



Longitudinal link between trait motivation and risk-taking behaviors via neural risk processing

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ABSTRACT

Prior research has emphasized the importance of the motivational system in risky decision-making, yet the mechanisms through which individual differences in motivation may influence adolescents' risk-taking behaviors remain to be determined. Based on developmental neuroscience literature illustrating the importance of risk processing in explaining individual differences in value-based decision making, we examined risk processing as a potential mediator of the association between trait motivations and adolescents' risk-taking behaviors. The sample consisted of 167 adolescents (47% females) annually assessed for three years (13–14 years of age at Time 1). Approach and avoidance motivations were measured using adolescent self-report. Risk preference was estimated based on adolescents' decisions during a modified economic lottery choice task with neural risk processing being measured by blood-oxygen-level-dependent responses in the bilateral insular cortex for chosen options. Adolescents' risk-taking behaviors were assessed by laboratory-based risky decision making using the Stoplight task. Longitudinal mediation analyses revealed a significant indirect effect of approach motivation, such that higher motivation was correlated with increases in risk-taking behaviors via decreases in neural activation in the bilateral insular cortex during risk processing. The findings illustrate a neural pathway through which approach motivation is translated into the vulnerability to risk taking development.

1. Introduction

Adolescence is a period characterized by heightened risk-taking behaviors with dire health consequences related to morbidity and mortality, such as substance use, unprotected-sex, and reckless driving (Dahl, 2004). Notable increases in risk-taking behaviors are seen between childhood and adolescence, with adolescents engaging in riskier activities than younger or older individuals (Humphrey and Dumontheil, 2016; Figner et al., 2009; Steinberg, 2008). These risk-taking behaviors not only have long-lasting effects on individuals' health, social, and career development, but also constitute a public health issue that threatens the overall well-being of young people (Dumontheil, 2016; Steinberg, 2008). Thus, it is critical to identify the factors and mechanisms that underlie heightened risk-taking behaviors in adolescence.

Prior research has emphasized the importance of the motivational system in risky decision-making processes (Franken and Muris, 2006; Luna et al., 2013; Kim-Spoon et al., 2016a; Urošević et al., 2014; van Leeuwen et al., 2011), yet the mechanisms through which individual differences in motivation may influence adolescents' risk-taking behaviors are not well documented. Accumulating evidence suggests that neural representations of risk (i.e., the variance of potential outcomes) play an important role in risky decision-making behaviors (Mohr et al., 2010). Compared to children and adults, adolescents show greater inter-individual variability in behavioral risk preference as well as a peak in risk-related neural activation during adolescence (van Duijvenvoorde et al., 2015). In the current longitudinal study, we investigate whether adolescents' behavioral risk preference and neural risk processing under uncertainty may partially explain the association between

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approach and avoidance motivations and laboratory-based risk-taking behaviors in adolescents. We note that the definition of risk in risk preference and risk processing in the current study is consistent with the behavioral economics views on risk, namely variance of potential outcomes. As reviewed by [Schonberg et al. \(2011\)](#), this definition of risk is different from the clinical definition of risk (i.e., potential for negative outcomes) that is implied by risky behaviors (i.e., behaviors that harm oneself or others).

A number of personality theories have suggested the existence of two main motivational systems, approach and avoidance, that influence decision-making processes and goal-directed behaviors ([Cacioppo et al., 1999](#); [Carver and White, 1994](#); [Elliot and Thrash, 2002](#); [Gray, 1990](#)). These theories posit that approach motivation is a general neurobiological sensitivity to positive/desirable stimuli (i.e., reward) that is accompanied by a behavioral predisposition toward such stimuli, whereas avoidance motivation represents a general neurobiological sensitivity to negative/undesirable stimuli (i.e., punishment) accompanied by a behavioral predisposition away from such stimuli ([Elliot and Thrash, 2002](#)). Adolescence is an important developmental period to understand relative contributions of approach and avoidance motivations related to risk-taking behaviors, because it is a critical period of brain development related to risky decision making, and also has observed distinctive developmental patterns between approach and avoidance. Notably, greater approach and less avoidance have been repeatedly found among adolescents compared to adults ([Ernst et al., 2006](#); [Geier and Luna, 2009](#); [Urošević et al., 2012](#)). For instance, [Cauffman et al. \(2010\)](#) found that approach motivation toward potential reward displayed an inverted U-shape relation with age, such that the maximal sensitivity to positive feedback occurred during mid-to late adolescence. In contrast, tendencies to avoid negative outcomes strengthen with age in a linear function, not showing full maturity until the adulthood.

The different developmental patterns of approach and avoidance motivations lend support to the theoretical perspective that heightened risk-taking behaviors observed in adolescence may be derived not only from increased motivation to rewards and new experiences, but also from the insensitivity to avoid undesirable punishment ([Somerville et al., 2010](#)). Empirical studies reveal consistent evidence for heightened approach (reward-related) motivation among adolescents compared to adults ([Galván, 2013](#)). However, evidence for reduced avoidance (punishment-related) motivation is less consistent, indicating that adolescents show comparable or even higher levels of risk aversion than adults ([Paulsen et al., 2012](#); [Tymula et al., 2012](#)). A growing body of evidence points to approach motivation as a key risk factor for risk-taking behaviors, with higher approach motivation being linked to an earlier onset of substance use, higher levels of substance use, and increased risky sexual behaviors ([Kim-Spoon et al., 2016a](#); [Urošević et al., 2014](#); [van Leeuwen et al., 2011](#)). In contrast, findings on the relation between avoidance motivation and risk-taking behaviors are less consistent. While some studies have reported no link between avoidance motivation and substance use ([Colder et al., 2013](#); [Kim-Spoon et al., 2016a](#)), one study revealed that avoidance motivation was negatively associated substance use in college students ([Franken and Muris, 2006](#)), and another suggested that low avoidance was linked to a progression into regular substance use in adolescents ([van Leeuwen et al., 2011](#)). Such mixed findings call for further investigation to evaluate the joint effects of approach and avoidance motivations on other types of risk-taking behaviors and explore the underlying mechanisms of the above associations.

In behavioral economics, expected utility models provide a specific conceptual framework to understand the process of decision making. These models allow for the decomposition of decision-making components, which allows for increased precision in understanding which elements (e.g., expected value, risk) contribute to risky decision making ([Schonberg et al., 2011](#)). Extant neuroeconomics literature has implicated anterior insular cortex as a key region in both the processing and

learning of risk information ([Mohr et al., 2010](#); [Paulus et al., 2003](#); [Platt and Huettel, 2008](#); [Smith et al., 2013](#); [van Duijvenvoorde et al., 2015, 2016](#)). Specifically, the insular cortex has been found to respond to increasing levels of risk when evaluating decision options in uncertain environments ([Blankenstein et al., 2018](#); [Mohr et al., 2010](#); [Xue et al., 2010](#)). Greater activation in the anterior insular cortex is associated with greater risk avoidance ([Paulus et al., 2003](#)) and subsequent switching from a risky to a safe option ([Kuhnen and Knutson, 2005](#)). Moreover, patients with insular cortex lesions are insensitive to the risk associated with decision options, indicating that the insular cortex may play a key role in signaling the likelihood of aversive outcomes ([Clark et al., 2008](#)).

Developmental neuroscience work has emphasized neurobiological pathways underlying adolescent risk-taking behaviors, suggesting that individual differences in the subcortical, motivational systems involved in the processing of reward are linked to risk-taking development ([Casey et al., 2008](#); [Luna and Wright, 2016](#); [Steinberg, 2010](#)). Research on adolescent reward processing showed that heightened activation in the regions such as the ventral and dorsal striatum is linked to greater risky decision making ([van Duijvenvoorde et al., 2014](#)). However, there is emerging evidence suggesting that risk processing (i.e., heightened sensitivity to risky options shown by insular cortex activation) is related to decreased risk taking in adolescents in both laboratory-based and real-world behaviors. A study by [van Duijvenvoorde et al. \(2015\)](#) revealed that adolescents displayed greater insula activation in response to increasing risk compared to children and adults. That is, adolescents may have greater emotional responses to risks, as increased engagement of the insular cortex may represent a signal leading decision makers to exhibit caution and thoroughly evaluate risky options. Behaviorally, adolescents displayed substantial individual differences in risk sensitivity, however, ranging from risk seeking to risk averse, whereas adults were uniformly risk averse. Further, [Kim-Spoon et al. \(2017\)](#) demonstrated that low levels of risk-related activation in the insular cortex during anticipation of uncertain outcomes predicted high levels of health risk behaviors among adolescents, particularly for those who exhibited neural patterns indicating poor cognitive control.

To date, however, it remains unclear as to what contributes to substantial individual differences in risk sensitivity and risk-related neural processing observed among adolescents. Given the critical role of the insular cortex in the integration of cognitive, emotional, and motivational information, it is likely that risk processing may be influenced by internal states such as emotions and motivations ([Craig, 2009](#); [Smith et al., 2013](#); [van Duijvenvoorde et al., 2015](#)). It follows that individual differences in approach and avoidance motivations may be linked to individual differences in insular risk processing during decision making, which in turn are linked to individual differences in risk-taking behaviors. In the current study, we examined the associations among approach and avoidance motivations, insular risk processing, and laboratory-based risk-taking behaviors in adolescents using longitudinal data repeatedly measured annually over three years. We used a longitudinal design for testing a developmental cascade model, focusing on individual differences in neural risk processing, being influenced by trait motivations and predicting changes in risk-taking behaviors during adolescence. Specifically, our hypothesized *longitudinal progression* model tested whether approach and avoidance motivations measured at Time 1 were related to risk-taking behaviors measured at Time 3 indirectly through parallel mediators of behavioral risk preference and neural risk processing measured at Time 2. Furthermore, our hypothesized *longitudinal change* model tested whether approach and avoidance motivations measured at Time 1 were statistically predictive of behavioral risk preference and neural risk processing measured at Time 2 (controlling for baseline at Time 1), which in turn were related to risk-taking behaviors measured at Time 3 (controlling for baseline at Time 1).

2. Methods

2.1. Participants

The sample included 167 adolescents (47% females, 53% males), 13 to 14 years of age at Time 1 ($M = 14.13$, $SD = 0.54$), 14 to 15 years of age at Time 2 ($M = 15.05$, $SD = 0.54$) and 15 to 16 years old at Time 3 ($M = 16.07$, $SD = 0.56$). The current sample was representative of rural southwest Virginia for household income and race/ethnicity. At all three times, median household income in the sample was \$35,000 - \$49,999, which is close to the median annual household income range (\$36,000 - \$59,000) of the area. Adolescent participants are primarily Caucasian (82%), African-American (12%), and other (6%). At Time 1, a total of 157 adolescents were recruited to participate in a longitudinal study. At Time 2, 10 additional adolescents were recruited, leading to a final sample of 167 dyads. Between Time 1 and Time 3, 19 adolescents did not complete the study for reasons such as: ineligibility for neuroimaging tasks ($n = 1$), moved away ($n = 1$), extenuating circumstances ($n = 1$), lost contact ($n = 8$), and declined participation ($n = 8$). Attrition analyses indicated that the 19 adolescents who did not return for Time 2 or Time 3 were not significantly different on demographic (age, income, race, sex) or main study variables (approach, avoidance, risk processing, and risk-taking behaviors at Time 1) from the adolescents who did return (all $ps > .09$). Exclusion criteria included claustrophobia, history of head injury resulting in loss of consciousness for more than 10 min, orthodontia impairing image acquisition, and contraindications to magnetic resonance imaging.

2.2. Procedure

Adolescents and their families were recruited via flyers and emails that were distributed in schools and other community locations. Research assistants described the nature of the study to interested individuals over the telephone and invited them to participate. Data collection took place at the university's offices, where adolescents and their primary caregivers were interviewed by trained research assistants and received monetary compensation for participation. All participants provided written consent for a protocol approved by the institutional review board of the university.

2.3. Measures

2.3.1. Approach and avoidance

At Time 1, trait approach was measured using the Sensation Seeking Scale (Zuckerman et al., 1978) and the Behavioral Activation Scale (Carver and White, 1994), which included three subscales of drive, fun-seeking, and reward-responsiveness. A principal component analysis was conducted on the three subscales of the Behavioral Activation Scale and the Sensation Seeking Scale, and the result indicated that the first component explained a large portion of the total variance (56.46%), with all factor loadings above .65. These scores were standardized, averaged and standardized again to generate the approach scores. Trait avoidance was measured using the Behavioral Inhibition Scale (Carver and White, 1994) and Shyness and Fear subscales from the Early Adolescents Temperament Questionnaire-Revised Short Form (EATQ-R; Capaldi and Rothbart, 1992). A principal component analysis was conducted on these three scales and the result indicated that the first component explained a large portion of the total variance (64.48%), with all factor loadings above .74. These three scores were standardized and averaged and standardized again to generate the avoidance scores. Both approach and avoidance variables are highly stable across three assessments. The zero-order correlations of approach variables across three waves were .65–.77 ($ps < .001$). The correlations of avoidance variables across three waves were .69–.84, ($ps < .001$).

2.3.2. Risk-taking behaviors

At Time 1 and Time 3, the Stoplight task (Chein et al., 2011; Steinberg et al., 2008) was used to measure laboratory-based risk-taking behaviors. Stoplight is a computerized first-person driving task in which participants control the progression of a vehicle along a straight track. The goal is to advance through a series of intersections to reach a finish line as quickly as possible and receive a monetary reward. At each intersection, as the vehicle approaches a changing traffic signal cycling from green to yellow to red, participants must make a decision about whether to brake and lose time by waiting for the light to return to green or run through the light and chance a crash. Successfully crossing an intersection without braking saves time, whereas braking and waiting for the signal to turn green again results in a time delay. However, if participants do not brake and a crash ensues, the loss of time is even greater than if they were to brake and wait for the light. Adolescent participants completed one round involving 32 intersections which were treated as separate trials. The degree of risk taking was indicated by the number of intersections the participant went through without braking divided by the total number of intersections traversed. Prior research indicated that this laboratory-based measure of risk-taking behaviors is significantly related to real-world health risk behaviors among adolescents (Kim-Spoon et al., 2016b).

2.3.3. Imaging acquisition and analysis

Functional neuroimaging data were acquired on a 3 T Siemens Tim Trio MRI scanner with a standard 12-channel head matrix coil. Structural images were acquired using a high-resolution magnetization prepared rapid acquisition gradient echo sequence with the following parameters: TR = 1200 ms, TE = 2.66 ms, FoV = 245 x 245 mm, and 192 slices with the spatial resolution of 1 x 1 x 1 mm. Echo-planar images (EPIs) were collected using the following parameters: slice thickness = 4 mm, 34 axial slices, field of view (FoV) = 220 x 220 mm, repetition time (TR) = 2 s, echo time (TE) = 30 ms, flip angle = 90 degrees, voxel size = 3.4 x 3.4 x 4 mm, 64 x 64 grid, and slices were hyperangulated at 30 degrees from anterior-posterior commissure. Imaging data were preprocessed and analyzed using Statistical Parametric Mapping (SPM8: Wellcome Trust Neuroimaging Center, London). For each scan, data were corrected for head motion using a six-parameter rigid body transformation and realigned. Functional volumes were normalized using parameters from a segmented anatomical image coregistered to the average EPI and smoothed using a 6 mm full-width-half-maximum Gaussian filter. Reasons for excluding scans included not meeting MRI safety criteria ($n = 3-6$), excessive head motion (>3 mm; $n = 3-10$), and technical errors ($n = 3-5$).

2.3.4. Economic lottery choice task

At Time 1 and Time 2, adolescents participated in a modified economic lottery choice task (Holt and Laury, 2002), during which they chose between pairs of uncertain gambles while blood-oxygen-level-dependent (BOLD) response was monitored using functional magnetic resonance imaging (fMRI; Fig. 1). Each gamble consisted of a high and low monetary outcome associated with different probabilities. To facilitate comprehension of likelihood information for adolescents, colorful pie charts were used to present probabilities for different outcomes. Each pie was separated into 10 equal slices, with each slice representing 10%. Monetary outcomes and probabilities varied across 72 trials, and it took approximately 30 min to complete all the trials. Risk for each gamble was calculated using coefficient of variation (CV), a scale-free metric calculated by dividing the standard deviation by expected value. Prior research has shown that CV is a better metric for explaining choice behavior compared to standard deviation or variance, because outcome variability is often encoded relative to the average outcome rather than in an absolute manner (Bach et al., 2017; Weber et al., 2004). For each pair of gambles, one option was always riskier (higher CV) than the other (lower CV). To incentivize performance, participants were informed that they would receive

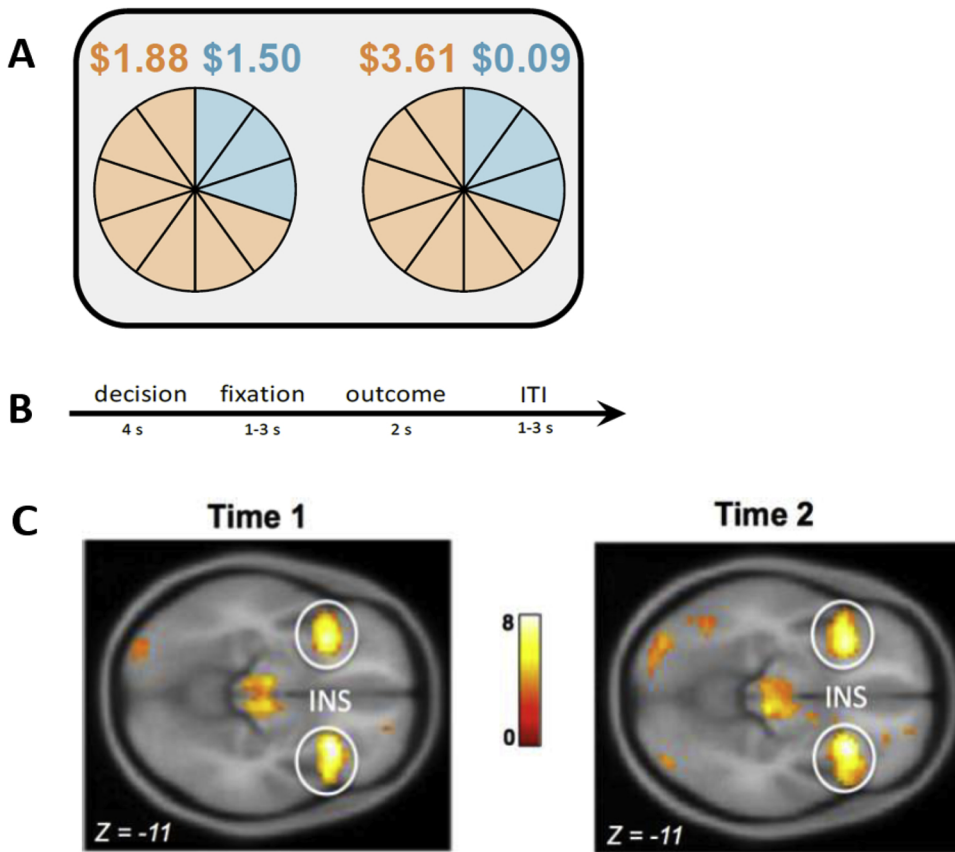


Fig. 1. A) In the economic lottery choice task, adolescents chose between pairs of uncertain gambles. For each trial, there was a high and low monetary outcome, each associated with a specific probability. The monetary outcomes and probabilities were presented using different colors. B) Each trial included a decision phase, a jittered fixation phase, an outcome phase (where the result of the participant's choice was shown), and a jittered intertrial interval (ITI). C) During the decision process, adolescents exhibited greater BOLD responses in the bilateral anterior insular cortex to higher, relative to lower, levels of risk at both Time 1, $t(145) = 7.22$, p (FWE correction) $< .05$, and Time 2, $t(135) = 7.91$, p (FWE correction) $< .05$. FWE = family-wise error. Adapted from "Neural cognitive control moderates the association between insular risk processing and risk-taking behaviors via perceived stress in adolescents," by Maciejewski et al. (2018), *Developmental Cognitive Neuroscience*, 30. p. 153. Copyright 2018 by the Elsevier Ltd.

compensations based on their actual winnings from four randomly selected trials.

2.3.5. Behavioral risk preference

Risk preference was estimated from each participant's 72 decisions in the economic lottery choice task using a standard power utility function (Arrow, 1965; Holt and Laury, 2002; Pratt, 1964), in which the utility for money X , where $X \geq 0$, is described as,

$$U(X) = X^\alpha$$

where α represents risk preference, such that $\alpha = 1$ indicates risk neutrality, $\alpha < 1$ indicates risk aversion, and $\alpha > 1$ indicates risk seeking. Expected utilities (EU) for each option were then computed by multiplying utilities by associated probabilities, where P_{high} and P_{low} represent the probabilities of the high and low outcome, X_{high} and X_{low} represent the monetary values of the high and low outcomes within each gamble, respectively.

$$EU = P_{high} * X_{high}^\alpha + P_{low} * X_{low}^\alpha$$

Using maximum likelihood estimation, behavioral choices from the modified lottery choice task for each adolescent were fit to a logistic function,

$$P(\text{chosen}) = \frac{1}{1 + e^{\gamma(EU_{riskier} - EU_{safer})}}$$

Where $\gamma \geq 0$ represents the inverse temperature, a metric of relative consistency across choice behavior, in which greater values indicated greater consistency across decisions.

2.3.6. Neural risk processing

Using general linear model (GLM), the decision and outcome events of the task were analyzed with a duration of 4 and 2 s, respectively at the

subject level. The model included a parametric regressor of the decision event representing the CV for chosen gambles. An additional parametric regressor of the outcome event was also included in the model to represent whether, during the outcome phase, subjects received high or low monetary outcomes. At the group level of the GLM, whole brain analysis was conducted to examine how CV for chosen gambles was related to BOLD responses during decision making. Based on prior literature suggesting the critical role of insular cortex in risk processing (Mohr et al., 2010), we hypothesized that BOLD responses in the bilateral insular cortex would be modulated by the level of CV. Through region of interest (ROI) analyses in SPM8, eigenvariate values were extracted for the left and right insular cortex using a 6 mm sphere around the peak voxel coordinates for each region (left: $x = -30$, $y = 17$, $z = -14$; right: $x = 30$, $y = 20$, $z = -11$). Activation in the bilateral insular cortex during the lottery choice task was illustrated in Fig. 1. For all regions associated with increasing CV during the decision phase at Time 1 and Time 2, see Appendix A.

A confirmatory factor analysis, with standardized left and right anterior insula activation scores loaded on an overall insula factor score, were conducted. Factor loadings were constrained to be equal for model identification purposes. In the three fully saturated models ($\chi^2 = 0$, $df = 0$), factor loadings were all significant (.86 for Time 1 and .93 for Time 2, $ps < .001$). The bilateral insula factor scores were used in the analyses as the neural risk processing variable, with higher scores indicating higher BOLD responses in the insula.

2.4. Statistical analyses

Descriptive analyses were performed to examine the normality of distributions and outliers for all study variables. For skewness and kurtosis, the acceptable levels were less than 3 and less than 10, respectively (Kline, 2011). Outliers ($n = 8$) were identified as values more than 3 SD from the mean and were winsorized to retain statistical

power and attenuate bias resulting from elimination (Ghosh and Vogt, 2012). Multivariate GLM analyses exhibited that demographic variables (adolescent age, gender, race, and family income) at Time 1 did not significantly predict behavioral and neural risk processing at Time 2 and risk-taking behaviors at Time 3 (all p s $>.10$), thus, they were not included as covariates in the main analyses.

The hypothesized mediation models were examined using Structural Equation Modeling (SEM) in *Mplus* 7.4 (Muthén & Muthén, 1998–2012). In the first model, we examined a longitudinal progression model by testing indirect effects of approach and avoidance at Time 1 on risk-taking behaviors at Time 3 via neural risk processing at Time 2 (see Fig. 2). Next, we examined a longitudinal change model by testing indirect effects of approach and avoidance at Time 1 on risk-taking behaviors at Time 3 via neural risk processing at Time 2 while controlling for initial levels of the mediator and outcome variables (see Fig. 3). Overall model fit indices were determined by χ^2 value, degrees of freedom, corresponding p -value, Root Mean Square Error of Approximation (RMSEA), and Confirmatory Fit Index (CFI). RMSEA values of less than .05 were considered a close fit while values less than .08 were considered a reasonable fit (Browne and Cudeck, 1993), and CFI values of greater than .90 were considered an acceptable fit while values greater than .95 were considered an excellent fit (Bentler, 1990). Indirect effects were calculated using the IND command in *Mplus*. Bias-corrected bootstrap confidence intervals (CIs) for these indirect effects were calculated using 10,000 bootstrapping samples (Preacher and Hayes, 2008). These CIs take non-normality of the estimates into account and are therefore not necessarily symmetric (Muthén and Muthén, 2012). Given that full information maximum likelihood (FIML) estimates are superior to those obtained with listwise deletion or other ad hoc methods (Schafer and Graham, 2002), FIML estimation procedure was performed to deal with missing data in our model (Arbuckle, 1996).

3. Results

Descriptive statistics and correlations for all study variables are presented in Table 1. Neural risk processing and risk-taking behaviors all showed moderate stability from Time 1 to Time 2 and from Time 1 to Time 3, respectively. Meanwhile, adolescents showed more insula activation [$t(116) = -6.52, p < .001$ for left insula and $t(116) = -6.93, p < .001$ for right insula] and slightly lower risk-taking behaviors [$t(130) = 1.75, p = .08$] at Time 3 compared to Time 1.

We first fit the *longitudinal progression model* to examine whether approach and avoidance motivations at Time 1 predicted risk-taking behaviors at Time 3 via neural risk processing at Time 2 (see Fig. 2). This model estimated all possible paths among study variables, thus was a fully saturated model with $\chi^2 = 0, df = 0, CFI = 1.00, RMSEA = .00$. High approach motivation at Time 1 predicted low neural risk processing at Time 2 ($b = -0.39, SE = 0.11, p < .001$), which in turn

predicted high risk-taking behaviors at Time 3 ($b = -0.03, SE = 0.01, p = .037$). Approach at Time 1 did not directly predict risk-taking behaviors at Time 3 ($b = 0.03, SE = 0.02, p = .19$) and approach and avoidance motivations at Time 1 did not covary ($\sigma = -.03, SE = 0.05, p = .58$). The bias corrected bootstrap test for mediation revealed that the indirect effect from high approach at Time 1 to high risk-taking behaviors at Time 3 via low neural risk processing at Time 2 was significant ($b = 0.013, SE = 0.01, 95\% CI [0.002; 0.032], b^* = .055$). In contrast, avoidance motivation at Time 1 was not associated with neural risk processing at Time 2 ($b = -0.02, SE = 0.10, p = .81$) or risk-taking behaviors at Time 3 ($b = -0.03, SE = 0.02, p = .13$). The indirect effect from avoidance at Time 1 to risk-taking behaviors at Time 3 via neural risk processing at Time 2 was not significant ($b = 0.001, SE = 0.003, 95\% CI [-0.007; 0.10], b^* = .004$).

Next, we fit the *longitudinal change model* by controlling the levels of neural risk processing and risk-taking behaviors at Time 1. This model allowed us to examine whether approach and avoidance motivations at Time 1 predicted changes in risk-taking behaviors from Time 1 to Time 3 via changes in neural risk processing from Time 1 to Time 2 (see Fig. 3). This model fit the data well, with $\chi^2 = 6.11, df = 6, p = .41, CFI = .99, RMSEA = .01$. High approach motivation at Time 1 significantly predicted decreases in neural risk processing ($b = -0.45, SE = 0.11, p < .001$), which in turn predicted increases in risk-taking behaviors ($b = -0.04, SE = 0.01, p = .019$). Though approach at Time 1 was not directly associated with changes in risk-taking behaviors ($b = 0.01, SE = 0.02, p = .638$), the indirect effect from high approach to increases in risk-taking behaviors via decreases in neural risk processing was significant ($b = 0.016, SE = 0.008, 95\% CI [0.003; 0.037], b^* = .066$). In turn, high avoidance motivation at Time 1 was marginally associated with decreases in risk-taking behaviors ($b = -0.15, SE = 0.08, p = .065$), however, the indirect effect of avoidance on changes in risk-taking behaviors via changes in neural risk processing was not significant ($b = 0.003, SE = 0.004, 95\% CI [-0.006; 0.014], b^* = .012$).

We also tested the *longitudinal progression model* using behavioral risk preference to examine whether the effects of approach and avoidance motivations at Time 1 on risk-taking behaviors at Time 3 were mediated by behavioral risk preference at Time 2. Results indicated no significant indirect effects of approach or avoidance motivations at Time 1 on risk-taking behaviors at Time 3 via behavioral risk preference at Time 2 ($b = 0.005, SE = 0.005, 95\% CI [-0.006; 0.022], b^* = .021$ for Approach; $b = -0.002, SE = 0.005, 95\% CI [-0.016; 0.011], b^* = -0.01$ for Avoidance). We then ran the *longitudinal change model* using behavioral risk preference to examine whether approach and avoidance motivations predicted changes in risk-taking behaviors via changes in behavioral risk preference (by controlling for the levels of behavioral risk preference and risk-taking behaviors at Time 1). Similarly, the effects of approach and avoidance motivations on changes in risk-taking behaviors were not mediated by changes in behavioral risk preference ($b = 0.005, SE = 0.004, 95\% CI [-0.002; 0.019], b^* = .021$ for

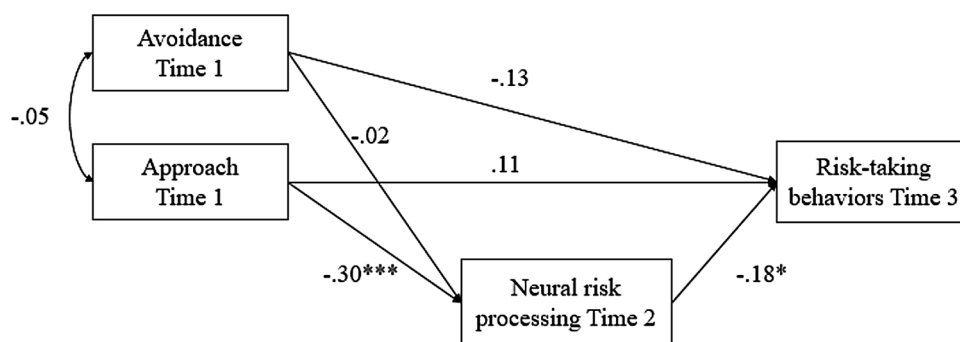


Fig. 2. Standardized parameter estimates for the associations among approach and avoidance motivation at Time 1, neural risk processing at Time 2 and risk-taking behaviors at Time 3.

* $p < .05$, ** $p < .01$, *** $p < .001$.

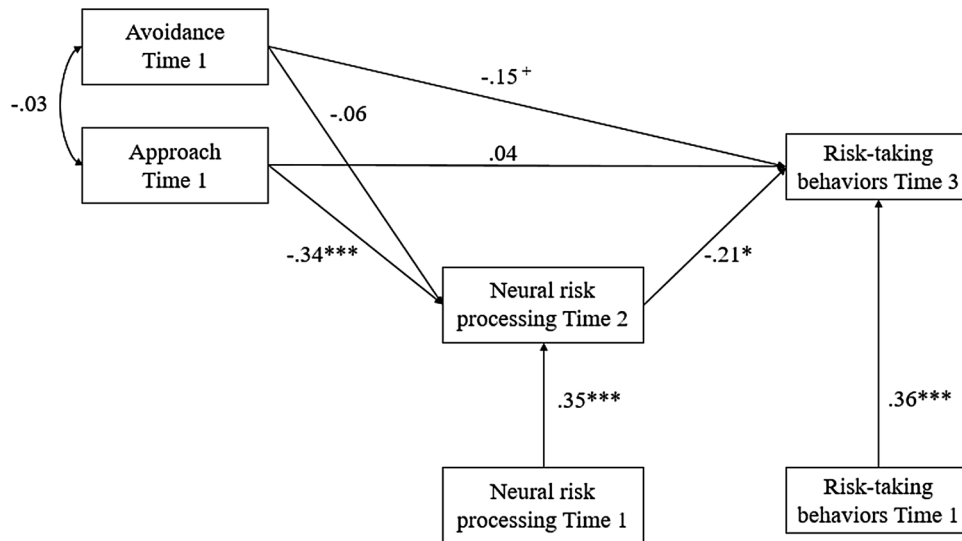


Fig. 3. Standardized parameter estimates for the associations among approach and avoidance motivation at Time 1, neural risk processing at Time 2 and risk-taking behaviors at Time 3 while controlling for neural risk processing and risk-taking behaviors at Time 1.
⁺ $p = .06$, * $p < .05$, ** $p < .01$, *** $p < .001$.

Table 1
 Descriptive statistics of and correlations among study variables.

	1	2	3	4	5	6	7	M	SD
1. Approach at Time 1								.00	.75
2. Avoidance at Time 1	-.05							.00	.80
3. Beh. risk preference at Time 1	-.02	.15						.76	.56
4. Beh. risk preference at Time 2	.08	-.05	.43***					.56	.53
5. Insular risk processing at Time 1	-.03	.00	-.40***	-.13				.00	.93
6. Insular risk processing at Time 2	-.30**	-.02	-.20*	-.33**	.34***			.00	.97
7. Risk-taking behaviors at Time 1	.15	-.09	.22**	.26**	-.16	-.11		.32	.15
8. Risk-taking behaviors at Time 3	.18*	-.13	.17	.28**	-.19*	-.20*	.40***	.29	.17

Note. Beh. = Behavioral.

* $p < .05$.
 ** $p < .01$.
 *** $p < .001$.

Approach; and $b = -0.005$, $SE = 0.004$, 95% CI [-0.021; 0.002], $b^* = -0.025$ for Avoidance). Detailed results are reported in Appendix B.

Finally, as supplemental analyses, we further tested the specificity of our results to the bilateral insula by exploring the extent to which additional brain regions may play a mediating role between trait motivations and adolescent risk taking. We selected brain regions that were consistently activated in both Time 1 and Time 2: the dorsal anterior cingulate cortex (dACC), left middle occipital cortex, right middle occipital cortex, right precentral gyrus, and right superior orbitofrontal cortex (see Supplemental Tables in Appendix A). We chose this conservative approach to focus on reliable brain activations across both waves and to limit the number of tests performed. We re-ran the longitudinal progression model and longitudinal change model on each of the five ROIs and found that only the longitudinal analyses on dACC were significant. Specifically, in the longitudinal progression model, the indirect effect from high approach at Time 1 to high risk-taking behaviors at Time 3 via low dACC activation at Time 2 was significant ($b = 0.011$, $SE = 0.006$, 95% CI [0.002; 0.027], $b^* = .05$). In the longitudinal change model, the indirect effect from high approach to increases in risk-taking behaviors (from Time 1 to Time 3) via decreases in dACC (from Time 1 to Time 2) was significant ($b = 0.013$, $SE = 0.007$, 95% CI [0.003; 0.030], $b^* = .057$). The results are not surprising because dACC is known for its involvement in decision making such as integrating information about the reward and costs to estimate expected value associated allocating control (Shenhav et al., 2013), whereas the

other regions (middle occipital cortex, precentral gyrus, and superior orbitofrontal cortex) are not.

4. Discussion

Prior research has emphasized the importance of the motivational system in risky decision-making processes (Ernst et al., 2006; Franken and Muris, 2006; Kim-Spoon et al., 2016a; Urošević et al., 2014; van Leeuwen et al., 2011), yet the developmental pathways from approach and avoidance motivation to adolescents' risky behaviors are not clearly understood in the extant literature. Given the crucial role of the insula in evaluating risk during decision-making process (Mohr et al., 2010), and the substantial individual differences in risk preference among adolescents (Paulsen et al., 2012; van Duijvenvoorde et al., 2015), we tested the potential mediating effects of both behavioral risk preference and neural risk processing in the association between approach versus avoidance motivations and laboratory-based risk-taking behaviors. Our longitudinal data indicated that high approach motivation was related to lower bilateral insular cortex activation, which in turn was linked to higher risk-taking behaviors measured by the Stoplight task, a computerized measure of risk-taking propensity. This indirect path was also obtained when controlling for baseline levels of neural risk processing and risk-taking behaviors at Time 1. Specifically, high approach motivation was related to decreases in bilateral insular cortex activation which in turn were associated with increases in risk-taking behaviors. In

contrast, we found no clear evidence that avoidance motivation was directly or indirectly related to risk-taking behaviors over time.

Our results demonstrating the crucial role of the insula in the association between approach-oriented motivation and risky behaviors largely corresponds with prior neuroscience literature implying that insular processing may be influenced by motivations and emotions (Craig, 2009; Naqvi and Bechara, 2009), and that lower insula activation during risk processing is associated with greater health risk behaviors among adolescents (Kim-Spoon et al., 2017). Anatomically, the insular cortex is often thought of as an integration center, which receives inputs from the sensory cortices, while also projecting to brain areas involved in action-oriented functions, such as the prefrontal cortices and anterior cingulate cortex (Smith et al., 2013). The insula is well positioned to receive affective and cognitive information and has been implicated as a key neural substrate in linking motivation, affective processing, decision making, and behaviors (Naqvi and Bechara, 2009; Preusschoff et al., 2008). In particular, Singer et al. (2009) proposed an integrative model for the function of the insular cortex, suggesting that the insular cortex integrates information from internal bodily states with individual preferences for risk and contextual information to produce a global feeling state to regulate subsequent behaviors. Following this model, increased engagement of the insula may reflect a thorough evaluation of both internal states and contextual factors. Mismatch between anticipated outcomes and negative consequences associated with risky options may evoke anxiety and fear, which in turn can facilitate behaviors that avoid risks (van Duijvenvoorde et al., 2015). In contrast, decreased engagement of the insula may represent difficulties fully integrating information from different inputs, and decisions may be influenced by individual risk preference. For adolescents who have a strong approach motivation, the failure to engage the insula to process risk by evaluating potential negative outcomes may contribute to heightened risky behaviors, as seen in the present study.

The longitudinal effect of avoidance motivation at Time 1 indicated no significant direct or indirect effects on risk-taking behaviors at Time 3 in general. However, the direct association between avoidance motivation at Time 1 and changes in risk-taking behaviors from Time 1 to Time 3 approached significance. Specifically, low avoidance motivation was marginally related to increases in risk-taking behaviors. This finding is consistent with prior research which found that low avoidance predicted progression into regular substance use (van Leeuwen et al., 2011). It is likely that adolescents with low avoidance motivation are less sensitive to aversive outcomes associated with risky decision making, making them less prone to engage in risk-taking behaviors over time. Taken together, these findings highlight the importance of utilizing a longitudinal design to fully capture the temporal relations between avoidance motivation and risk-taking behaviors.

Our data further clarified that the association between avoidance motivation and changes in risk-taking behaviors is not mediated by variations in neural risk processing. The null results may be partly due to the fact that the economic lottery choice employed in this study included gambles in which potential outcomes could only be gained; the task did not include potential loss trials. It has been shown that adolescents show less harm-avoidance brain responses to reward omission than adults do (Ernst et al., 2005). In our study, the lack of gain (i.e., reward omission) may be perceived as loss by the participants, although it may not elicit negative emotions as intense as loss does. Prior work has indicated that risk within a loss context might be processed by both distinct and overlapping neural substrates when potential losses are possible. Specifically, in addition to the insula, the thalamus and the dorso-medial prefrontal cortex were also likely to be activated to process the negative emotion associated with potential losses and adjust strategies for better outcomes (Mohr et al., 2010). It is plausible that loss-related brain areas may be related to avoidance motivation. Future studies would benefit from utilizing tasks that include both explicit gain and loss conditions to better understand the link between avoidance motivation and risk-related processing.

We also tested the mediating role of behavioral risk preference in the link between approach and avoidance motivations and laboratory-based risk-taking behaviors. Despite the moderate phenotypic correlations between behavioral risk preference and neural risk processing, the results showed that it was insula activation, rather than behavioral risk preference, that significantly mediated the effects of approach motivation on adolescents' risk-taking behaviors. Our results suggest that risk-related neural response was more sensitively affected by approach motivation than behavioral risk preference. One interpretation of this finding is that behavioral risk preference and risk-related neural response reflect slightly distinct processes of risky decision making, with behavioral risk preference indicating estimates based on decisions made in the task, but risk-related neural responses indicating the neural responses immediately before a decision is made. An alternative explanation could be that behavioral risk preferences may be limited in capturing real-world behavioral responses, while risk-related neural processing is able to more accurately represent individual differences in neurobiological processes (Richards et al., 2013). Overall, our findings highlight the critical importance of conducting analyses at both behavioral and neural levels in order to better understand the multi-faceted and complex nature of risk processing during decision making under uncertainty that plays a role in determining risk-taking behaviors.

Findings from the current study should be interpreted in light of limitations. First, the economic lottery choice task used in the current study includes only gain conditions, not loss conditions. Although the lack of (anticipated) gain in the task may have the effects of loss, future research is warranted to test possible distinctive effects of explicit gain versus loss conditions. Second, while our primary interest was to examine how insular risk-related processing prior to decision making played a mediating role between trait motivations and adolescent risk taking, future studies should examine the extent to which brain activations in other phases of the decision making process such as the outcome phase may play similar or dissimilar roles. Third, approach motivation did not directly predict laboratory-based risk-taking behaviors, but only indirectly through its influences on neural insula activation. Given the significant predictive effects of approach motivation on substance use and risky sexual behaviors (Kim-Spoon et al., 2016a; Urošević et al., 2014; van Leeuwen et al., 2011), it could be that approach motivation is more sensitively related to real-world risk-taking behaviors than laboratory-based risk-taking behaviors. Fourth, while the current study focused on the insular cortex, which was grounded in theoretical and empirical work, future research should consider investigating how other brain regions interface with the insula in risk-related decision making. Such future investigations may provide important insight into the neural mechanisms through which normal and atypical risk processing occurs. Relatedly, prior research indicates that the insula and inferior frontal gyrus are key players in cognitive control (e.g., McTeague et al., 2017; Tervo-Clemmens et al., 2017), with the insula being important for detecting behaviorally salient events and the inferior frontal gyrus being important for implementing inhibitory control (Cai et al., 2014). Lastly, given the association between mathematical cognition and cognitive control systems including insula (see Menon, 2016 for review), we suggest that future research should consider mathematical and cognitive abilities that may influence insular risk processing.

In conclusion, the current findings provide a window into understanding how trait motivation may influence adolescents' risk taking. Notably, our data provide insight into aspects of brain functioning that mediate trait-level individual differences and risk-taking behavioral outcomes over time throughout adolescence. Adolescents high in approach motivation seem to become less thorough in the neural processing of risk information over time (as reflected by decreased insula activation), which in turn, seems to make them vulnerable to engaging in risky behaviors. Intervention work could benefit from the current work, as we provide new insights into identifying adolescents who are vulnerable to develop risk-taking behaviors.

Disclaimer

The views and opinions expressed in this article are those of the authors and do not necessarily reflect the official policy or position of any agency of the U.S. government.

Declaration of Competing Interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.dcn.2019.100725>.

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