli (e.g., illicit drugs). Indeed, these features could be candidate explanations that distinguish between the parity seen on the BART (played without any external input) and the differences seen in real-world behavior (where the insecurely-attached group reported higher levels). Furthermore, future research should build on the current work by investigating which neural changes across development (e.g., trajectories of function in dopaminergic circuits) might mediate the relationship between early experiences (such as those in the attachment context) with emergent behavioral outcomes in adolescence.

In conclusion, we employed a prospective longitudinal design to understand the associations between early attachment and differences in dopamine systems during adolescence. Attachment security, as assessed during the toddler years, predicted differential sensitivity to risk and reward during adolescence, such that insecurely-attached adolescence showed heightened sensitivity to increases in reward value, while showing blunted sensitivity to increases in risk levels in striatal regions important for learning and behavioral shifts. This pattern of both heightened and blunted sensitivity to different information in the task suggests that early attachment security has long-range relationships with how motivational signals are processed in the brain, providing an important first step in understanding the mechanisms of brain development which may mediate the impact of early experiences on later cognition and behavior.

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