Greater response variability in adolescents is associated with increased white matter development

Diane Goldenberg[1], Eva H. Telzer[2], Matthew D. Lieberman[1,3], Andrew J. Fuligni[1,3] and Adriana Galván[1,*]

[1]Department of Psychology, University of California, Los Angeles, CA, USA, [2]Department of Psychology, University of North Carolina, Chapel Hill, NC, USA and [3]Department of Psychiatry and Biobehavioral Sciences, University of California, Los Angeles, CA, USA

*Correspondence should be addressed to Adriana Galván, University of California, 1285 Franz Hall, Box 951563, Los Angeles, Los Angeles, CA 90095, USA.
E-mail: agalvan@ucla.edu

Abstract

Adolescence is a period of learning, exploration, and continuous adaptation to fluctuating environments. Response variability during adolescence is an important, understudied, and developmentally appropriate behavior. The purpose of this study was to identify the association between performance on a dynamic risky decision making task and white matter microstructure in a sample of 48 adolescents (14–16 years). Individuals with the greatest response variability on the task obtained the widest range of experience with potential outcomes to risky choice. When compared with their more behaviorally consistent peers, adolescents with greater response variability rated real-world examples of risk taking behaviors as less risky via self-report. Tract-Based Spatial Statistics (TBSS) were used to examine fractional anisotropy (FA) and mean diffusivity (MD). Greater FA in long-range, late-maturing tracts was associated with higher response variability. Greater FA and lower MD were associated with lower riskiness ratings of real-world risky behaviors. Results suggest that response variability and lower perceived risk attitudes of real-world risk are supported by neural maturation in adolescents.

Key words: risky decision making; response variability; adolescence; diffusion tensor imaging

Adolescence is a time of instability and change. Fluctuations in social environments are paralleled by dynamic restructuring of neural architecture. During adolescence, long-range connections between spatially segregated regions of the brain strengthen, both structurally and functionally (Hagmann *et al.*, 2010). Paradoxically, as the brain becomes more integrated and control over behavior increases (Luna *et al.*, 2010), there is a concomitant increase in risk taking during this period. Previous research has generally demonstrated an increase in risky decision making in adolescents, compared with children or adults (Steinberg, 2007), focusing largely on mean differences in behavior or neural response in developmental groups. Mean-level differences provide useful predictive information when variability is small among the individuals that comprise each group. However, small variability is not characteristic of adolescent behavior. Recent work has begun highlighting the importance of

individual differences during adolescence, revealing that adolescents have the highest degree of variation during risky choice (Van Duijvenvoorde *et al.*, 2015). This suggests that behavioral variability between adolescents may be systematic, rather than the result of random error. When variability does not occur by random error, calculating mean performance from a single measurement can lead to flawed estimates of average group differences and erroneous conclusions (Zilles and Amunts, 2013). Given that adolescents have the highest degree of variability 'between' individuals, the purpose of the present study was to conduct a fine-grained investigation of the variability 'within' adolescents during decisions made under risk.

Within-person variability reflects a transient change in behavioral performance for a single individual. In the present study, adolescents performed a dynamic risky decision-making task from which a measure of response variability was

calculated. According to a dynamic systems approach, the degree of variability within individuals can change according to the developmental stage of the individual (Smith and Thelen, 2003). When learning a new skill or behavior, the degrees of freedom for performing that behavior are initially constrained. The classic developmental example of the non-linear trajectory of response variability is an infant acquiring mobility for walking (Piek, 2002). Initially, motor response is not variable because the joints connecting the hip, leg, and ankle are tightly connected, restricting range of movement. These physical constraints reduce complexity, allowing attention to be focused on particular aspects of the task. As development progresses, these tight couplings are physically loosened, resulting in an increase in variability and an ability to explore more complex patterns. Eventually, preferred patterns emerge, and variability is again reduced as this preferred solution is refined through practice.

A greater understanding of individual differences in adolescent behavior can be achieved through an examination of the structural connectivity in regions that support risky decision making (Crone *et al.*, 2016). Structural connectivity is commonly examined through diffusion tensor imaging (DTI), which measures water diffusion displacement and directionality (Basser, 1995). A number of outcome variables are obtained to characterize this diffusion, including fractional anisotropy (FA) and mean diffusivity (MD). FA is an index of the degree of restricted water diffusion and MD a measure of overall water diffusion. Higher FA values and lower MD values are hypothesized to reflect qualities in white matter microstructure such as increased axonal caliber, myelination and fiber organization (Beaulieu, 2002). The maturation of white matter appears to improve efficiency of communication between brain regions, facilitating higher-order cognitive functioning and complex behaviors (Barnea-Goraly *et al.*, 2005; Bava *et al.*, 2010).

In this study, white matter microstructure was evaluated using DTI in adolescent participants. Additionally, participants performed the Balloon Analogue Risk Task (BART), a laboratory paradigm designed to assess decision-making under risk and shown to elicit individual differences in response variability (Jentsch *et al.*, 2010; Congdon *et al.*, 2013; DeMartini *et al.*, 2014). Tract-Based Spatial Statistics (TBSS) were used to investigate the association between task performance and white matter microstructure. Self-report questionnaires also assessed adolescents' decision-making processes in a variety of behavioral domains relevant to real-world risky choices.

Materials and methods

Participants

DTI was collected on 48 adolescents [14–16 years (M_{age} = 14.79; 27 females)]. Subjects were right-handed, free of metal, reported no current medication except birth control and reported no diagnosis of learning or mood disorders. Parents provided written consent and adolescent participants completed written assent in accordance with UCLA's Institutional Review Board and were compensated for their participation.

Laboratory decision-making task

Balloon Analog Risk Task. Participants completed the BART (Lejuez *et al.*, 2002) to examine decision making under risk (Figure 1). On each trial of the task, participants were presented with a red balloon. Participants were instructed to press one of two buttons to either pump the balloon or to cash-out. With each pump, there was the possibility that the balloon would either grow larger or explode. The larger the balloon was inflated, the greater the monetary reward but the higher the probability of explosion. Each trial began with the presentation of a balloon and ended when the balloon either exploded or the participant chose to cash out. For each pump on which the balloon did not explode, the participant received a payment (25 cents) and could stop pumping the balloon at any point to keep the accumulated payoff. If the balloon exploded before cashing out, the participant received no payoff for that trial. The number of pumps before explosion was varied probabilistically according to a Poisson distribution with a range of 1–12. As pumping progressed during a trial, explosion probability increased exponentially. The task was self-paced, such that participants could make decisions to pump or cash out at their own pace. The task was adapted for use with fMRI and was performed during a 9 minute run. Findings from the fMRI data are reported elsewhere (Telzer *et al.*, 2013). Participants received total earnings at the end of the task.

Response variability was measured by calculating the coefficient of variation (CV), which has previously been used as a measure of response variability on the BART (Congdon *et al.*, 2013; DeMartini *et al.*, 2014). Values were calculated for cash-out and explosion trials in the following manner:

$$CV_{cash-out} = \frac{SD[\text{total pumps across cash} - \text{out trials}]}{Mean[\text{total pumps across cash} - \text{out trials}]}$$

$$CV_{explosion} = \frac{SD[\text{total pumps across explosion trials}]}{Mean[\text{total pumps across explosion trials}]}$$

Since many of the statistics in this article rely on mean and SD, the distribution of the data, as based on Shapiro-Wilk tests of normality, is presented in Supplementary Materials.

Questionnaire measures

Domain-Specific Risk-Taking Scale. The Domain-Specific Risk-Taking Scale (DOSPERT; Weber *et al.*, 2002), a 30-item self-report measure adapted for use with adolescents (Figner and Weber, 2011), was used to evaluate decision-making processes in
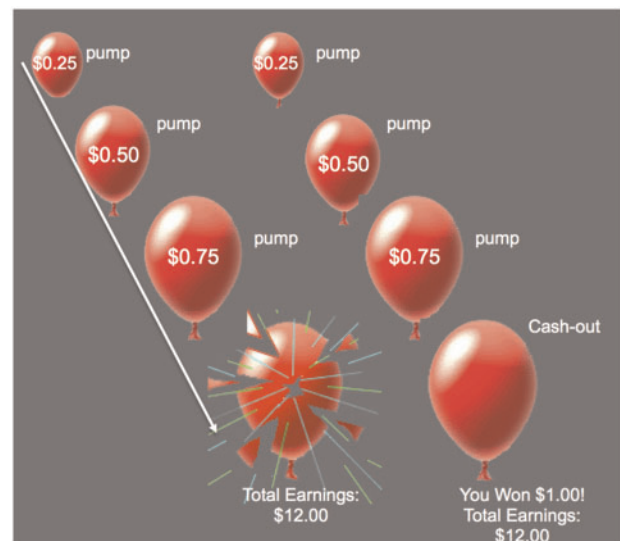

Fig. 1. Schematic of the BART.

real-world domains. Participants were instructed to rate the likelihood that they would engage in risky activities using a 7-point Likert scale (1 = 'extremely unlikely' to 7 = 'extremely likely') in addition to indicating perceived risk attitudes (1 = 'not at all risky' to 7 = 'extremely risky') and expected benefits (1 = 'no benefits at all' to 7 = 'great benefits') of each activity. Risky activities were categorized by five situational domains: financial (e.g. 'betting all your pocket money on the outcome of a sporting event'), health/safety (e.g. 'drinking at a party'), recreational (e.g. 'skateboarding down a steep hill'), ethical (e.g. 'cheating on an exam') and social (e.g. 'speaking out against a popular opinion at school'). Cronbach's alphas for these domains were 0.87, 0.91, 0.80, 0.87 and 0.78, respectively.

Image acquisition

Imaging data were collected using a 3 Tesla Siemens Trio MRI scanner. Diffusion weighted images were acquired using an echo-planar imaging sequence (64 directions, TR/TE = 7200/93 ms, 50 slices; slice thickness = 2 mm, FOV = 190 mm, voxel size = 2 × 2 × 2 mm). This sequence also provides a T2-weighted volume (B0).

Image processing and statistical analyses

DTI processing and voxelwise statistical analysis were performed with FSL v4.1.6 (www.fmrib.ox.ac.uk/fsl). Datasets were corrected for head motion, eddy current distortion, and signal loss using the FMRIB Diffusion Toolbox. Two participants displayed > 3 mm of translational motion and were excluded from analyses for a final sample size of 46 [14–16 years (M_{age} = 14.80; 25 females)]. Degree of diffusion was assessed with FA and MD.

Voxelwise statistical analysis of the FA and MD data was carried out using TBSS (Smith *et al.*, 2006), part of FSL (Smith *et al.*, 2004). TBSS projects all subjects' FA data onto a mean FA tract skeleton, before applying voxelwise cross-subject statistics. To minimize partial-volume effects and areas of high inter-subject variability, values were thresholded at FA > 0.2. Data from each point on the skeleton formed the basis of voxelwise statistical comparisons. DTI-based voxelwise statistics were carried out using FSL Randomise with 5000 permutations and a standard GLM design. Randomise (FMRIB's Software Library, www.fmrib.ox.ac.uk/fsl/) uses a permutation based statistical inference that does not rely on a Gaussian distribution (Nichols and Holmes, 2002). A single-group average with covariate design was applied to assess voxelwise differences among individuals based on behavioral variables of interest (e.g. response variability), which were demeaned and individually entered as regressors in the GLM model. A statistical threshold $P < 0.05$, corrected for multiple comparisons with familywise error correction (FWE) and Threshold-Free Cluster Enhancement (TFCE), was used for analyses. TFCE helps identify cluster-like structures in images without definition of an initial cluster-forming threshold or carrying out a large amount of data smoothing (Smith and Nichols, 2009). The same procedure is carried out for MD data. Identification of the significant white-matter tracts revealed by TBSS was based on the Johns Hopkins University—ICBM-DTI-81 white-matter labels atlas and the white-matter tractography atlas (Wakana *et al.*, 2004). Results were thickened using tbss_fill for visualization.

Results

Behavioral results

Measures of interest for task performance were: mean pumps on cash-out trials, mean pumps on explosion trials, response variability on cash-out trials, response variability on explosion trials, task earnings, and number of explosions. Descriptive statistics and associations between earnings and each BART variable are listed in Table 1. Explosion trials represented 34% of total trials (SD = 0.1). Participants pumped significantly more during cash-out compared with explosion trials [$t(45)$ 3.06, $P < 0.01$] and had greater response variability on explosion trials compared with cash-out trials [$t(45) = -5.52$; $P < 0.001$]. Due to the self-paced nature of the task, participants were presented with different total numbers of balloons (M = 28.67, SD = 3.69). As such, total task earnings for each participant were divided by number of balloons presented to standardize task earnings.

There was no significant association between response variability and age for cash-out or explosion trials. An independent samples *t*-test revealed no gender differences in response variability for cash-out trials, but a significant difference for explosion trials $t(44) = 3.14$, $P < 0.01$, with males exhibiting significantly higher response variability (M = 0.66, SD = 0.18) than females (M = 0.49, SD = 0.16). Results are reported for equal variances assumed, as Levene's test for the homogeneity of variance was not violated $F(1,44) = 0.30$, $P = 0.59$.

Descriptive statistics and normality of DOSPERT measures are reported in Table 2. Associations between DOSPERT measures and task performance were examined and Bonferroni corrected for multiple comparisons, reported in Table 3. A significant negative association between response variability on explosion trials and perceived risk attitudes for risky behaviors in the social domain was found ($r = -0.53$, $P < 0.001$). In other words, adolescents with greater response variability rated real-world examples of socially risky behaviors (e.g. 'speaking out against a popular opinion at school') as less risky. All results remained after controlling for age and gender. No other significant associations between task performance and self-report were observed.

Main effects of gender and age on DTI indices

WM microstructure was assessed using FA and MD. Main effects of gender were examined, revealing significantly higher FA values for males compared with females. Tracts of significance

Table 1. Correlations and descriptive statistics for task performance

Variables	1	2	3	4	5	6
1. Mean pumps (cash-out)	–					
2. Mean pumps (explosion)	0.69***	–				
3. Response variability (cash-out)	−0.28	−0.02	–			
4. Response variability (explosion)	0.02	0.03	0.21	–		
5. Total explosions	0.14	0.02	0.01	−0.07	–	
6. Standardized earnings	0.71***	0.55***	−0.34*	−0.01	−0.44**	–
M	3.79	3.41	0.40	0.58	6.80	0.77
SD	1.07	1.05	0.15	0.18	2.23	0.18

*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.

included the anterior thalamic radiation, anterior and poster limb of the internal capsule, external capsule, inferior fronto-occipital fasciculus, splenium of the corpus callosum, posterior thalamic radiation, inferior longitudinal fasciculus, superior and anterior corona radiata and the corticospinal tract (Table 4). There were no tracts in which females exhibited higher FA than males. There were no significant correlations with FA and age. No significant correlations were found between MD and gender or age.

Correlations between DTI indices and behavioral measures

Analyses between FA values and task performance revealed an association with respect to response variability on explosion trials. Results identified a significant positive correlation (P < 0.05,

corrected for FWE) in the superior, posterior, and anterior corona radiata, anterior thalamic radiation, superior longitudinal fasciculus, body and splenium of the corpus callosum and posterior limb of the internal capsule (Table 5; Figure 2A and B). Analyses remained significant after controlling for gender and age. There were no significant negative correlations between FA and response variability on explosion trials. As there were no significant findings for response variability during cash-out trials, discussion of results will refer to 'response variability' with respect to explosion trials. Additional analyses examined the correlation between FA and response variability within males and females separately, but no significant associations were found. There were no significant correlations between FA and other measures of task performance. No significant associations were found with MD and task performance.

With respect to self-reported decision making in behavioral domains relevant to adolescents' real-world choices (i.e. the DOSPERT), there was a significant negative association between FA and perceived risk attitudes for risk taking in the social

Table 2. Descriptive statistics for DOSPERT measures

DOSPERT	M	SD
Engagement		
Health[a]	2.67	1.10
Social[a]	3.0	1.04
Financial	1.73	0.82
Ethical[a]	4.57	0.82
Rec	2.91	1.33
Perceived benefits		
Health	2.30	1.14
Social	3.07	1.24
Financial	2.63	1.26
Ethical	4.65	1.00
Rec	3.28	1.60
Risk attitudes		
Health	5.27	1.45
Social[a]	4.14	1.34
Financial[a]	4.11	1.75
Ethical[a]	6.28	1.31
Rec[a]	4.57	1.39

[a]Measure met tests for normality (P < 0.05).

Table 4. Regions of FA that differed by gender

Region	x	y	Z	P-value	Voxels
Male > Female					
R anterior thalamic radiation	11	0	−10	0.03	10 265
R inferior fronto-occipital fasciculus	30	−31	12	0.04	
Splenium of corpus callosum	10	−33	23	0.04	
R anterior limb of internal capsule	10	0	0	0.03	
L posterior limb of internal capsule	−25	−15	9	0.02	4251
L posterior thalamic radiation	−31	−66	0	0.04	
L inferior longitudinal fasciculus	−40	−36	0	0.04	
L superior corona radiata	−19	−12	43	0.05	426
L external capsule	−29	11	−9	0.05	130
L anterior corona radiata	−16	23	−14	0.05	101
L corticospinal tract	−21	−30	42	0.05	89
L inferior fronto-occipital fasciculus	−39	31	−8	0.05	15

Note: x, y and z refer to MNI coordinates; Voxels refers to the number of voxels in each significant cluster; L and R refer to left and right hemispheres.

Table 3. Correlations between task performance and DOSPERT measures

	Mean pumps cash-out	Mean pumps explosion	Response variability cash-out	Response variability explosion	Number of explosions	Standardized earnings
Likelihood						
Health	0.37	0.37	−0.18	−0.46	0.25	0.20
Social	0.10	0.20	−0.08	−0.41	0.25	−0.09
Financial	−0.02	0.37	0.10	−0.17	0.01	−0.02
Ethical	−0.02	0.10	−0.09	−0.38	0.27	−0.17
Rec	0.05	0.11	0.09	−0.27	0.08	−0.01
Benefits						
Health	0.10	0.26	−0.13	−0.20	0.08	0.02
Social	−0.04	0.03	−0.04	−0.40	0.20	−0.20
Financial	−0.18	−0.02	−0.08	−0.35	−0.13	−0.16
Ethical	−0.02	0.09	−0.11	−0.31	−0.01	−0..07
Rec	−0.03	−0.03	−0.18	−0.23	−0.01	−0.10
Risks						
Health	−0.14	0.02	0.01	−0.43	−0.18	−0.11
Social	−0.40	−0.14	0.02	−0.53[a]	−0.26	−0.29
Financial	−0.28	−0.02	0.14	−0.39	−0.28	−0.14
Ethical	−0.21	−0.08	−0.05	−0.43	−0.12	−0.24
Rec	−0.16	−0.10	0.04	−0.43	−0.10	−0.20

[a]Significant using Bonferroni adjusted alpha levels of 0.0006 per test (0.05/90).

domain in the posterior and superior corona radiata, superior longitudinal fasciculus, posterior thalamic radiation, and body of the corpus callosum (Table 6; Figure 3A and B). There was also a significant positive association between this DOSPERT measure and MD in the posterior and anterior thalamic radiations, posterior, superior, and anterior corona radiata, body and splenium of the corpus callosum, posterior and anterior limb of the internal capsule, superior longitudinal fasciculus, inferior front-occipital fasciculus, and uncinate fasciculus (Table 6; Figure 3C and D). There was also a significant negative association between FA and perceived risk attitudes for risk taking in the health domain; however, since this DOSPERT measure did not meet assumptions of normality, results are not reported here. There were no other significant associations between self-report and FA or MD. All analyses were corrected for age and gender.

Discussion

This study examined the association between adolescent response variability and white matter microstructure. Adolescents with greater FA exhibited more response variability on a risk taking task and had lower perceptions of real-world risk than those with less FA. We speculate that response variability during adolescence reflects the natural tendency to approach and explore the environment despite the potential

for negative consequences, during a developmental period when individuals are primed to distance themselves from the safety of caregivers (Ellis *et al.*, 2012; Spear, 2000). In this study, this behavior was associated with lower salience of social risks, a domain that is perhaps most relevant to adolescent development.

Response variability during the task was associated with greater FA in tracts connecting cortical and subcortical structures hypothesized to underpin decision making under risk and uncertainty (Bartra *et al.*, 2014). For example, the corona radiata is an important tract connecting the anterior cingulate cortex (ACC) to regions such as the striatum (Mori *et al.*, 2009). The ACC is part of an attentional network implicated in monitoring salient environmental cues (Tang *et al.*, 2010). The corona radiata

Table 5. Regions of FA that correlated with task performance

Region	x	y	z	P-value	Voxels
Positive correlations with FA					
Response variability					
R posterior corona radiata	26	−25	22	0.01	9268
L posterior corona radiata	−26	−28	27	0.03	
R superior corona radiata	28	7	29	0.01	
L superior corona radiata	−26	7	22	0.02	
L anterior corona radiata	−23	29	2	0.03	
R anterior thalamic radiation	24	−39	27	0.01	
Body of corpus callosum	−8	−19	27	0.02	
Splenium of corpus callosum	13	−40	21	0.02	
R superior longitudinal fasciculus	28	13	27	0.02	
L superior longitudinal fasciculus	−35	−31	27	0.04	
L posterior limb of internal capsule	−23	−9	14	0.03	

Note: x, y and z refer to MNI coordinates; p-values controlled for multiple comparisons with family-wise error correction (i.e. 'FWE-corrected'); Voxels refers to the number of voxels in each significant cluster; L and R refer to left and right hemispheres.

Table 6. Regions of FA and MD that correlated with self-report

Region	x	y	z	P-value	Voxels
Negative correlations with FA					
Perceived risk attitudes (social domain)					
R posterior corona radiata	27	−46	24	0.04	2102
R superior corona radiata	22	−19	38	0.04	
R superior longitudinal fasciculus	26	−60	32	0.05	
Body of corpus callosum	−10	−19	29	0.05	
L posterior thalamic radiation	−32	−46	12	0.05	202
Positive Correlations with MD					
Perceived risk attitudes (social domain)					
R posterior thalamic radiation	33	−54	14	0.01	21 622
R anterior thalamic radiation	24	−36	27	0.01	
Body of corpus callosum	7	2	26	0.01	
Splenium of corpus callosum	−9	−34	22	0.01	
R posterior corona radiata	27	−36	21	0.01	
L posterior corona radiata	−27	−34	22	0.03	
L superior corona radiata	−28	−13	20	0.02	
R superior corona radiata	27	4	32	0.03	
R posterior limb of internal capsule	21	−13	3	0.03	
L anterior limb of internal capsule	−12	−1	2	0.04	
L inferior fronto-occipital fasciculus	−37	−30	2	0.03	
R superior longitudinal fasciculus	38	−43	32	0.03	
L superior longitudinal fasciculus	−50	−43	−3	0.04	
L uncinate fasciculus	−27	16	−6	0.05	
R anterior corona radiata	28	17	25	0.05	243
L anterior corona radiata	−26	17	12	0.05	

Note: x, y and z refer to MNI coordinates; P-values controlled for multiple comparisons with family-wise error correction (i.e. 'FWE-corrected'); Voxels refers to the number of voxels in each significant cluster; L and R refer to left and right hemispheres.
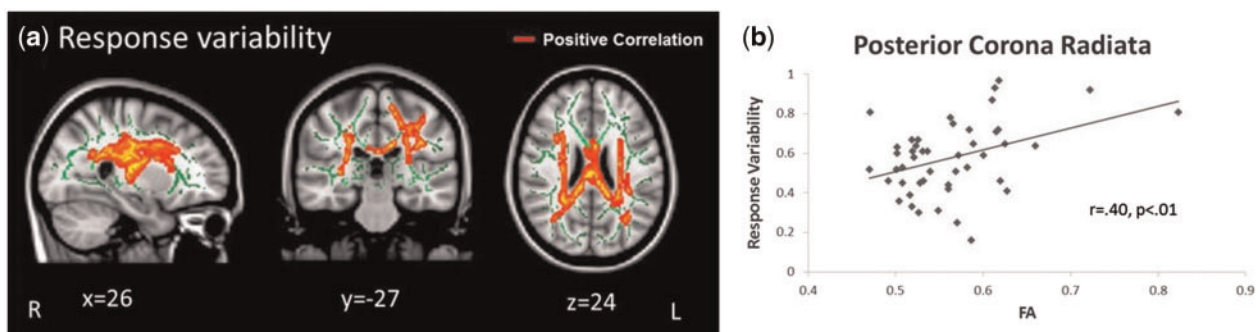

Fig. 2. Significant correlation between FA and response variability on laboratory task. (a) Positive correlation between FA and response variability (x = 26, y = −27, z = 24). (b) Scatterplot showing a visual depiction of the association within the posterior corona radiata shown in (a) (r = 0.40, P < 0.01). Results remained significant in analyses conducted without the apparent outlier (r = 0.36, P < 0.05). The mean white matter skeleton is shown in green. Coordinates presented in MNI space. L, left; R, right.
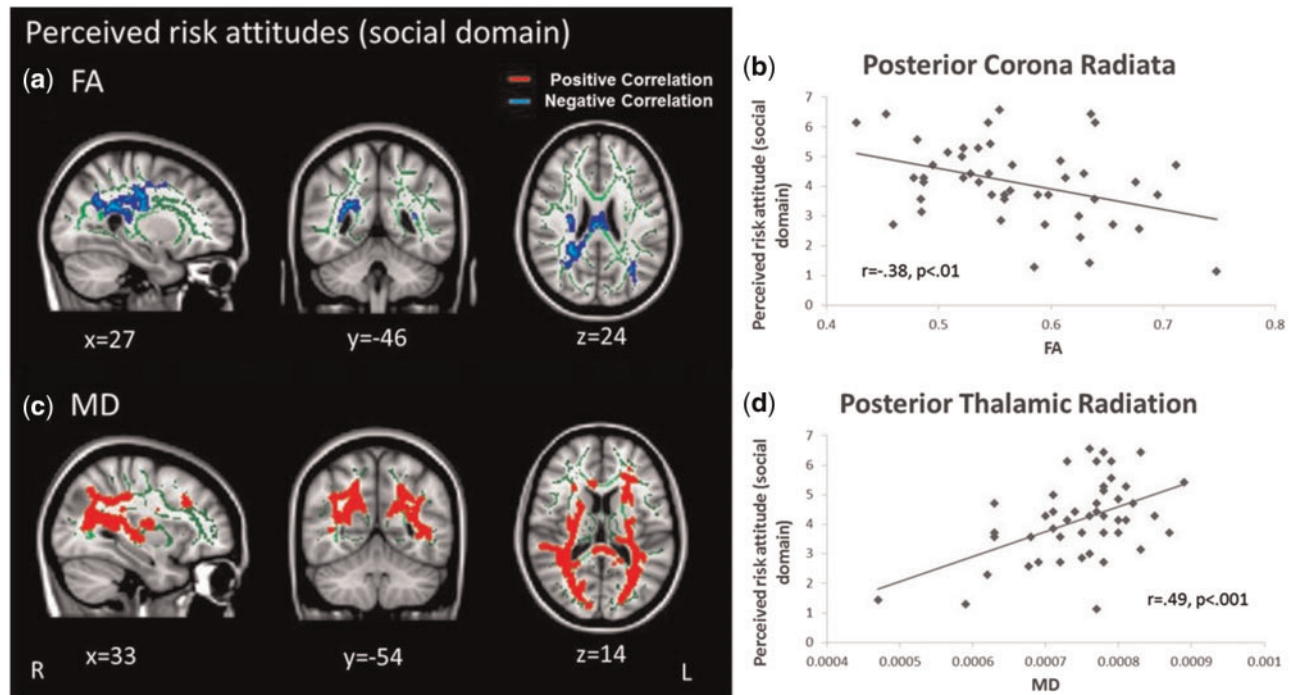
Fig. 3. Significant correlations with DTI indices and risk attitudes for socially risky behaviors. **(a)** Negative correlation between FA and perceived risk attitudes for behaviors in the social domain (x = 27, y = −46, z = 24). **(b)** Scatterplot showing a visual depiction of the association within the posterior corona radiata in (a) (r = −0.38, P < 0.01). **(c)** Positive correlation between MD and perceived risk attitudes for behaviors in the social domain (x = 33, y = −54, z = 14). **(d)** Scatterplot showing a visual depiction of the association within the posterior thalamic radiation in (c) (r = 0.49, P < 0.001). Results remained significant in analyses conducted without the apparent outlier (r = 0.41, P < 0.01). The mean white matter skeleton is shown in green. Coordinates are presented in MNI space. L, left; R, right.

continues ventrally and becomes the internal capsule, a subcortical structure that physically separates regions important for motivation (Haber, 2003) and contains a high concentration of motor projection fibers (Werring *et al.*, 1998). Response variability under conditions of risk may involve the integration of pathways that mediate attention, motivation, and motor control.

It makes adaptive sense for higher response variability to be associated with greater FA within these tracts in adolescents, given that adolescent risky decision making varies depending on context (Chein *et al.*, 2011), motivation (Geier *et al.*, 2010, 2009) and the probability of a positive outcome (Barkley-Levenson and Galván, 2014). White matter structure continues to shape and strengthen well into adolescence (Hagmann *et al.*, 2010), which may grant an adaptive flexibility optimized to navigate the uncertainty typically encountered in the environment at the time of an individual's transition to independence (Spear, 2000; Crone and Dahl, 2012). Associations with response variability were found for FA and not MD. FA is hypothesized to reflect microstructural properties of white matter (e.g. increased tract organization, greater myelination, or denser axon packing) though is not sensitive enough to characterize specific tissue changes (Alexander *et al.*, 2011). MD may be a more robust measurement of white matter maturation, but only in fiber tracts without a high degree of organization (Schmithorst *et al.*, 2002). Perhaps response variability in adolescents is related to fine-scale organization rather than large-scale changes in myelination. This speculation is consonant with the ongoing development of white matter that continues through the mid-adolescent years and into the mid-20s (Ladouceur *et al.*, 2012).

In this study, participant self-report provided information on the real-world domains potentially most important for adolescent behavior. Individuals who evaluated risky behaviors as less risky (i.e. perceived risk attitudes) demonstrated greater FA and lower MD, specifically for behaviors within the social domain. Socially risky behaviors may provide adolescents with the experiences most relevant to fostering adult independence and peer connection (e.g. 'disagreeing with an authority figure on a major issue'). Tracts of significance included frontolimbic connections such as the anterior thalamic radiation, which connects nerve fibers between the thalamus and the prefrontal cortex (Wakana *et al.*, 2004). The prefrontal cortex is critical for higher-level cognition (Miller and Cohen, 2001) and undergoes protracted development well into adolescence (Giedd *et al.*, 1999; Sowell *et al.*, 2003). The thalamus has a central position within the basal ganglia loops and drives attentional and behavioral shifts to changing external cues (Smith *et al.*, 2011). As such, it is an important structure in the reward neurocircuitry that links motivation with complex behavioral response (Cho *et al.*, 2013). Self-report complemented task performance findings, such that adolescents with greater response variability on the risk taking task were more likely to evaluate real-world behaviors as less risky. This suggests that lower salience of the potential negative consequences of risk is related to a greater willingness to engage with uncertainty through more response variability. No associations were observed for FA or MD and likelihood to engage in risky behaviors in the current study. While these adolescents may perceive risk taking as less risky, they are not necessarily engaging in these behaviors in the real-world.

The goal of this study was to examine the association between white matter microstructure and risk taking on the BART. Exploratory analyses revealed that the measure most consistently and significantly associated with FA and adolescent self-report was response variability on explosion trials.

Although mean number of pumps on cash-out trials is the commonly used measure of risk taking on the BART, research in recent years has begun exploring response variability on task as a unique predictor of behavior. Reports of response variability on cash-out trials have typically observed this parameter to be associated with lower task earnings (Jentsch *et al.*, 2010; DeMartini *et al.*, 2014), a finding upheld in the present study. It is hypothesized that response variability on cash-out trials reflects combinations of both higher than optimal and lower than optimal trials completions (Jentsch *et al.*, 2010). Alternatively, explosion trials may reflect adaptive sensation seeking or exploratory behavior on the task, as suggested by prior studies. For example, one study operationalized number of explosions as a measure of untempered risk-taking, given that participants with higher levels of sensation seeking made more explosions (Humphreys *et al.*, 2013). Another study found an association between a greater number of explosion trials and higher levels of neurobiological indicators of maturity in boys (Peper *et al.*, 2013). The authors hypothesize that more advanced pubertal development (greater endogenous testosterone) may lead to more sensation seeking (the thrill of pumping the balloon further) in the service of task exploration. Highlighting the importance of explosion trials in exploring task environment, another study found increased activation in regions of the brain implicated in feedback processing (e.g. insula, ACC, lateral PFC) during explosions compared with cash-outs (Claus and Hutchison, 2012).

We hypothesize that response variability during explosion trials demonstrated significant associations with FA because explosion trials provide feedback on the outcome likelihood of a negative consequence of a risky choice, while cash-out trials do not. Prior work has demonstrated that the adolescent brain is uniquely sensitive to unexpected outcome feedback, over and above reward valuation (Cohen *et al.*, 2010). There is an implicit assumption that trials ending in explosions do so independently of respondents' behavior. This assumption is incorrect, given that the more times respondents choose the risky option within a trial, the more likely the trial will terminate with an explosion (Pleskac *et al.*, 2008). We posit that response variability on explosion trials represents a response pattern that facilitates a wider range of experience with the unknown probability distribution of negative consequences of the task. This interpretation is supported by the finding that adolescents who rated real-world examples of risk taking behaviors as less risky also exhibited greater response variability on explosion trials. In other words, greater response variability on explosion trials was likely related to a decreased salience of potential negative outcomes (explosions) when evaluating risky choice (deciding to continue pumping on a trial).

It is important to note the limitations of the present findings. First, there were no child or adult comparison groups, which would have allowed for an examination of whether response variability during risky choice develops linearly over time or is uniquely manifested during adolescence. However, adolescents have a high degree of individual differences with respect to risky choice (van Duijvenvoorde *et al.*, 2015) and this behavior may be most developmentally appropriate during this period. By implementing a narrow age range, the potential effects of age-related differences in neuronal maturation were minimized. Second, pubertal status was not assessed. Males demonstrated significantly higher FA (but not MD) compared with females of the same age. This finding is consistent with prior literature showing that boys demonstrate greater absolute and relative white matter volumes compared with girls and considerably steeper white matter increases during adolescence (Giedd *et al.*, 1999; De Bellis *et al.*, 2001; Lenroot *et al.*, 2007; Perrin *et al.*, 2009), perhaps due to the presence of testosterone (Herting *et al.*, 2012, but see Peper *et al.*, 2015). The collection of pubertal hormone measures will be crucial to understand how sex hormones shape the developing brain. Finally, this study was not longitudinal, which precludes inferences of directionality.

Despite limitations, the present study contributes to our growing understanding of the dynamic nature of adolescent behavior and its neural underpinnings. Dominant views of adolescent risk taking have previously emphasized its maladaptive nature (e.g. Lavery *et al.*, 1993); however, risk taking can result in optimized outcome and adaptive learning (Humphreys *et al.*, 2013; Peper *et al.*, 2013; Reyna *et al.*, 2011). The present study provides novel evidence that response variability during a dynamic risk taking task is supported by lower perceived risk attitudes and increased FA. Much like an infant gaining the mobility to walk, behavioral variability in adolescents under conditions of risk or uncertainty may facilitate developmentally-appropriate behavior in the service of exploring relevant environments. The peaks and valleys of variability during adolescence may, depending on the vantage point, reflect points of susceptibility or windows of opportunity and growth.

Supplementary data

Supplementary data are available at *SCAN* online.

Conflict of interest. None declared.

Funding

References

Alexander, A.L., Hurley, S.A., Samsonov, A.A., *et al.* (2011). Characterization of cerebral white matter properties using quantitative magnetic resonance imaging stains. *Brain Connectivity* **1**(6), 423–46.

Barkley-Levenson, E., Galván, A. (2014). Neural representation of expected value in the adolescent brain. *Proceedings of the National Academy of Sciences*, **111**(4), 1646–51.

Barnea-Goraly, N., Menon, V., Eckert, M., *et al.* (2005). White matter development during childhood and adolescence: a cross-sectional diffusion tensor imaging study. *Cerebral Cortex*, **15**(12), 1848–54.

Bartra, O., McGuire, J.T., Kable, J.W. (2013). The valuation system: a coordinate-based meta-analysis of BOLD fMRI experiments examining neural correlates of subjective value. *Neuroimage*, **76**, 412–27.

Basser, P.J. (1995). Inferring microstructural features and the physiological state of tissues from diffusion-weighted images. *NMR in Biomedicine*, **8**(7), 333–44.

Bava, S., Tapert, S.F. (2010). Adolescent brain development and the risk for alcohol and other drug problems. *Neuropsychology Review*, **20**(4), 398–413.

Beaulieu, C. (2002). The basis of anisotropic water diffusion in the nervous system–a technical review. *NMR in Biomedicine*, **15**(7–8), 435–55.

Chein, J., Albert, D., O'Brien, L., Uckert, K., Steinberg, L. (2011). Peers increase adolescent risk taking by enhancing activity in the brain's reward circuitry. *Developmental Science*, **14**(2), F1–10.

Cho, Y.T., Fromm, S., Guyer, A.E., *et al.* (2013). Nucleus accumbens, thalamus and insula connectivity during incentive anticipation in typical adults and adolescents. *Neuroimage*, **66**, 508–21.

Claus, E.D., Hutchison, K.E. (2012). Neural mechanisms of risk taking and relationships with hazardous drinking. *Alcoholism: Clinical and Experimental Research*, **36**(6), 932–40.

Cohen, J.R., Asarnow, R.F., Sabb, F.W., *et al.* (2010). A unique adolescent response to reward prediction errors. *Nature Neuroscience*, **13**(6), 669–71.

Congdon, E., Bato, A.A., Schonberg, T., *et al.* (2013). Differences in neural activation as a function of risk-taking task parameters. *Frontiers in Neuroscience*, **7**, 173.

Crone, E.A., Dahl, R.E. (2012). Understanding adolescence as a period of social–affective engagement and goal flexibility. *Nature Reviews Neuroscience*, **13**(9), 636–50.

Crone, E.A., Duijvenvoorde, A.C., Peper, J.S. (2016). Annual Research Review: Neural contributions to risk-taking in adolescence: Developmental changes and individual differences. *Journal of Child Psychology and Psychiatry and Allied Disciplines*, *Nature Neuroscience*, **57**(3), 353–68

De Bellis, M.D., Keshavan, M.S., Beers, S.R., *et al.* (2001). Sex differences in brain maturation during childhood and adolescence. *Cerebral Cortex*, **11**(6), 552–7.

DeMartini, K.S., Leeman, R.F., Corbin, W.R., *et al.* (2014). A new look at risk-taking: Using a translational approach to examine risk-taking behavior on the balloon analogue risk task. *Experimental and Clinical Psychopharmacology*, **22**(5), 444.

Ellis, B.J., Del Giudice, M., Dishion, T.J., *et al.* (2012). The evolutionary basis of risky adolescent behavior: implications for science, policy, and practice. *Developmental Psychology*, **48**(3), 598.

Figner, B., Weber, E.U. (2011). Who takes risks when and why? Determinants of risk taking. *Current Directions in Psychological Science*, **20**(4), 211–6.

Giedd, J.N., Blumenthal, J., Jeffries, N.O., *et al.* (1999). Brain development during childhood and adolescence: a longitudinal MRI study. *Nature Neuroscience*, **2**(10), 861–3.

Geier, C.F., Terwilliger, R., Teslovich, T., Velanova, K., Luna, B. (2010). Immaturities in reward processing and its influence on inhibitory control in adolescence. *Cerebral Cortex*, **20**(7), 1613–29.

Haber, S.N. (2003). The primate basal ganglia: parallel and integrative networks. *Journal of chemical neuroanatomy*, **26**(4), 317–30.

Hagmann, P., Sporns, O., Madan, N., *et al.* (2010). White matter maturation reshapes structural connectivity in the late developing human brain. *Proceedings of the National Academy of Sciences of the United States of America*, **107**(44), 19067–72.

Herting, M.M., Maxwell, E.C., Irvine, C., Nagel, B.J. (2012). The impact of sex, puberty, and hormones on white matter microstructure in adolescents. *Cerebral Cortex*, **22**(9), 1979–92.

Humphreys, K., Lee, S., Tottenham, N. (2013). Not all risk taking behavior is bad: Associative sensitivity predicts learning during risk taking among high sensation seekers. *Personality and Individual Differences*, **54**, 708–15.

Jentsch, J.D., Woods, J.A., Groman, S.M., Seu, E. (2010). Behavioral characteristics and neural mechanisms mediating performance in a rodent version of the Balloon Analog Risk Task. *Neuropsychopharmacology*, **35**(8), 1797–806.

Ladouceur, C.D., Peper, J.S., Crone, E.A., Dahl, R.E. (2012). White matter development in adolescence: the influence of puberty and implications for affective disorders. *Developmental Cognitive Neuroscience*, **2** (1), 36–54.

Lavery, B., Siegel, A.W., Cousins, J.H., Rubovits, D.S. (1993). Adolescent risk-taking: An analysis of problem behaviors in problem children. *Journal of Experimental Child Psychology*, **55**(2), 277–94.

Lejuez, C.W., Read, J.P., Kahler, C.W., *et al.* (2002). Evaluation of a behavioral measure of risk taking: the Balloon Analogue Risk Task (BART). *Journal of Experimental Psychology: Applied*, **8**(2), 75.

Lenroot, R.K., Gogtay, N., Greenstein, D.K., *et al.* (2007). Sexual dimorphism of brain developmental trajectories during childhood and adolescence. *Neuroimage*, **36**(4), 1065–73.

Luna, B., Padmanabhan, A., O'Hearn, K. (2010). What has fMRI told us about the development of cognitive control through adolescence? *Brain and Cognition*, **72**(1), 101–13.

Miller, E.K., Cohen, J.D. (2001). An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience*, **24**(1), 167–202.

Mori, S., Oishi, K., Faria, A.V. (2009). White matter atlases based on diffusion tensor imaging. *Current Opinion in Neurology*, **22**(4), 362.

Nichols, T.E., Holmes, A.P. (2002). Nonparametric permutation tests for functional neuroimaging: a primer with examples. *Human Brain Mapping*, **15**(1), 1–25.

Peper, J.S., Koolschijn, P.C.M., Crone, E.A. (2013). Development of risk taking: contributions from adolescent testosterone and the orbito-frontal cortex. *Journal of Cognitive Neuroscience*, **25**(12), 2141–50.

Peper, J.S., de Reus, M.A., van den Heuvel, M.P., Schutter, D.J. (2015). Short fused? associations between white matter connections, sex steroids, and aggression across adolescence. *Human Brain Mapping*, **36**(3), 1043–52.

Perrin, J.S., Leonard, G., Perron, M., *et al.* (2009). Sex differences in the growth of white matter during adolescence. *Neuroimage*, **45**(4), 1055–66.

Piek, J.P. (2002). The role of variability in early motor development. *Infant Behavior and Development*, **25**(4), 452–65.

Pleskac, T.J., Wallsten, T.S., Wang, P., Lejuez, C.W. (2008). Development of an automatic response mode to improve the clinical utility of sequential risk-taking tasks. *Experimental and Clinical Psychopharmacology*, **16**(6), 555.

Reyna, V., Estrada, S., DeMarinis, J., Myers, R., Stanisz, J., Mills, B. (2011). Neurobiological and memory models of risky decision making in adolescents versus young adults. *Journal of Experimental Psychology. Learning, Memory and Cognition*, **37**, 1125–42.

Schmithorst, V.J., Wilke, M., Dardzinski, B.J., Holland, S.K. (2002). Correlation of white matter diffusivity and anisotropy with age during childhood and adolescence: a cross-sectional diffusion-tensor MR imaging study 1. *Radiology*, **222**(1), 212–8.

Spear, L.P. (2000). The adolescent brain and age-related behavioral manifestations. *Neuroscience & Biobehavioral Reviews*, **24**(4), 417–63.

Smith, L.B., Thelen, E. (2003). Development as a dynamic system. *Trends in Cognitive Sciences*, **7**(8), 343–8.

Smith, S.M., Jenkinson, M., Woolrich, M.W., *et al.* (2004). Advances in functional and structural MR image analysis and implementation as FSL. *Neuroimage*, **23**, S208–19.

Smith, S.M., Jenkinson, M., Johansen-Berg, H., *et al.* (2006). Tract-based spatial statistics: voxelwise analysis of multi-subject diffusion data. *Neuroimage*, **31**(4), 1487–505.

Smith, S.M., Nichols, T.E. (2009). Threshold-free cluster enhancement: addressing problems of smoothing, threshold dependence and localisation in cluster inference. *Neuroimage*, **44**(1), 83–98.

Smith, Y., Surmeier, D.J., Redgrave, P., Kimura, M. (2011). Thalamic contributions to basal ganglia-related behavioral switching and reinforcement. *The Journal of Neuroscience*, **31**(45), 16102–6.

Sowell, E.R., Peterson, B.S., Thompson, P.M., Welcome, S.E., Henkenius, A.L., Toga, A.W. (2003). Mapping cortical change across the human life span. *Nature Neuroscience*, **6**(3), 309–15.

Steinberg, L. (2007). Risk taking in adolescence new perspectives from brain and behavioral science. *Current Directions in Psychological Science*, **16**(2), 55–9.

Tang, Y.Y., Lu, Q., Geng, X., Stein, E.A., Yang, Y., Posner, M.I. (2010). Short-term meditation induces white matter changes in the anterior cingulate. *Proceedings of the National Academy of Sciences of the United States of America*, **107**(35), 15649–52.

Telzer, E.H., Fuligni, A.J., Lieberman, M.D., Galván, A. (2013). Meaningful family relationships: Neurocognitive buffers of adolescent risk taking. *Journal of Cognitive Neuroscience*, **25**(3), 374–87.

van Duijvenvoorde, A.C., Huizenga, H.M., Somerville, L.H., *et al.* (2015). Neural correlates of expected risks and returns in risky choice across development. *The Journal of Neuroscience*, **35**(4), 1549–60.

Wakana, S., Jiang, H., Nagae-Poetscher, L.M., Van Zijl, P.C., Mori, S. (2004). Fiber tract–based atlas of human white matter anatomy 1. *Radiology*, **230**(1), 77–87.

Weber, E.U., Blais, A.R., Betz, N.E. (2002). A domain-specific risk-attitude scale: Measuring risk perceptions and risk behaviors. *Journal of Behavioral Decision Making*, **15**(4), 263–90.

Werring, D.J., Clark, C.A., Barker, G.J., *et al.* (1998). The structural and functional mechanisms of motor recovery: complementary use of diffusion tensor and functional magnetic resonance imaging in a traumatic injury of the internal capsule. *Journal of Neurology, Neurosurgery and Psychiatry*, **65**(6), 863–9.

Zilles, K., Amunts, K. (2013). Individual variability is not noise. *Trends in Cognitive Sciences*, **17**(4), 153–5.