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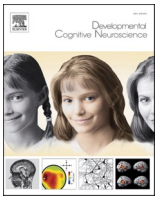

Positive risk taking and neural sensitivity to risky decision making in adolescence

Natasha Duell *, Seh-Joo Kwon, Kathy T. Do, Caitlin C. Turpyn, Mitchell J. Prinstein, Kristen A. Lindquist, Eva H. Telzer

Department of Psychology and Neuroscience, University of North Carolina at Chapel Hill, 235 E. Cameron Avenue, Chapel Hill, NC 27599-3270, United States

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ABSTRACT

This study examines associations between adolescents' positive risk taking and neural activation during risky decision-making. Participants included 144 adolescents ages 13–16 years (M_{age} = 14.23; SD_{age} = 0.7) from diverse racial and ethnic groups. Participants self-reported their engagement in positive and negative risk taking. Additionally, participants played the Cups task during fMRI, where they chose between a safe choice (guaranteed earning of 15 cents) and a risky choice (varying probabilities of earning more than 15 cents). Using a risk-return framework, we examined adolescents' sensitivity to both risks (safe versus risky) and returns (expected value, or potential reward as a function of its probability of occurring) at the behavioral and neural levels. All participants took more risks when the expected value of the choice was high. However, high positive risk taking was uniquely associated with dampened dmPFC tracking of expected value. Together, results show that adolescents' positive risk taking is associated with neural activity during risky decision-making. Findings are among the first to identify brain-behavior correlations associated with positive risk taking during adolescence.

1. Introduction

Risk taking is a normal and adaptive characteristic of adolescence (Ellis et al., 2012; Spear, 2000), allowing youth to meet key developmental milestones such as identity development and independence (Duell and Steinberg, 2019). Heightened sensitivity in dopamine-rich limbic regions support risk behavior during adolescence by increasing the growing individual's sensitivity to rewards and drive to explore their environment (Spear, 2000). Although this propensity for risk taking during adolescence leads some youth to engage in harmful risks such as substance use and delinquency (i.e., negative risk taking), adolescents are also drawn to positive risks, or risks that are socially acceptable and beneficial to development (Duell and Steinberg, 2019). In fact, youth generally engage in both positive (e.g., initiating a new friendship) and negative (e.g., vandalizing) risk behaviors (Duell and Steinberg, 2020; Dworkin, 2015; Fischer and Smith, 2004). Thus, adolescence marks a developmental period rich with opportunities to reinforce engagement in positive risks that promote, rather than hinder development and well-being. To cultivate positive risk taking among adolescents, it is essential to identify the decision-making processes supporting it. To this end, the present study examines associations between adolescents' self-reported positive risk taking with behavioral and neural processing of risky decision-making.

In the broadest sense, risks are choices characterized by uncertainty (i.e., the probability of any outcome occurring is greater than 0 and less than 1) and the potential for an undesirable outcome (Crone et al., 2016; Duell and Steinberg, 2019, 2021). Within this broad definition of risk, risk behaviors exist along a spectrum (see Duell and Steinberg, 2021). On one end of the spectrum are negative risks, which are antisocial and unconstructive behaviors such as fighting, having unprotected sex, and using substances. On the other end of the spectrum are positive risks, which are socially acceptable and beneficial to development, such as initiating friendships, trying new activities, and standing up for one's beliefs. A common misconception is that positive risks do not yield the potential for negative outcomes, but this is not true (Duell and Steinberg, 2021). For example, enrolling in a challenging course yields the potential negative outcome of failing the course, and standing up for one's beliefs yields the potential negative outcome of ridicule from peers or worse, harm (e.g., if attending a protest) (Duell and Steinberg, 2021). Whether positive or negative, risk taking is a normal and adaptive part of life (Duell and Steinberg, 2019). However, what distinguishes positive from negative risks is that positive risks allow youth to meet their goals

* Corresponding author.
E-mail address: natashaduell@unc.edu (N. Duell).

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(e.g., forging friendships) and fulfill their desires for novelty and excitement through activities that are socially acceptable (Duell and Steinberg, 2021). In this case, socially acceptable behaviors refer to those conforming to the norms and standards of society, which may be distinct from norms and standards within adolescent peer groups (Dishion and Tipsord, 2010). Although both positive (Véronneau et al., 2010) and negative (Dishion and Tipsord, 2010) behaviors can earn social acceptance from adolescents' peers, positive risks are theorized to be behaviors that are uniquely accepted and supported by society. For example, an adolescent who wants to audition for a play (positive risk) is likely to receive support and resources from their community, whereas an adolescent who wants to binge drink with friends (negative risk) is not.

Parallel with advances in cognitive development, adolescents are faced with increasingly complex decision-making demands (Hartley & Somerville, 2015). Given that adolescence is a developmental period wherein life experiences have significant impacts on brain development and functioning (Larsen & Luna, 2018), it is important to identify behaviors that may provide them with opportunities to practice and reinforce adaptive decision-making (Crone and Dahl, 2012). Positive risk taking may be one such behavior, but empirical work is needed to link positive risk taking with the neuropsychological processes supporting decision-making. One useful approach is to decompose complex decisions into component processes (Hartley & Somerville, 2015). The risk-return model (Weber, 2010) decomposes risky decisions into two components—the risk and the return—and may be a useful starting point. Risk refers to the variability associated with the potential outcome of a choice. For example, a safe option with a 100% chance of success is more appealing than a risky option with only a 25% chance of success. Granted, the appeal of any choice depends on its potential return. The return refers to the potential reward of a choice as a function of its likelihood of occurring (i.e., reward x probability)—also referred to as the expected value. For example, the expected value (EV) of winning $1 with a 100% probability of success (EV = $1) is lower than the expected value of winning $5 with a 25% probability of success (EV = $1.25), making the risky choice more advantageous.

Although adolescents were once characterized as being indiscriminately drawn to risks, we know that adolescents are in fact quite capable of taking risks in a strategic or thoughtful way. In fact, prior work has shown that expected value (EV) has a stronger influence on adolescents' decisions than on adults' decisions, as indicated by heightened activation in adolescents' reward-sensitive brain regions (Barkley-Levenson and Galván, 2014). This heightened sensitivity to EV supports strategic decision-making among adolescents in that they only take risks when the EV is high, but not low (Barkley-Levenson and Galván, 2014). Whether the neural correlates of adaptive decision-making also support real-world positive risk taking, however, is still unknown. Thus, examining positive risk taking with a risk-return framework will help clarify whether positive risk taking is associated with (a) a general tolerance or preference for risk, and (b) a pattern of decision-making wherein risky decisions are made strategically, in the interest of optimizing rewards and minimizing loss.

Some have speculated that positive risk taking is associated with strategic or thoughtful decision-making that maximizes rewards and minimizes losses (Duell and Steinberg, 2019), which may be subserved by still-developing prefrontal brain regions implicated in strategizing (e.g., Venkatraman et al., 2009). One reason positive risk taking may be associated with greater strategizing is because many positive risks can be taken in pursuit of long-term goals, such as enrolling in a challenging course to make oneself more competitive for college (Duell and Steinberg, 2019). Thus, rather than simply selecting an option that yields the most compelling reward, youth engaging in positive risks may be more likely to consider the expected value of their choices, which requires deliberation about both potential rewards and losses. The association between positive risk taking and heightened loss sensitivity may support such strategic deliberation (Duell and Steinberg, 2020). In general, adolescents seem to be particularly adept at maximizing rewards by tracking changes in the expected value of those choices (Barkley-Levenson and Galván, 2014), which is supported by elevated sensitivity in dopamine-rich brain regions during this developmental period (Do et al., 2020). Coupled with heightened loss sensitivity that is uniquely explained by positive risk taking, perhaps positive risk taking is associated with individual differences in the ability to integrate expected value into risky decision-making.

Findings from prior literature have shed light on adolescents' neural sensitivity to both the risks and the returns of their decisions. With respect to the risk aspect of decisions, much research has examined the neural mechanisms supporting an adolescent's decision to choose a risky–as opposed to safe–choice. This work has shown that adolescents recruit brain regions implicated in reward-processing, such as the ventral striatum (VS), to a greater extent when making risky than safe decisions (Kahn et al., 2015). Heightened activation in reward-sensitive brain regions during risky choice may reflect adolescents' sensitivity to the potential rewards of the risk, or perhaps the thrill of taking a risk more generally. Additionally, adolescents evince heightened activation in regions important for integrating regulatory and affective processes, such as the dorsomedial prefrontal cortex (dmPFC) (van Duijvenvoorde et al., 2015), as well as in regions implicated in conflict monitoring and cognitive control, including the ventrolateral prefrontal cortex (vlPFC) and dorsolateral prefrontal cortex (dlPFC), during risky versus safe choices (Eshel et al., 2007). Thus, adolescents' decisions to take risks are supported by brain regions implicated in reward processing, strategizing, and behavioral control.

With respect to the return component of the decision-making process, adolescents are highly sensitive to expected value, which supports advantageous risk taking that maximizes rewards and minimizes losses (Barkley-Levenson and Galván, 2014). Because the expected value of a choice changes throughout the course of an experiment, the measurement of neural sensitivity to expected value must also be dynamic. This is achieved by measuring neural tracking of expected value, or how brain activation changes as a function of changes in expected value. Several studies have demonstrated evidence for a value-coding network that responds positively to increasing returns (i.e., expected value), including the vmPFC (Levy and Glimcher, 2012; Winecoff et al., 2013), dmPFC, and dlPFC (Blankenstein and van Duijvenvoorde, 2019). These regions undergo continued development during adolescence and are important for integrating and representing reward-related information during decision-making (Liu et al., 2011). Thus, adolescents may recruit executive control regions in response to increasing value as a means of strategically guiding choice behavior (van Duijvenvoorde et al., 2015). If positive risk taking is meant to represent strategic risk taking, perhaps positive risk taking can explain variability in neural tracking of expected value.

Although findings from prior literature tell us which neuropsychological processes are likely at play when adolescents make risky decisions, it is unclear whether these processes are related to risk taking in the real world. Given the field's limited understanding about what motivates youth to engage in positive risks, the present study has two aims: (1) explore the association between positive risk taking and neural activation during risky versus safe decision making; (2) examine the association between positive risk taking and neural tracking of expected value. To test whether these associations are specific to positive risk taking, we will also conduct exploratory fMRI analyses with negative risk taking, controlling for positive risk taking. We hypothesize that higher positive risk taking is associated with greater activation in prefrontal regions implicated in behavioral control and planning when selecting risky choices. Further, we anticipate that positive risk taking is associated with greater neural tracking of expected value, particularly in brain regions supporting reward processing and strategizing.

2. Materials and methods

2.1. Participants

Adolescent participants were part of a larger study of 873 sixth and seventh grade students from three public middle schools who elected to participate in a longitudinal fMRI study. A total of 173 participants completed up to three fMRI sessions annually across three waves. Participants were compensated for completing the session. At the start of Wave 1 data collection, participants had to be at least twelve years old (or within two months of turning twelve years old) and in sixth or seventh grade. Participants were excluded if they had any metal in their body, including braces or a permanent retainer, claustrophobia, history of seizure or head trauma, learning disability, or non-fluency in English. If participants regularly took medications (e.g., ADHD medication), they were asked to abstain from using their medication 24 h prior to the scan. All participants and their parents provided informed assent and consent, respectively. The University's Institutional Review Board approved all aspects of the study.

At each wave of data collection, participants completed experimental and fMRI tasks and self-report questionnaires, totaling a 4-hour session with a 1.5 h fMRI session. Prior to completing the fMRI scan, participants trained for the tasks, were acclimated to a mock scanner, and completed self-report measures. In the event the participant could not participate in the fMRI session after the first wave (e.g., braces), they completed the tasks on a laptop computer outside of the scanner. At the end of the session, participants received monetary compensation ($90), prizes worth up to $20 for doing well in the scan (e.g., gift cards, headphones), and a meal after the scan. The participating parent/guardian received monetary compensation ($50), parking and gas reimbursement ($27), and a meal. At each subsequent wave, returning families received an additional $25 returning bonus (i.e., additional $25 for completing 2 waves; additional $50 for completing 3 waves). Adolescent participants had the opportunity to earn additional money for themselves, their parent, and their best friend based on their performance during some of the tasks.

The data for the present study are from the third wave of data collection, which included 145 youth ($n = 74$ females; $n = 2$ nonbinary) ages 13–16 years ($M_{age} = 14.23$; $SD_{age} = 0.7$) from diverse racial and ethnic backgrounds ($n = 33$ Black; $n = 48$ Hispanic or Latinx; $n = 45$ White; $n = 19$ other). Experimental task data was excluded for one ($n = 1$) participant for low task engagement (i.e., $< 60\%$ response on task). Neural data were excluded for an additional twenty eight ($n = 28$ participants (i.e., completing the task behaviorally, outside of the scanner, or not enough behavioral data or variability across trial types to model behavior at the neural level)). An additional sixteen ($n = 16$) participants were excluded from the neural analyses for not completing the self-report measures of interest. Thus, the final Wave 3 sample size includes self-report and behavioral data for 144 participants and fMRI data for 100 participants.

2.2. Experimental design

2.2.1. Experimental gambling task

Adolescents completed a modified version of the Cups Task (Levin and Hart, 2003), which has been used to examine risky decision-making for oneself and others in developmental samples (e.g., Guassi Moreira and Telzer, 2018). Participants completed three rounds of the Cups Task: one in which they made decisions for themselves, one for their parent, and one for their best friend. The order in which participants completed each round was counterbalanced. In the present study, data were only analyzed from the round in which participants made decisions for themselves.

Each round consisted of 48 trials. On each trial, participants were presented with two scenarios of cups on a screen (see Fig. 1), shown for 3000 ms. The left side of the screen was the "safe" option, because it always showed one cup with a guaranteed 15-cents hidden underneath. On the right side of the screen was the "risky" option, as the number of cups (either 2, 3, or 5 cups) as well as the amount of money hidden (either 30-, 45-, or 75-cents) varied. The risky option always offered more than 15-cents hidden under one of the cups. Participants were told that if they chose the safe option, they were guaranteed to earn 15-cents, whereas if they chose the risky option, the computer would randomly select one of the cups and they had the potential to earn the higher amount or 0-cents (see Fig. 1 for a schematic representation of the response options).

After each decision, a fixation cross was jittered at an average of 2300 ms (range: 526.68 to −4017.12 ms) and then participants were shown the outcome of their decision for 1000 ms. If participants did not decide within the given time, participants were presented with a screen that said, "too late" and there was no change in the total points earned. Finally, there was an intertrial fixation cross that jittered at an average of 2521.39 ms (range: 521.14 to −3913.31 ms). Outcomes of each decision were added to the running total for that round, which was shown to the participant at the end of each round. At the end of the session, adolescent participants received the money they earned while playing the task.

2.2.2. Decision-making on the Cups task

Decision-making on the Cups task was examined by measuring participants' decisions to select the safe versus risky option, accounting for the expected value of the risky option. Consistent with prior work, expected value (EV) consisted of two factors: magnitude of reward and probability of reward, both of which contribute to taking risks when rewards are at stake (Guassi Moreira and Telzer, 2018; van Duijvenvoorde et al., 2015). EV was calculated by dividing the amount of money under the cup (i.e., magnitude of reward) by the number of cups (i.e., probability of reward) for that trial. For instance, on a trial with 2 cups with 30-cents hidden under one of them, the EV is $30/2 = 15$. Given the parameters of the magnitudes and probabilities of reward, the EVs for risky decisions are: 6, 9, 10, 15, 22.5, 25, 37.5. The EV of the safe decision is always 15 since making a safe decision guarantees a gain of 15-cents. In this task, it is advantageous to make a risky decision when the EV is greater than 15, whereas it is disadvantageous to make a risky decision when the EV is 15 or less.

2.3. Self-report measures

2.3.1. Positive risk taking

Self-reported positive risk taking was measured using 10 items from the positive risk taking scale that prior research has shown to demonstrate strong reliability (Duell and Steinberg, 2020). Participants were asked to indicate whether they had ever engaged in ten activities (e.g., started a friendship with someone new; tried a new hairstyle or outfit; taken a class in a new or challenging subject). Scores were converted from frequency scores (*0 = never engaged in the activity* to *4 = engaged in the activity more than five times*) to dichotomous variables indicating whether participants had engaged in the activity at least once over the past six months (coded 1) or had not engaged in the activity (coded 0). Dichotomous scores were averaged to index the proportion of the ten positive risks endorsed ($\alpha = 0.822$), consistent with prior research using this scale (Duell and Steinberg, 2020). So-called "variety scores" have been widely used in risk taking research because they are highly correlated with frequency measures but are less susceptible to participant recall bias and unreliable estimates, a problem in the case of activities that some individuals engage in frequently. Thus, while variety and frequency scores are thought to represent the same propensity for risk taking, variety scores are the preferred method of measurement (e.g., Hindelang et al., 1981). To confirm that the variety and frequency scores yielded similar measures of risk taking, we correlated each adolescent's frequency score with their variety score. As expected, this correlation was very high ($r = 0.91$, $p < .001$).

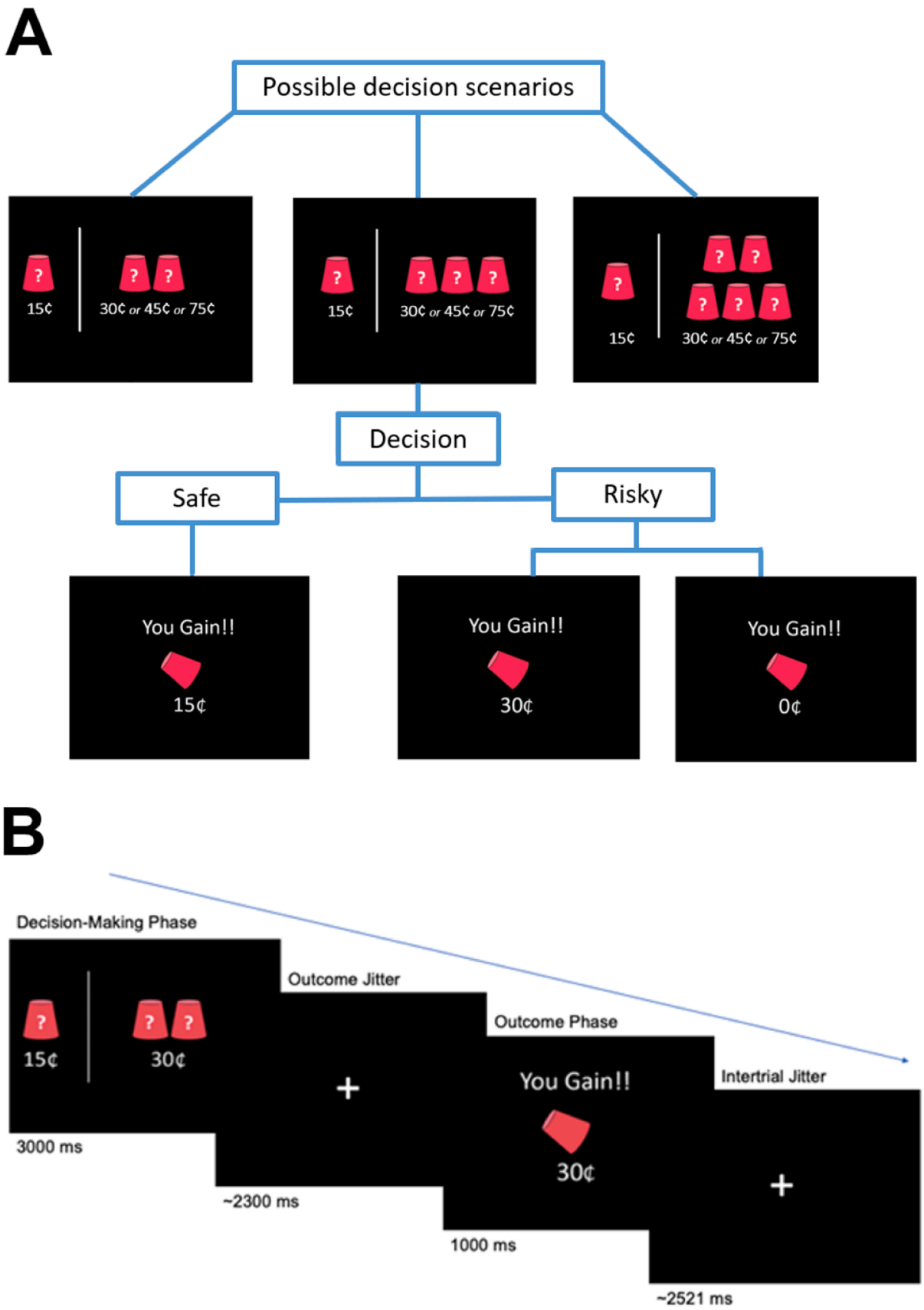

Fig. 1. (A) Schematic of decision-making options on the Cups Task; (B) Example trial of the Cups Task. During fMRI, participants chose between two options: a safe bet of earning 15 cents or a risky bet of winning more than 15 cents (either 30, 45, or 75 cents). If participants selected the risky choice, they either earned the higher value or 0 cents. Participants did not lose money.

2.3.2. Negative risk taking

Self-reported negative risk taking was measured using an adapted version of the adolescent risk taking scale (Alexander et al., 1990), in which adolescents reported on the frequency with which they engaged in 17 risky activities (e.g., stealing, cheating on an exam, riding in a car without a seatbelt, having unprotected sex). To maintain consistency with the positive risk taking scale, frequency scores (*0 = never engaged in the risk* to *3 = engaged in the risk many times*) were recoded into dichotomous variables where endorsing a risk at least once yielded a score of 1 and not endorsing the activity yielded a score of 0. The average of the dichotomous items ($\alpha = 0.70$) was then computed to estimate the proportion of negative risks endorsed by participants (i.e., a variety score just like the positive risk taking scale). The variety score and frequency scores were highly correlated ($r = 0.907$, $p < .001$).

2.4. fMRI data acquisition

Imaging data were collected using a 3 Tesla Siemens Prisma MRI scanner. The Cups Task was presented on a computer screen and projected through a mirror. A high-resolution T2 * -weighted echo-planar imaging (EPI) volume (TR = 2000 ms; TE = 25 ms; matrix = 92 ×92; FOV = 230 mm; 37 slices; slice thickness = 3 mm; voxel size = 2.5 ×2.5×3 mm^3) was acquired coplanar with a high-resolution T2 * -weighted, matched-bandwidth (MBW), structural scan (TR = 5700 ms; TE = 65 ms; matrix = 192 ×192; FOV = 230 mm; 38 slices; slice thickness = 3 mm). In addition, a T1 * magnetization-prepared rapid-acquisition gradient echo (MPRAGE; TR = 2400 ms; TE = 2.22 ms; matrix = 256 ×256; FOV = 256 mm; 208 slices; slice thickness = 0.8 mm; sagittal plane) was acquired. The orientation for the EPI and MBW scans was oblique axial to maximize brain coverage and to reduce noise.

2.5. fMRI data preprocessing and analysis

Preprocessing was conducted using FSL (FMRIB's Software Library, version 6.0; www.fmrib.ox.ac.uk/fsl) and included the following steps: Skull stripping using BET; motion correction with MCFLIRT; spatial smoothing with a Gaussian kernel of 6 mm, full-width-at-half maximum; high-pass temporal filtering with a filter width of 128 s (Gaussian-weighted least-squares straight line fitting, with sigma = 64.0 s); grand-mean intensity normalization of the entire 4D dataset by a single multiplicative factor; and individual level ICA denoising for artifact signal using MELODIC (version 3.15), combined with an automated signal classifier (Tohka et al., 2008; Neyman-Pearson threshold =0.3). For the spatial normalization, the EPI data were registered to the T1 image with a linear transformation, followed by a white-matter boundary-based transformation using FLIRT, linear and non-linear transformations to standard Montreal Neurological Institute (MNI) 2-mm brain using Advanced Neuroimaging Tools, and then spatial normalization of the EPI image to the MNI. A quality check during preprocessing and analyses ensured adequate signal coverage.

The task was modeled using an event-related design within the Statistical Parametric Mapping software package (SPM8; Wellcome Department of Cognitive Neurology, Institute of Neurology, London, UK). Individual-level fixed-effects models were created for each participant using the general linear model in SPM with regressors for the following 5 conditions: trials for each decision (uncertain and certain) and trials for each outcome (15-cents, zero cent, or >15-cents). Trials in which participants did not respond, the final outcome trial, and volumes containing motion in excess of 2 mm were included as separate regressors of no interest. Each trial was modeled using the onset of the cups (or outcome) and a duration equal to zero. Jittered intertrial periods (e.g., fixation cross) were not explicitly modeled and therefore served as the implicit baseline for task conditions. A parametric modulator (PM) was included for each uncertain decision, which modeled the EV of the uncertain decision of each trial. The PM served to examine neural activity that tracks the EV of adolescents' decisions.

The individual-level contrast images were submitted to random-effects group-level analyses. In the current study, our contrasts of interest included a comparison between *Risky>Safe Choices* (with the EV set to 0) and risky decisions with EV included as parametric modulator (*Risky-PM*), which allowed us to examine neural activity that tracks EV. For the primary analyses, we regressed positive risk taking on the *Risky>Safe Choice* and *Risky-PM* contrasts, and for each, controlled for self-reported negative risk taking. We also conducted secondary analyses wherein negative risk taking was regressed on *Risky>Safe Choice* and *Risky-PM* contrasts, controlling for positive risk taking. Our choice to control for positive/negative risk taking allows us to examine the unique association of each pattern of risk taking with neural activation. However, we also conducted analyses without controlling for positive/negative risk taking. Results from those analyses are tabled in the supplemental material.

To ensure adequate variability in decision-making on the task, we excluded participants who made risky choices on fewer than 5 trials (10% of trials across the entire task) and participants who made decisions exclusively on advantageous (EV>15) or disadvantageous (EV<15) trials. This approach was used to remain consistent with other published work in our lab (Kwon et al., 2021). Group-level analyses were conducted using GLMFlex, which removes outliers and sudden activation changes, partitions error terms, analyzes all voxels containing data, and corrects for variance-covariance inequality (http://mrtools.mgh.harvard.edu/index.php/GLM_Flex). We corrected all analyses for multiple comparisons using Monte Carlo simulations through 3DClustSim (updated version November 2016) in the software package AFNI (Ward, 2000). Smoothness was estimated with the -acf option (-acf a,b,c parameters: 0.550, 4.549, 12.436), which used an average of individual-level autocorrelation function parameters (obtained using each participants' residuals from the first-level model). The simulation indicated a voxel-wise threshold of $p < .005$ and minimum cluster size of 195 voxels, corresponding to $p < .05$, FWE cluster-corrected. All results are available on NeuroVault (Gorgolewski et al., 2015): https://neurovault.org/collections/11782/.

3. Results

3.1. Behavioral results

Behavioral data were available for 144 participants. At the behavioral level, we tested the hypothesis that individuals endorsing high levels of positive risk taking would be more likely to select the risky (versus safe) choice on the experimental Cups task, particularly when the expected value of the risky choice was high. All behavioral analyses were conducted using Mplus Version 8 (Muthén and Muthén, 2017).

3.1.1. Descriptive statistics

On average, participants selected the risky option on the Cups task on 52.359% (SD = 20.322) of trials. Participants generally endorsed more positive risks (M =0.466, SD =0.296) than negative risks (M =0.242, SD =0.159) ($t(144) = 16.97$, $p < .001$). Risky decisions on the task were not significantly associated with positive ($r = 0.145$, *ns*) or negative ($r = -0.073$, *ns*) risk taking. Further, positive and negative risk taking were not significantly correlated ($r = -0.021$, *ns*). Negative risk taking was significantly correlated with older age ($r = 0.213$, $p < .05$), but decision-making on the Cups task and positive risk taking were not associated with age. There were no gender differences in Cups decision-making, positive risk taking, or negative risk taking (all $t(138) < 1.28$, all $p > .2$). Supplemental tables S2-S7 provide additional descriptive visualizations of the raw data (e.g., risky decisions across positive risk taking separated by gender).

3.1.2. Mixture model

We first conducted a mixture model to examine whether positive risk

taking was associated with decisions to choose the safe versus risky option on the Cups decision-making task on a trial-by-trial basis (see Fig. S1 in the supplement for a schematic representation of the model). The outcome variable was a dichotomous variable indicating the participant's choice to select the safe or risky choice. Positive risk taking was included at the between-subjects level as a predictor of choice (safe or risky option). Additionally, self-reported negative risk taking and block order (i.e., the order in which participants completed the "self" round of the Cups task) were added as covariates. At the within-subjects level, we included the expected value of the trial as a predictor of choice (safe or risky). Additional covariates at the within-subjects level included the trial number and the outcome of the previous trial (to account for the fact that earning money on a risky choice in one trial may increase the likelihood of selecting the risky option in the subsequent trial). Finally, we tested a cross-level interaction between expected value and positive risk taking to test the hypothesis that positive risk taking was associated with selecting the risky option on the Cups task only when the expected value of that choice was high.

Results (see Table 1) indicated that participants were more likely to select a risky choice when the previous trial resulted in a win. Further, participants were more likely to choose the risky option as its expected value increased. However, self-reported positive and negative risk taking were not significantly associated with the decision to choose the safe or risky option, nor did positive risk taking moderate the association between expected value and risky choice. Supplemental analyses indicated that negative risk taking also did not moderate the association between expected value and risky choice. In other words, independent of individual differences in self-reported risk behavior, all participants were more likely to choose the risky option on the Cups task when its expected value was high.

3.2. fMRI results

3.2.1. Risky versus safe decisions

Neural data were available for 100 participants. At the whole brain level, we compared neural activation when participants selected risky versus safe choices as a function of individual differences in self-reported positive risk taking and controlling for negative risk taking. Only activation in the occipital lobe survived our conservative threshold of 195 voxels (Table 2). However, there was subthreshold activation (170 voxels) in the dorsomedial prefrontal cortex (dmPFC). For descriptive purposes, we extracted parameter estimates of signal intensity from the dmPFC and plotted them against positive risk taking. As shown in Fig. 2, adolescents reporting higher positive risk taking tended to show greater dmPFC activation when making risky versus safe choices (R^2 =.118).[1] Reciprocally, lower positive risk taking was associated with greater dmPFC activation for safe choices. Finally, we conducted analyses wherein self-reported negative risk taking was regressed on the *Risky>Safe* contrast controlling for positive risk taking. However, there were no significant activations to report.[2]

Supplemental analyses were conducted examining the *Risky>Safe* contrast regressed on positive and negative risk taking without controlling for the other type of risk taking. For positive risk taking, results were largely unchanged. In addition to the occipital lobe, activation in the left linual gyrus survived threshold (see Table S1 in the supplemental material). For negative risk taking, there was only subthreshold activation in the right superior temporal gyrus for risky versus safe decisions ($k = 69$, $t = 3.519$, $x = 64$, $y = -36$, $z = 10$).

3.2.2. Neural tracking of expected value during risky decisions

Next, we explored neural tracking of expected value during risky decisions as a function of self-reported positive risk taking by including the expected value of each trial as a parametric modulator and regressing positive risk taking. Positive risk taking was associated with dampened neural tracking of expected value in the cuneus and the dmPFC (Table 3). For descriptive purposes, we extracted parameter estimates of signal intensity from the dmPFC, which represent voxels that increase in activation as EV increases. We plotted this against positive risk taking, which was divided into individuals with low (less than 50% endorsement) and high (greater than 50% endorsement) positive risk taking. As shown in Fig. 3, youth endorsing high levels of positive risk taking evinced de-activation of the dmPFC as the expected value of the risky choice increased, whereas youth endorsing low levels

Table 1
Results from a two-level random path analysis predicting decision-making (safe vs. risky choices) on the Cups experimental risk task (n = 144). Decision-making was a dichotomous variable (0 = safe choice; 1 = risky choice). Block order = the order in which participants completed the "self" round of the Cups task; EV = expected value; RT = risk taking.

Level	Variables	Statistics		
		B	SE (B)	*p*-value
Within	Trial	.004	.003	.182
	Previous Outcome	.340	.110	.002
	Expected Value	.156	.024	.000
Between	Block Order	-0.137	.120	.256
	Positive Risk Taking	.567	.414	.171
	Negative Risk Taking	-0.960	.760	.207
Cross-Level	EV x Positive RT	.019	.041	.634
	EV x Negative RT[a]	.008	.078	.920

[a] Estimated in a separate analysis that did not include the (EV x Positive RT) interaction.

Table 2
Neural regions showing significant change in activation for risky>safe decisions as a function of self-reported positive risk taking, controlling for self-reported negative risk taking (n = 100). The map was thresholded at p < .005. Monte Carlo Simulation yielded a minimum cluster size of 195 contiguous voxels for whole-brain analysis. For full descriptive purposes and to avoid false negatives, we include all clusters at p < .005 and a minimum of 50 contiguous voxels.

				MNI Coordinates		
Contrast	**Region**	***k***	***t***	**x**	**y**	**z**
Risky > Safe	L Dorsomedial Prefrontal Cortex	170	3.614	-6	62	12
	R Dorsomedial Prefrontal Cortex	73	3.311	10	60	24
	L Dorsolateral Prefrontal Cortex	81	3.794	-20	42	32
	R Posterior Cingulate Cortex	126	4.336	8	-52	32
	R Precuneus	119	3.598	6	-80	46
	R Inferior Temporal Gyrus	55	3.464	42	-68	-2
	R Middle Temporal Gyrus	79	3.851	60	0	-26
	R Middle Occipital Gyrus	321	3.275	34	-86	10
	L Middle Occipital Gyrus	370	3.602	-32	-82	8
	L Superior Occipital Gyrus	50	3.294	-20	-76	30
	R Superior Occipital Gyrus	119	3.032	18	-94	30
	R Inferior Frontal Gyrus	55	3.591	34	20	30
	R Cerebelum (VI)	136	3.649	26	-64	-12
Safe > Risky	Brain Stem	69	-3.852	-8	-30	-14

[1] Using the formula for converting *t*-statistics into R^2: $R^2 = t^2 / (t^2 + DF)$ where DF = 98 degrees of freedom.

[2] Sub-threshold activation for negative risk taking regressed on the *Risky>Safe* contrast controlling for positive risk taking was observed in the R Cerebellum VIII ($k = 79$, $t = 3.260$, x = 28, y = −46, z = −38) and L Cerebellum VIII ($k = 69$, $t = 3.4$, x = −18, y = −72, z = −42).

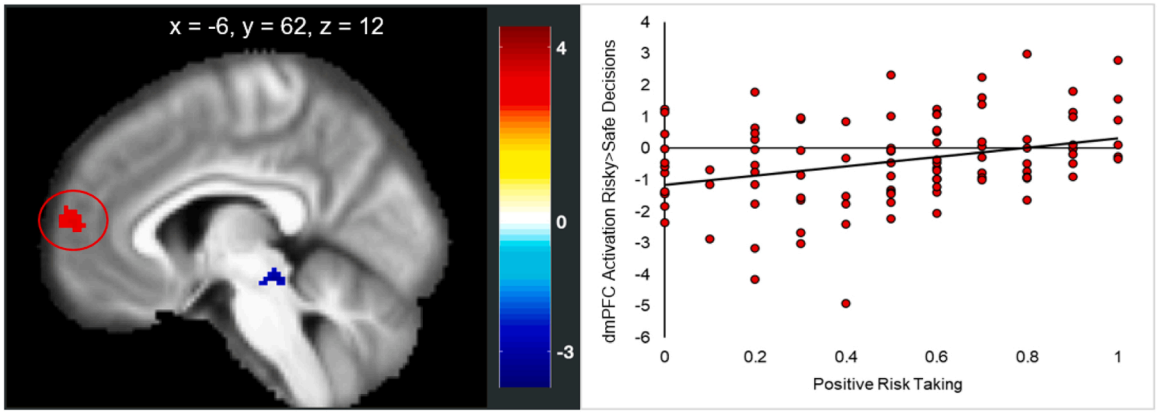

Fig. 2. Descriptive plot showing changes in dmPFC activation when making risky>safe decisions as a function of positive risk taking. Note that the Monte Carlo simulation yielded a minimum cluster size of 195 contiguous voxels for the whole-brain analysis. The cluster size for the dmPFC is 170 voxels. $R^2 = .118$.

Table 3
Neural regions tracking expected value during risky decisions as a function of self-reported positive risk taking (negative = greater neural tracking of lower expected value), controlling for self-reported negative risk taking (n = 100). The map was thresholded at $p < .005$. Monte Carlo Simulation yielded a minimum cluster size of 195 contiguous voxels for whole-brain analysis. For full descriptive purposes and to avoid false negatives, we include all clusters at $p < .005$ and a minimum of 50 contiguous voxels. $R^2 = .14$.

				MNI Coordinates		
Contrast	Region	*k*	*t*	x	y	z
Negative	R Dorsomedial Prefrontal Cortex	280	-3.995	10	66	18
	R Dorsolateral Prefrontal Cortex	153	-3.238	30	26	42
	L Ventromedial Prefrontal Cortex	65	-3.714	-2	18	-20
	L Cuneus	937	-4.024	0	-84	26

of positive risk taking evinced heightened activation of the dmPFC with increasing expected value (R^2 =.14). Additionally, positive risk taking was associated with subthreshold (153 voxels) de-activation in the dorsolateral prefrontal cortex with increasing expected value. Finally, we conducted an additional analysis wherein self-reported negative risk taking was regressed on the *Risky-PM* contrast controlling for positive risk taking. However, we do not have data to report, as there was no significant or sub-threshold activation.

Supplemental analyses were conducted examining neural tracking of expected value as a function of positive and negative risk taking without controlling for the other type of risk taking. For positive risk taking, results were comparable. Tracking in the dorsolateral prefrontal cortex (dlPFC) survived thresholding ($k = 202$), indicating that positive risk taking was associated with dampened dlPFC tracking of expected value (see Table S2 in the supplemental material). Additionally, there was sub-threshold activation in the left superior occipital gyrus. There were no significant or sub-threshold activations for negative risk taking.

4. Discussion

Despite decades of research on adolescent risk taking, little is understood about adolescents' engagement in positive risks, which are thought to support youth meeting personal goals and developmental milestones in socially acceptable ways (Duell and Steinberg, 2019). To understand how to motivate youth to engage in positive risks, scholars must first identify the mechanisms supporting it. In this study, we examined the association between positive risk taking and neural activation on an experimental risk task during fMRI. Using a risk-return framework, we compared neural activation between risky and safe choices and neural tracking of expected value during decision-making. Although positive risk taking was not associated with individual differences in decision-making on the experimental risk task, youth endorsing high levels of positive risk taking evinced parametric de-activation of the dmPFC when the expected value of the risk increased. These findings highlight the utility of examining neural sensitivity to distinct aspects of the decision-making process (i.e., the

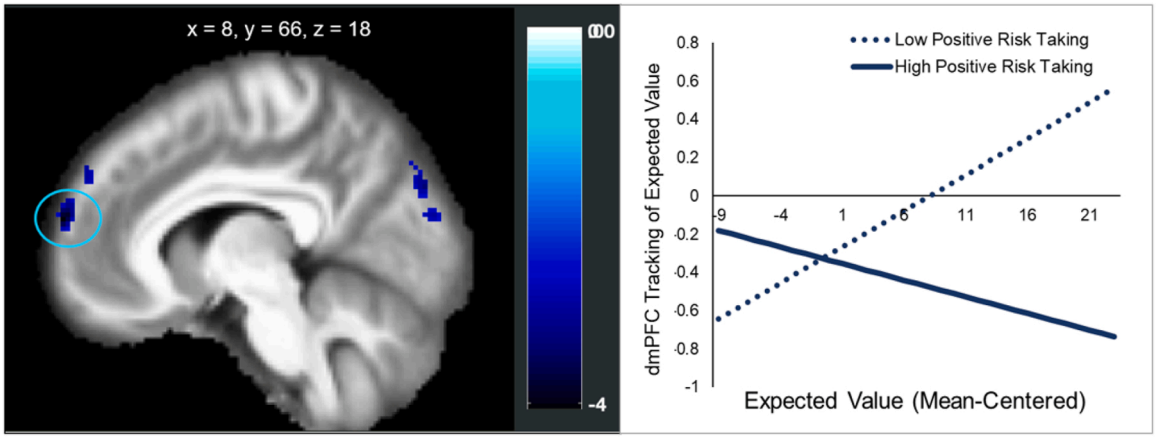

Fig. 3. Descriptive plot showing changes in neural tracking of expected value in the dmPFC during risky decisions among low and high positive risk takers. Values on the Y-axis represent changes in dmPFC activation as expected value (X-axis) changes across trials. For individuals high on positive risk taking, dmPFC activation decreases as expected value increases. $R^2 = .14$.

risk and the return) and provide initial evidence that positive risk taking is associated with the neural processes associated with risky decision-making during a developmental period when these processes are still undergoing development.

4.1. Positive risk taking, risk, and reward

Perhaps the most striking finding in this study was that positive risk taking was associated with dampened dmPFC tracking of expected value. The dmPFC has been implicated in strategic control in decision-making (Venkatraman and Huettel, 2012), decision making under risk (Rushworth et al., 2004), and conflict resolution (de Wit et al., 2006). Supplemental to the extensive body of literature focusing on reward sensitivity as a key motivator of risky decision-making during adolescence, results from this study reinforce the fact that youths' decisions to take risks are also supported by processes involved in deliberation and strategizing, which may be exaggerated among those who take positive risks. That positive risk taking explained some variability in neural tracking of expected value offers preliminary support for our hypothesis that positive risk taking may reflect strategic decision-making. Given that brain development in regions supporting deliberation and strategizing is still ongoing during adolescence, it would be exciting for longitudinal research to explore whether positive risk taking supports the development of these advanced decision-making abilities.

Findings also suggested that positive risk taking was associated with greater dmPFC activation during risky versus safe choices, though it is important to recognize that this trend was driven primarily by participants showing low positive risk taking. Thus, it may be equally meaningful to consider that low positive risk taking is associated with greater dmPFC activation for safe choices. We are hesitant to over-interpret this finding since it was below our threshold for statistical significance. Thus, the association between positive risk taking and dmPFC sensitivity to risky versus safe choices is an important area for future research to investigate. Nevertheless, our results preliminarily suggest a link between positive risk taking and neural activation during decision making under risk.

With respect to dampened dmPFC tracking of expected value, there are two potential interpretations. First, it may be that individuals endorsing high levels of positive risk taking evince less dmPFC tracking of expected value because choices with high expected value require less deliberation and strategizing. Reciprocally, it may be that high positive risk taking is associated with greater neural sensitivity to disadvantageous risks where the expected value of the risky choice is lower than the expected value of the safe choice (i.e., greater dmPFC activation as expected value decreases). This finding is consistent with prior behavioral work suggesting an association between positive risk taking and punishment sensitivity (Duell and Steinberg, 2020), but also challenges the notion that adolescents are less sensitive to punishment (Ernst et al., 2006). Thus, it will be useful for future work to further examine the extent to which positive risk taking is associated with neural sensitivity to punishments or disadvantageous outcomes.

Positive and negative risk taking are thought to be related but distinct constructs. Prior studies have shown that positive and negative risk taking are positively correlated (Duell and Steinberg, 2020; Fischer and Smith, 2004). However, this was not the case in the present study. One reason for these discrepant findings could be that prior studies finding a correlation between positive and negative risk taking are with samples of late adolescents (ages 16–20 years), whereas this study included youth in middle adolescence. It may be that the association between positive and negative risk taking changes across age (e.g., Armstrong-Carter et al., 2021, preprint), another compelling avenue for future inquiry.

Behaviorally, we did not observe an association between positive or negative risk taking and decision-making on the Cups risk task. Thus, behavioral preference for risk and sensitivity to expected value are not explained by individual differences in real-world risk taking, providing evidence against our hypothesis that positive risk taking would be associated with greater risk taking when expected value was high. However, we did observe variability in neural activation during the decision-making process as a function of positive risk taking. Thus, although adolescents came to the same decisions regardless of their positive risk-taking tendencies, the neuropsychological processes involved in the decision-making process varied. For this reason, the use of fMRI was essential for understanding individual differences in the decision-making process among individuals endorsing different patterns of risky behavior. In future work, this information may be used to isolate some of the decision-making processes distinguishing between low- and high-positive risk takers.

Additionally, it was somewhat surprising to find that negative risk taking was not associated with neural activation during decision-making on the experimental risk task. Thus, the brain-behavior associations observed in this study were unique to positive risk taking, further suggesting that positive and negative risk taking are psychologically distinct. One possible distinction to explore is that between decision-making under risk, as in this task, and decision-making under ambiguity, where outcome probabilities are completely unknown, such as on tasks like the Balloon Analog Risk Task. Prior work has shown that decision-making under ambiguity recruits different brain regions than decision making under risk (Blankenstein et al., 2021). Although more careful work is warranted, at least one study has shown that decision-making under ambiguity is associated with self-reported negative risk taking (Qu et al., 2015). These differences would be meaningful to explore, as risk and ambiguity represent related but distinct factors contributing to risk behavior (for a review, see Blankenstein et al., 2021).

4.2. Contributions, limitations, and future directions

The present study offers a few key contributions to the literature. First, findings from this study provide initial evidence for links between positive risk taking and neural activity during risky decision-making among adolescents. This offers a useful starting point for future work to develop methods for identifying the neuropsychological processes motivating positive risk taking among youth. In correlating neural activity during risky decision-making with self-reported risk behavior, findings additionally offer insight to individual difference factors (i.e., positive risk taking) associated with the neuropsychological factors contributing to adolescents' risk behavior. Moreover, our use of a risk-return framework for analyzing risky decision-making allowed us to decompose adolescents' decisions into (a) overall sensitivity to risk, and (b) sensitivity to the risk-value tradeoff, or expected value of the risk. Ultimately, this approach affords a more nuanced understanding of decision-making than approaches that collapse risk and return into a single decision-making process. Finally, our analyses linking positive risk taking to neural activity on the Cups task controlled for negative risk taking, strengthening our confidence that the links between brain activation and self-reported behavior are unique to positive risk taking.

In addition to the strengths and contributions of this study to the developmental literature, there are limitations that must be considered when interpreting the results. One limitation is that the experimental risk task used in this study explicitly presents the probabilities of each risky choice. While this methodological design is useful for understanding complex decision-making under risk, it is not entirely ecologically valid since adolescents are typically not aware of the probabilities associated with their choices in real-world risk scenarios. This may explain why self-reported risk behavior was not associated with decision-making on the task (for further reading on weak correlations between self-report and behavioral measures, see Dang et al., 2020). Additionally, this study focused only on adolescents' decisions and did not measure neural activity related to the anticipation or receipt of outcomes. Several prior studies have shown that different phases of the decision-making process recruit distinct brain regions (Cao et al., 2018;

Filimon et al., 2020; Hoogendam, 2013). Thus, to get a comprehensive understanding of the neuropsychological processes associated with risk taking, it will be important for future work to examine brain function across the entire range of the decision-making process, from decision to outcome. Finally, our methodological approach did not lend itself to directly comparing the neuropsychological correlates linked to positive and negative risk taking, respectively. Future work interested in comparing the neural mechanisms of positive and negative risk taking will have to use more sophisticated methods to identify the neural processes uniquely linked to specific patterns of risk behavior. Despite these limitations, this study extends the neurodevelopment literature on adolescent risk taking by considering an understudied pattern of risk behavior: positive risk taking.

5. Conclusions

Risk behavior during adolescence increases dramatically, as young people are afforded with greater independence and changes in brain development prime youth to explore their environment and try new things. Risk behavior is not ubiquitous, however. Some risks are dangerous and antisocial, whereas others are more developmentally adaptive and socially acceptable. Identifying ways to promote adolescent engagement in positive rather than negative risks is an important objective for scholars and practitioners alike. As an initial step towards identifying the decision-making processes supporting positive risk taking, this study is the first to link neural activation during risky decision-making to self-reported positive risk taking among adolescents. The unique association between positive risk taking and brain activation during risky decision-making suggests that positive risk taking is associated with the recruitment of brain regions important for integrating reward-processing and cognitive control during decision-making. Findings provide a preliminary foundation for the field's understanding of the neural processes associated with positive risk taking in adolescence.

Data statement

Behavioral and self-report data from this study are not available for public access because the study participants did not consent to the public use of their data. Please contact the senior author directly to request these data. Un-thresholded brain maps from the fMRI analyses are available on NeuroVault at the following link: https://neurovault.org/collections/11782/.

CRediT authorship contribution statement

Natasha Duell: Conceptualization; Formal Analysis; Writing – Original Draft, Review & Editing. **Seh-Joo Kwon**: Conceptualization; Formal Analysis. **Caitlin C. Turpyn**: Conceptualization. **Kathy T. Do**: Conceptualization; Writing – Review & Editing. **Mitchell J. Prinstein**: Funding acquisition; Project Administration; Writing – Review & Editing. **Kristen Lindquist**: Funding acquisition; Project Administration; Writing – Review & Editing. **Eva Telzer**: Conceptualization; Funding acquisition; Project Administration; Supervision; Writing – Review & Editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.dcn.2022.101142.

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