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Friendship changes differentially predict neural correlates of decision-making for friends across adolescence

Seh-Joo Kwon, 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, USA

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ABSTRACT

Adolescents' peer world is highly dynamic with constant dissolution of old friendships and formation of new ones. Though many of adolescents' risky decisions involve their peers, little is known about how adolescents' ever-changing friendships shape their ability to make these peer-involving risky decisions, particularly adaptive ones, and whether this association shifts over time. In a 5-wave longitudinal fMRI study, 173 adolescents (at wave 1: $M_{age} = 12.8$, $SD_{age} = 0.52$; range = 11.9–14.5) made risky choices to win money for their best friend. We assessed whether participants nominated the same or different best friend as their previous participation year (a total of 340 data points of friendship maintenance / change). In early adolescence, adolescents with the same best friend took more adaptive risks for that best friend than those with a different best friend. In late adolescence, however, adolescents with a different best friend took more adaptive risks for the new best friend than those with the same best friend. Further, the amygdala was differentially sensitive to friendship maintenance / change during these peer-involving adaptive risks across time. This study has implications for how stable and flexible peer landscapes differentially modulate social motivation and social decision-making over the course of adolescence.

1. Introduction

Adolescence is characterized by increasing incidents of taking risks that can positively or negatively impact others (e.g., Do et al., 2017; Crone et al., 2008). Adolescence is also marked by rapid transformations in one's social world. As ties with different peers form and hierarchies in peer systems emerge, relationships with peers become salient and complex (Brown, 2004; Brown and Larson, 2009). Yet, there are inconsistencies as to whether changing friendships during adolescence are beneficial or harmful (Brown, 2004; Flannery and Smith, 2016, 2021). The present study examines whether friendship changes differentially shape adolescents' ability to take adaptive risks for their best friend over time, and the neural correlates that parallel this behavior.

As youth spend more unsupervised, quality time with their friends, opportunity for making risky decisions that involve and impact their friends rises (Brown, 2004; Brown and Larson, 2009). These risks for friends can be *adaptive* if adolescents *selectively* take risks when the potential gains for a friend outweigh the potential losses, and thus strategically switch between safe and risky choices by tuning to cues within their environment (Barkley-Levenson and Galván, 2014). For instance, a teen may be more likely to allow their friend to copy their homework in an empty classroom than when their peers are around, which may be more likely than when their teacher is present, demonstrating their changing likelihood of taking risks for their friends depending on the contextual conditions. In experimental paradigms of economic decision-making, adaptive risks are often operationalized as the sensitivity to the expected value (EV) of reward during risk taking (Barkley-Levenson and Galván, 2014; Levin et al., 2007; Rosenbaum et al., 2021). Adolescents indeed use EV to take risks for their friend, with strategies for using EV shifting over time (Powers et al., 2018). Yet, to our knowledge, all studies probing the development of adaptive risk taking for friends have been cross-sectional, which misses the opportunity to leverage unique within-person changes such as shifts in youth's peer network or friendships.

One important consideration about adaptive risk taking for friends is that the targets of these risks likely change across the years, since adolescents' social world rapidly grows and who adolescents interact with diversifies (Brown, 2004). Indeed, adolescents tend to seek out friends who they share similar interests with and are simultaneously influenced by friends they are surrounded by, and so it is imperative to investigate

* Correspondence to: 235 E. Cameron Avenue, Chapel Hill, NC, USA.
E-mail address: ehtelzer@unc.edu (E.H. Telzer).

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how youth's evolving social world molds their behaviors (Simons-Morton and Farhat, 2010). A key factor that depicts the expansion of adolescent friendships is its maintenance and dissolution across time (Brown, 2004). Friendship maintenance or stability requires the ability to navigate any interpersonal conflicts by thinking about their friends' perspectives and forgiving friend's transgressions (Flannery and Smith, 2017). Similarly, friendship dissolution or instability may be indicative of poor social skills, in the event that adolescents are broken up with. Given that friendship stability and EV-based decision-making for others are both thought to involve successful perspective-taking, friendship stability may shape how adaptive decisions for friends are made using perspective-taking (Crone et al., 2008; Flannery and Smith, 2017). In particular, friendship stability may be associated with adolescents understanding the consequences of their actions on their peers and subsequently being strategic about making choices that can most benefit their peers.

Interestingly, it is friendship *instability* that is highly prevalent during adolescence, especially during transitory periods such as the middle to high school transition, with its prevalence also changing from early to late adolescence (e.g., Berndt and Hoyle, 1985; Eccles et al., 1996; Hardy et al., 2002; Lessard and Juvonen, 2018; Poulin and Chan, 2010; but see Meter and Card, 2016). Though majority of prior research points to the benefits of a stable friendship, unstable friendships may too be linked to positive outcomes (albeit no research has tested this empirically; e.g., Chan and Poulin, 2009; Ng-Knight et al., 2019; Valdes et al., 2021). For example, being able to break friendships may be a sign of social competence or "savviness" if these friendships are unhealthy, and also if ending friendships can result in new social connections (Flannery and Smith, 2017). New social connections may allow adolescents to expand their social network and seek social status, which is a salient social goal during adolescence (Li and Wright, 2014). Further, dissolution of friendships is not only met with sadness, but also with happiness and relief, indicating that malleable friendships at times have psychological benefits for youth (Flannery and Smith, 2021). Confirmatory empirical research is still needed to test the beneficial roles of friendship instability, but perhaps friendship instability is associated with adolescents reflecting on their social goals (e.g., impressing new peers), and subsequently result in being intentional about making decisions that can most benefit their peers in order to attain social goals. The role of shifting peer landscape in interacting with and making decisions for peers is thus unknown, for there are conflicting arguments as to whether it is friendship stability or instability that is linked to heightened social-cognitive functions.

Examining the differences in neural patterns between adolescents with stable and unstable friendships may be another way of characterizing and disentangling the two groups. Indeed, prior work revealed that adolescents with stable friendships evince curvilinear changes in the ventral striatum (VS) activation – a brain region involved in reward processing – when receiving rewards for their best friend, but those with unstable friendships do not evince any developmental changes in the VS (Schreuders et al., 2021). Thus, adolescents with stable and unstable friendships vary in their neural correlates of social motivation, which may potentially contribute to formations and dissolutions of friendships (Schreuders et al., 2021). The VS also positively tracks EV during risk taking, which is thought to support greater risk-taking behaviors under higher EV (Barkley-Levenson and Galván, 2014). This effect is stronger among adolescents than adults and so the VS differentially supports adaptive risk taking from adolescence to adulthood (Barkley-Levenson and Galván, 2014).

Another brain region involved in detecting motivational and emotionally salient cues that contributes to social cognition includes the amygdala (Adolphs, 2010; Scherf et al., 2013). Experiences based on social context such as stressful life events indeed alter amygdala reactivity, suggesting that the amygdala may be sensitive to changes in the peer environment (Swartz et al., 2015; White et al., 2019). Like the VS, the amygdala tracks EV during risk taking; but unlike the VS that positively tracks EV, the amygdala does so negatively (Barkley-Levenson and Galván, 2014). Finally, given the social-cognitive characteristics of friendship stability, adolescents with stable and unstable friendships may differentially mentalize about their friends and subsequently differentially recruit regions within the social brain network such as the medial prefrontal cortex (mPFC) and temporoparietal junction (TPJ; Blakemore, 2012; Crone et al., 2008; Flannery and Smith, 2017). These social brain regions also track social information such as social rewards and risks, suggesting that these regions track potential rewards attained for friends (Flores et al., 2018; McCormick et al., 2018; van Hoorn et al., 2018). However, whether tracking of social information within the social brain network is behaviorally adaptive or not appears to be contingent on the developmental stage and may not always be positively related (such that increased tracking correlates with better behavioral performance; Kwon et al., 2022; McCormick et al., 2018; van Hoorn et al., 2018).

The current study sought to understand whether friendship changes have varying effects on adaptive risk taking for best friends from 6th to 11th grade, both at behavioral and neural levels. 6th to 11th grade represents middle and high school years in the United States, and friendships are highly fluid during this time (e.g., Poulin and Chan, 2010). In a 5-wave longitudinal functional magnetic resonance imaging (fMRI) study, adolescents made risky decisions to win money for their best friend. Behavioral analyses examined the grade-dependent effect of perceived friendship status (defined as change in best friendship from prior participation year) on EV sensitivity during risk taking for a best friend. Longitudinal whole-brain neural analysis tested for brain regions that differentially tracked EV based on grade and perceived friendship status. We hypothesized that since friendship instability becomes more common with age, friendship instability may be associated with greater behavioral EV sensitivity and neural tracking of EV for best friend over time than does friendship stability. Alternatively, since friendship stability is known to lead to an array of positive outcomes, maintaining friendships in midst of an evolving social landscape may be important, and so friendship stability may be associated with greater behavioral EV sensitivity and neural tracking of EV for best friend over time than does friendship instability. Finally, we hypothesized that longitudinal whole-brain neural analysis would identify brain regions linked to motivation and social cognition.

2. Methods

This Methods section is adapted from a previously published study using the same experimental task (Kwon et al., 2022, 2023).

2.1. Participants

Adolescent participants were recruited as part of a larger study of 873 6th and 7th grade students from 3 public middle schools to participate in a longitudinal fMRI study, based on interest and eligibility. For this current study, participants had to be at least 12 years old and in 6th or 7th grade, or within 2 months of turning 12 years old, at wave 1 of data collection. Participants were excluded if they had any metal in their body including braces or permanent retainer. Other exclusion criteria included claustrophobia, history of seizure or head trauma, learning disability, and non-fluency in English. If participants regularly took medications, they were asked to do a 24-hour medication wash prior to the scan. A total of 173 participants completed between 1–5 sessions annually across 5 waves. All participants were compensated for completing the session. Also, all participants provided informed consent/assent and the University's Institutional Review Board approved all aspects of the study.

In order to reach our target sample size of 150 participants after accounting for attrition and for excluded participants between waves of data collection, we recruited 148 participants at wave 1 of the study and 30 additional participants at wave 2. At wave 1, 5 participants were excluded due to exclusionary criteria that were revealed after recruitment. These participants were not invited back for subsequent study participation. Out of the remaining 143 participants ($M_{age} = 12.8$, $SD_{age} = 0.52$; range = 11.9–14.5; 73 female-identifying), 1 participant was excluded for acute anxiety related to the fMRI scanner and 3 participants due to incomplete data (e.g., less than 60% of response on task; ending the scan early). Further, 3 participants were excluded only from the neural analysis for completing the task outside of the scanner, 11 for not having enough behavioral data (i.e., less than 5 safe or risky decisions) or variability across trial types (i.e., risky decisions not made in different types of EV) to be modeled at the neural level, and 9 for excessive motion (>0.9 mm framewise displacement on >10% of total volumes). The final wave 1 sample size with behavioral and fMRI data included 139 and 116 adolescents, respectively.

The same exclusionary criteria were used to determine the sample sizes for waves 2 to 5. See Table 1 for demographic information of participants and Table 2 for sample size information at each wave. Across 5 waves, there were 510 behavioral and 399 fMRI data for this particular project. Analyses using perceived friendship status were limited to participants with at least 2 waves of study participation and complete self-report measure of interest, leading to 336 behavioral and 252 fMRI data.

2.2. Procedures

At each wave of data collection, participants completed behavioral and fMRI tasks as well as self-report questionnaires, totaling a 4-hour session with a 1.5-hour fMRI session. Prior to completing the fMRI scan, participants received training 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 behaviorally, 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 (e.g., additional $25 for completing 2 waves). Adolescent participants also received additional money for themselves, their parent, and their best friend through the risky decision-making task.

Table 1
Participants demographic information.

	Number of Participants (%)
Adolescent Participant	
Biological Sex	
Female	91 (52.6%)
Male	82 (47.4%)
Race	
White	51 (29.5%)
Black	40 (23.1%)
Hispanic/Latinx	60 (34.7%)
Mixed	16 (9.3%)
Other	6 (3.5%)
Parent Participant	
Relationship with Adolescent Participant	
Biological mother	143 (82.7%)
Biological father	17 (9.8%)
Other guardians	13 (7.6%)
Education	
Less than middle school completion	18 (10.4%)
Middle school completion	6 (3.5%)
Some high school	19 (11%)
High school diploma	25 (14.5%)
Some college	52 (30.1%)
Associate's or Bachelor's degree	40 (23.1%)
Some graduate school	4 (2.3%)
Graduate or professional degree	9 (5.2%)

Table 2
Sample size information at each wave.

	Wave 1	Wave 2	Wave 3	Wave 4	Wave 5
Total N (female-identifying)	143 (73)	146 (78)	145 (74)	124 (64)	104 (55)
Mean age (SD)	12.8 (0.52)	13.7 (0.58)	14.7 (0.58)	15.9 (0.58)	17.0 (0.6)
Age range	11.9 - 14.5	12.4 - 15.4	13.4 - 16.3	14.7 - 17.7	15.8 - 18.6
N for behavioral analyses	139	143	144	11	73
N for neural analyses	116	115	100	9	59
N for remote session only				112	30

Note. Wave 4 was conducted just prior to and during the COVID-19 pandemic in 2020. All behavioral and neural data were collected prior to the pandemic.

2.3. Risky decision-making task

Adolescents completed a modified Cups Task (Levin and Hart, 2003), which has previously been utilized to examine risky decision-making for others in developmental samples (e.g., Guassi Moreira and Telzer, 2018). Participants completed 3 runs of the Cups Task: one in which they made decisions for the self, one for parent, and one for best friend. The order in which participants completed each run was counterbalanced. Prior to the fMRI session, participants provided the name of their best friend and completed a short questionnaire about their best friend, and prior to completing the task, participants were reminded of the name of the best friend whom they are winning money for.

Each of the 3 runs consisted of 45 trials. On each trial, participants were presented with two scenarios of cups: the left side always had 1 cup with a guaranteed 15-cents hidden under the cup (Fig. 1). On the right side, 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; however, the money was hidden under only one of the overturned cups. Participants were told that if they chose the right side (i.e., risky decision), then the computer would randomly select one of the cups and they may earn the higher amount or 0-cents, whereas if they chose the left side (i.e., safe decision), then they were guaranteed to earn 15-cents. After each decision, participants were shown the outcome.

On each trial, the cups were shown for 3000 ms, within which participants made their decision. Next, a fixation cross was jittered around an average of 2300 ms (range = 526.68–4017.12), which was followed by the outcome for 1000 ms. Finally, there was an intertrial fixation cross that was jittered around an average of 2521.39 ms (range = 521.14–3913.31). If participants did not make a decision within the given time, participants were told that they were "too late" and there was no change in the total points. Outcomes of each decision were added to the running total for that run, which was shown to the participant at the end of each run. At the end of each session, adolescents received the money they had earned for themselves, their parent was given the money their child had earned for them, and their best friend was provided with their earnings in cash. The participating best friend and parent did not know the adolescent was winning money for them until they received the award.

2.4. Operationalizing adaptive risk taking

To operationalize adaptive risk taking, we assessed adolescents' likelihood of making a risky decision for their best friend as a function of the EV of reward of the risky choice. Consistent with prior work, EV was comprised of two factors: magnitude 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)

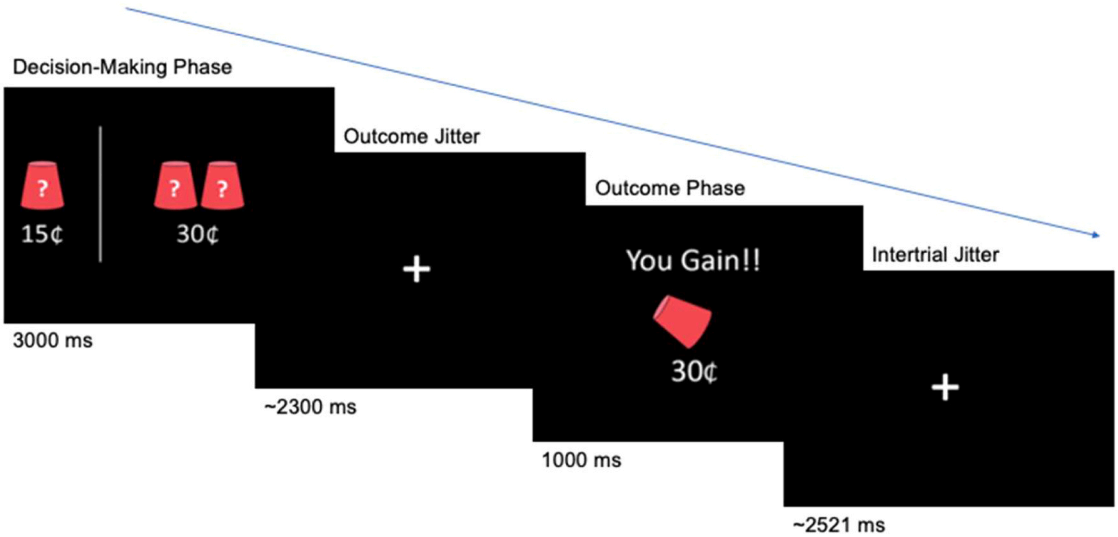

Fig. 1. Example trial of the modified Cups Task. In this example, participant chose the risky option and subsequently gained a reward of 30-cents.

for that trial. Given the parameters of the magnitudes and probabilities of reward, the EVs for risky decisions were: 6, 9, 10, 15, 22.5, 25, 37.5. The EV of safe decision was always 15. In this task, it is advantageous to take risks when the EV is greater than 15 (i.e., EV of safe decision), whereas it is disadvantageous to take risks when the EV is less than 15. It is therefore adaptive to take risks with increasing EV.

2.5. Friendship quality

Friendship quality with best friends was controlled for in all analyses, in order to ensure that the effect of perceived friendship status on behavior and brain activation is not confounded by the strength of friendship. To measure relationship quality with best friends, adolescents completed a shortened version (13 items) of the Network of Relationships Inventory (Furman and Buhrmester, 2009). Adolescents reported their positive (e.g., "How much does your best friend treat you like you're admired and respected?"; 7 items) and negative (e.g., "How often do you and your best friend disagree and quarrel with each other?"; 6 items) interactions with their best friend. Participants used a 5-point Likert scale (1 = "Little to None" to 5 = "The Most"). Only positive interaction scores were used since prior findings suggest that EV sensitivity during risk taking for close others do not differ by negative interactions (Guassi Moreira and Telzer, 2018). Positive interaction was calculated as the mean of the 7 items. This measure was assessed at every wave of data collection (α range = 0.71–0.89).

2.6. fMRI data acquisition and analysis

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; flip angle = 90°; 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; flip angle = 120°; 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; flip angle = 8°; 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.

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 6 mm Gaussian kernel, full-width-at-half maximum; high-pass temporal filtering with a 128 s filter width (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 =.3). For 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. 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 (SPM12; 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 with regressors for the following 5 conditions: trials for each decision (risky or safe) and trials for each outcome (15-cents, zero cent, or >15-cents). A parametric modulator (PM) was included for each decision, whereby the PM represented the EV (centered at 15) of the risky decision for that trial and served to examine neural activity that tracks EV when making decisions. Each condition was modeled using the onset of the cups (or outcome) and a duration equal to zero. It was also modeled separately for each run, totaling 15 conditions.

Further, trials in which participants did not respond, the final outcome trial, and volumes containing motion in excess of 0.9 mm framewise displacement were included as separate regressors of no interest. Six motion regressors were modeled as covariates of non-interest to control for head movement in six dimensions. Jittered intertrial periods (i.e., fixation cross) were not explicitly modeled and therefore served as the implicit baseline for task conditions.

3. Analysis plan

3.1. Effect of perceived friendship status on behavior

First, we followed a model-building procedure to determine the model that best fits the development of behavioral-level adaptive risk taking for a best friend. To do so, we used a series of 3-level growth models with trials (i = 45 trials maximum) nested within time points (j = 3 time points maximum), nested within individuals (k = 173 participants). EV that is centered at 15 was added as a level 1 predictor and grade that is centered at 6th grade as a level 2 predictor, and binary decision (0 = safe; 1 = risky) of each trial was the dependent variable. We estimated the following linear trajectory model with random intercepts only as the baseline model (lme4::glmer package in R; Bates et al., 2015). This baseline model includes fixed effects (denoted by γ) of intercepts, EV, grade, EV x grade interaction, as well as random effects (denoted by μ) of intercepts:

$$Logit(Decision_{ijk}) = \gamma_{000} + \gamma_{010}Grade_{0jk} + \gamma_{100}EV_{ijk} + \gamma_{110}Grade_{1jk}EV_{ijk} + u_{0jk} + u_{00k}$$

We next fitted a quadratic trajectory model by adding a quadratic growth term (i.e., grade x grade and grade x grade x EV). Whether the linear or quadratic trajectory model better fit our data was determined by comparing one another using a log likelihood ratio test with difference in degrees of freedom (i.e., difference between two models in their degrees of freedom) and level of significance of $p < .05$. Using this log likelihood ratio test, we then determined whether additional level 2 random effects were needed; and if so, we then tested whether additional level 3 random effects were also needed. All models were fit with full information maximum likelihood estimates. Further, to compare trajectories of adaptive risk taking for oneself relative to their best friend, we conducted a multivariate growth model, which simultaneously tested these two trajectories. Post hoc tests contrasted best friend- and self-related main effects (multcomp::glht package; Hothorn et al., 2008; significance level adjusted using Bonferroni correction).

Second, we determined whether changes in the best friend whom adolescents made risky decisions for differentially predicted adaptive risks for a best friend over time. Perceived friendship status was dummy-coded as "1" if an adolescent's best friend remained consistent between the concurrent and the previous participation year and as "0" if an adolescent's best friend differed between the two participation years (see Schreuders et al., 2021 for a similar assessment of best friend stability), and was therefore added to the model as a time-varying covariate. That is, a participant may have received a "1" in one grade, but a "0" in the subsequent grade, and so perceived friendship status varied across time. The grade variable was re-centered at 7th grade since the earliest change in friendship was determined at 7th grade (6th grade adolescents at wave 1 who were in 7th grade at wave 2). We included a perceived friendship status x EV x grade interaction to test whether the effect of perceived friendship status on adaptive risk taking is grade-dependent. That is, the effect of perceived friendship status on behavior may be different from 7th to 11th grade. We further controlled for within- and between-person effects of friendship quality by adding person-mean and group-mean centered friendship quality, respectively, as predictors, and for the number of waves between two consecutive participations. If there was a significant perceived friendship status x EV x grade interaction, we conducted post hoc tests that contrasted stable versus unstable friendships at 7th and 11th grades (significance level adjusted using Bonferroni correction).

Lastly, as part of exploratory analysis, we tested whether the overall level of changes in best friendships differentially predicted trajectories of adaptive risks for best friend. For each participant, we calculated an overall score by dividing the number of unique best friends by the total number of study participation years. For instance, if a teen nominated friend A at waves 1 and 2, friend B at waves 3 and 4, and friend C at wave 5, then that teen received an overall score of 0.6 (= 3 unique best friends / 5 years of study participation). This exploratory analysis allowed us to understand whether the *amount* of friendship changes (using an overall score), in addition to the *temporal significance* of friendship changes (using a time-varying covariate, as described above), contributes to the development of adaptive risks for best friend. We used the best-fit model from the above friendship status analysis and replaced the friendship status variable with the overall score.

3.2. *Effect of perceived friendship status on neural functions*

To identify brain regions that are differentially sensitive to perceived friendship status during adaptive risk taking for a best friend across grade, we conducted longitudinal whole-brain analysis using AFNI 3dLMEr models (Chen et al., 2013). This program allows for voxel-level whole-brain analysis of linear mixed effects (maximum-likelihood, multilevel model). Grade x perceived friendship status interaction (for linear model; grade x grade for quadratic model) was the predictor of interest. Individual-level fMRI contrast of risky decision-making for a best friend, with EV as the PM, was the dependent variable. To keep the behavioral and neural models as consistent as possible, the functional form (i.e., linear versus quadratic) of neural changes that we modeled was determined by that of behavioral changes. We controlled for the number of waves between two consecutive participations, and within- and between-person effects of friendship quality. Given the exploratory nature of the fMRI analysis, and the novelty and complexity of running whole-brain fMRI analysis with 5 waves of data and a time-varying covariate, we used a statistical threshold of $p < .005$ and a minimum cluster size of 20 voxels.

4. Results

4.1. *Description of best friendships*

Approximately 55.2% of adolescents in 7th grade, 64.9% in 8th grade, 68.1% in 9th and 10th grades, and 57.1% in 11th grade changed their best friend from their previous wave of participation. The average time between two consecutive waves of participation was 70.1 weeks, suggesting that adolescents' change in best friendships was assessed approximately every 1.3 years. Collapsing across grades, 62.7% of best friendships were unstable friendships and 37.3% were stable friendships. Also collapsing across grades, the average relationship quality with the specified best friend was 3.29 (SD = 0.84, range = 1.71–5) for data points of unstable friendships and 3.16 (SD = 0.85, range = 1.29–5) for those of stable friendships. The average relationship quality did not differ between the two groups of data points ($t(331) = 1.28$, CI = [− 0.07, 0.31], $p = 0.2$). Table 3 contains information about best friendships and relationship quality with best friends.

Table 3
Status of best friendships and relationship with best friend (BF).

	Grade					
	6	7	8	9	10	11
Status of Best Friendship						
Missing	69	90	10	1	0	0
Diff. BF (N)	N/A	32	85	47	32	20
Same BF (N)	N/A	26	46	22	15	15
Total BF Data (N)	N/A	58	131	69	47	35
Diff. BF (%)	N/A	55.17	64.89	68.12	68.09	57.14
Same BF (%)	N/A	44.83	35.11	31.88	31.91	42.86
Relationship with BF						
Missing Sex of BF	1	1	0	1	4	2
Diff. Sex as BF	14	14	21	14	19	5
Same Sex as BF	54	133	120	55	24	27
Avg. NRI Score for Diff. BF	N/A	3.74	3.14	2.85	3.53	3.78
Avg. NRI Score for Same BF	N/A	3.37	3.07	2.77	3.48	3.38
Avg. NRI Score for All	3.48	3.50	3.12	2.85	3.51	3.62

Note. Missing values for 6th and 7th graders are higher since statuses of best friendships were assessed starting at wave 2 of the study. "Relationship with BF" includes all adolescents (i.e., not limited to those with perceived friendship status data).

4.2. Behavioral results

We first examined longitudinal changes in adaptive risk taking for the best friend from 6th to 11th grade. The baseline model (linear trajectory with random intercepts only model) was determined as the best-fit model for our data. There was a significant positive cross-level interaction between EV and grade ($\gamma_{EVxGrade} = 0.017$, $p < 0.001$), suggesting a linear increase in EV sensitivity when making risky decisions for best friend from 6th to 11th grade. Therefore, adolescents took more adaptive risks for their best friend across grade (Fig. 2). Multivariate growth model revealed no differences in grade-related changes in adaptive risk taking for oneself relative to their best friend ($\gamma_{EVxGrade\ for\ BF-EVxGrade\ for\ Self} = -0.0004$, $p > 0.99$).

Next, we added perceived friendship status (0 = different best friend as previous participation, 1 = same) as a time-varying covariate to the above model to test whether these longitudinal changes differed based on perceived friendship status. We found a significant EV x grade x perceived friendship status interaction ($\gamma_{EVxGradexStatus} = -0.019$, $p < 0.001$; Fig. 2). Therefore, adaptive risk taking for the best friend was contingent on one's grade and perceived friendship status.

Post hoc tests revealed a significant positive EV x grade interaction among data points of unstable friendships ($\gamma_{EVxGrade} = 0.025$, $p < 0.001$), but not among data points of stable friendships ($\gamma_{EVxGrade} = 0.005$, $p = 0.35$). That is, younger and older adolescents with stable friendships did not differently take adaptive risks for their best friend, but older adolescents with unstable friendships took more adaptive risks for their best friend than younger adolescents with unstable friendships. Further, 7th graders with stable friendships took more adaptive risks for their best friend than 7th graders with unstable friendships ($\gamma_{Stable-Unstable} = 0.041$, $p < 0.001$); however, this association flipped across time such that 11th graders with unstable friendships took more adaptive risks for their best friend than 11th graders with stable friendships ($\gamma_{Stable-Unstable} = -0.038$, $p = 0.006$).

Lastly, exploratory analysis using an overall score (M = 0.67, SD = 0.28, range = 0–1) showed that the EV x grade x overall score interaction was not significant ($\gamma_{EVxGradexScore} = 0.01$, $p = 0.27$). Thus, during adolescence, the temporal occurrence of friendship changes may be more integral than the amount of friendship changes for understanding the development of adaptive risk taking for peers.

4.3. fMRI results

Longitudinal whole-brain analysis examining grade x perceived friendship status interaction yielded activations in the right amygdala (x, y, z = 12, −8, −20; k = 48 voxels), left amygdala (x, y, z = −18, 2, −30; k = 22 voxels), and left cerebellum (x, y, z = −26, −44, 56, k = 21 voxels). That is, perceived friendship status had grade-dependent effects on bilateral amygdala and left cerebellum activation that tracked EV during risk taking for a best friend (Fig. 3 A). Codes and outputs for longitudinal whole-brain analysis are available on GitHub (https://github.com/sehjookwon/BFStability_3dlmer).

Next, we ran post hoc tests to unpack this interaction by extracting parameter estimates within the bilateral amygdala (combining the right and left amygdala clusters) and fitting a 2-level growth model with perceived friendship status as a time-varying covariate. Post hoc tests revealed that amygdala activation that tracks EV during risk taking for a best friend linearly increased among data points of stable friendships ($\gamma_{Grade} = 0.024$, $p < 0.001$). That is, in Fig. 3B, 7th graders with the same best friend (dotted red line) showed a decreasing amygdala tracking of EV (i.e., decreasing amygdala activation to increasing EV) as indicated by the negative slope. This negative slope became increasingly positive from 7th to 11th grade such that 11th graders with the same best friend (dotted navy blue line) showed an increasing amygdala tracking of EV (i.e., increasing amygdala activation to increasing EV) as indicated by the positive slope. Therefore, the amygdala activation that tracks EV (i.e., slope) increased from 7th to 11th grades. However, amygdala activation that tracks EV during risk taking for a best friend did not significantly change among data points of unstable friendships ($\gamma_{Grade} = -0.008$, $p = 0.15$; Fig. 3B). Further, 7th graders with unstable friendships showed greater amygdala activation than 7th graders with stable friendships ($\gamma_{Stable-Unstable} = -0.064$, $p < 0.001$); however, this association flipped across time such that 11th graders with stable friendships showed greater amygdala activation than 11th graders with unstable friendships ($\gamma_{stable-Unstable} = 0.066$, $p = 0.002$). Note, given that the extracted parameter estimates of amygdala are associated with EV tracking (slope), we were unavailable to determine the lower and upper parameter estimates of amygdala at specific values of EV, which are used to determine the error bands.

Lastly, amygdala that tracks EV was significantly positive (i.e.,

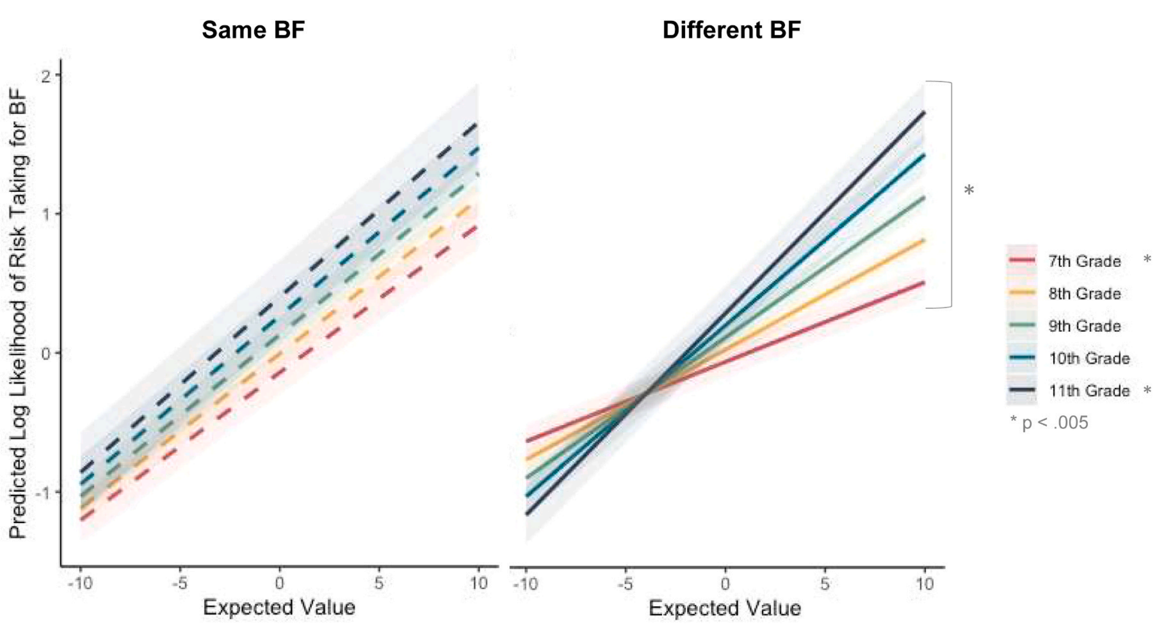

Fig. 2. Grade-dependent effect of perceived friendship status on adaptive risk taking for a best friend (BF). *Note*. Shaded areas indicate standard error bands. Asterisk next to a grade indicates adaptive risk taking differences between adolescents with the same and different best friends in that grade. Figures are separated for those with the same and different perceived best friend.

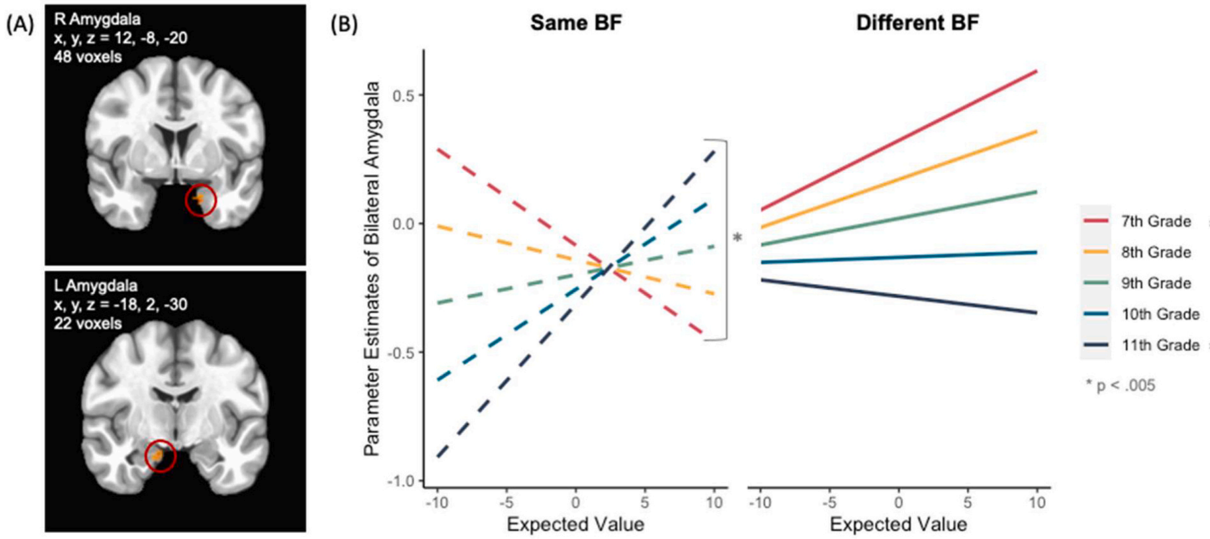

Fig. 3. (A) Grade-dependent effects of perceived friendship status within the right and left amygdala that tracks EV during risk taking for a best friend (BF). (B) Post hoc tests revealed that 7th graders with an unstable best friend showed greater amygdala activation than 7th graders with a stable best friend, but this effect flipped by 11th grade. *Note.* Asterisk next to a grade indicates amygdala differences between adolescents with the same and different best friends in that grade. Figures are separated for those with the same and different perceived best friend.

greater than zero) for 7th graders with a different best friend and 11th graders with the same best friend ($\gamma_{Intercept}s > 0.027$, $ps > 0.007$), indicating greater amygdala activation to greater EV. Amygdala tracking of EV was significantly negative for 7th graders with the same best friend ($\gamma_{Intercept} = -0.037$, $p = 0.004$), indicating greater amygdala activation to lower EV. However, amygdala tracking of EV was not significant for 11th graders with a different best friend ($\gamma_{Intercept} = -0.006$, $p = 0.99$), indicating similar amygdala activation across EV.

5. Discussion

Peers become highly salient during adolescence. In tandem, adolescents' peer network is rapidly shifting and evolving. The current study investigated how adolescents' changing social environment – as measured by changes in adolescents' best friendship across approximately a year – impacts their ability to make decisions that involve their best friend. We found that adolescents were more sensitive to EV during risk taking for their best friend from 6th to 11th grade and this trajectory differed based on changes in these best friendships. At the neural level, the average amygdala trajectory that tracks EV during risk taking for a best friend also differed based on changes in these best friendships.

Adolescents increasingly took adaptive risks for their best friend over time, yet this trajectory differed based on whether their current best friend was different or same as the prior year. In particular, *younger* adolescents (i.e., 7th graders) with a different best friend were *less* likely to take adaptive risks than those with the same best friend. However, *older* adolescents (i.e., 11th graders) with a different best friend were *more* likely to take adaptive risks than those with the same best friend. In addition, older adolescents with a different best friend were more likely to take adaptive risks than younger adolescents with a different best friend, but these grade-related differences were not observed among older and younger adolescents with the same best friend. Many previous studies that examined friendship stability during adolescence did not use longitudinal designs to evaluate the importance of such timing, or did indeed use longitudinal designs but did not consider any within-person variabilities in best friendships (e.g., Flannery and Smith, 2021; Ferguson et al., 2022; Schreuders et al., 2021). Taken together, these behavioral results suggest that whether friendships instability positively or negatively impacts peer-oriented behaviors relies on *when* this instability is occurring in adolescence.

Perhaps these differences are shaped by the changing psychological effect of friendship changes in adolescence. Though risky behaviors are typically considered as detrimental, prior research has shown that risky behaviors can also be developmentally appropriate, for they offer opportunities for exploration and learning (Ciranka and van den Bos, 2021; Ellis et al., 2012; Romer et al., 2017). For this reason, it is important to identify contexts that facilitate an optimal use of risky behaviors. Adolescents' peer environment becomes highly complex (e.g., Brown, 2004). Thus, one hypothesis we set forth is that taking advantage of one's rich social landscape and exploring friendships can allow older adolescents to take better risks, particularly ones that are favorable for their close others. It should be noted that in our study, specifying a different best friend does not necessarily signify a friendship dissolution. In contrast, younger adolescents may not reap the same benefits of a new best friendship as do older adolescents; rather, maintaining best friendships and forming a solid foundation of peer relationships may be more necessary for younger adolescents' social behaviors (Chan and Poulin, 2009; Ferguson et al., 2022; but see Bowker et al., 2006). In sum, adolescents' risk taking becomes more intentional over time, especially for older adolescents who have flexible best friendships, indicating that their ever-changing peer environment influences how they make social choices.

In parallel, amygdala activity during adaptive risk taking for a best friend was differentially sensitive to friendship changes over time. Younger adolescents with the same best friend took more adaptive risks and displayed a *lower* amygdala tracking of EV during risk taking than younger adolescents with a different best friend. In particular, unlike younger adolescents with the same best friend who displayed a positive tracking of EV, those with a different best friend evinced a negative tracking of EV, demonstrating greater amygdala activation to low EV or disadvantageous risks. The amygdala is involved in determining the relevance of stimuli, which include stimuli of social value in adolescence, and tracking reward magnitude (Adolphs, 2010; Barkley-Levenson and Galván, 2014; Scherf et al., 2013). Thus, a solid foundation of peer network may support an enhanced salience of potential losses for peers, which in turn may motivate greater strategic behaviors for peers in early adolescence.

In contrast, among older adolescents, it was those with a *different* best friend who took more adaptive risks and this behavioral pattern again corresponded to a *lower* amygdala sensitivity to EV. The pattern of "lower" amygdala sensitivity to EV, however, differed between early and late adolescence. That is, unlike older adolescents with the same best friend who displayed a positive tracking of EV, those with a different best friend did not show a significant tracking of EV and so perhaps potential losses and rewards for peers may be similarly salient. The amygdala responds to both positive and negative outcomes among adults (Gupta et al., 2011; Martins et al., 2021). Thus, older adolescents exploring their elaborate peer network may demonstrate a more unbiased amygdala sensitivity to both positive and negative valence information, which in turn may motivate greater strategic behaviors for peers in later adolescence. In conclusion, shifting peer landscape modulates amygdala reactivity to potential losses and rewards for peers, and thus may also modulate the motivation of social decision-making (e.g., impressing or disappointing peers) during adolescence.

Surprisingly, we did not observe differences within the social brain network or the VS. Prior research shows differences between adolescents with stable versus unstable best friendships in VS activation during vicarious reward processing, but the discrepancy in findings between this prior study and our study could be due to how stability of best friendship was defined (Schreuders et al., 2021). While this prior study assessed stability across three consecutive years (and so a participant either had a stable or an unstable best friendship), our study assessed within-person differences and time-varying effect of stability. Trajectories of ventral striatal activity, in particular, may therefore be sensitive to the rate of change in adolescent friendships across several years (rather than yearly variations in adolescent friendships), but this hypothesis needs to be empirically tested.

The current study comprises of many strengths, including using within-person changes in best friendships across the middle to high school years, a time of drastic changes in adolescents' social network (Temkin et al., 2018). However, our study is not without limitations. First, future studies should use social network analysis to understand the reciprocity of best friendship and consider the number of reciprocated best friendships since adolescents may have multiple best friends. Next, given that there are many reasons for shifts in adolescent friendships, future studies should query, for instance, whether a specific context or type of friendship maintenance is even more beneficial for younger adolescents in promoting social behaviors (Flannery and Smith, 2021; Hartl et al., 2015). Last but not least, future research should consider using an expected utility model, since it assumes that people have subjective experiences of objective rewards and therefore it is a better approach for modeling the use of EV during decision-making (Ciranka and van den Bos, 2019; Durbach and Stewart, 2009).

Our study demonstrates that stability in best friendships in early adolescence but instability in later adolescence is linked to greater strategic decision-making that directly affects adolescents' best friend. In parallel, at the neural level, stability in best friendships in early adolescence but instability in later adolescence is linked to lower EV tracking within the amygdala during decision-making for a best friend. Therefore, changes within adolescents' social world may alter the neurobiological processing of valence information for peers and have implications for how adolescents interact with their peers, in a grade-dependent manner.

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CRediT authorship contribution statement

Kwon Seh-Joo: Conceptualization, Data curation, Formal analysis, Investigation, Writing – original draft. **Prinstein Mitchell J.:** Conceptualization, Funding acquisition, Investigation, Writing – review & editing. **Lindquist Kristen A.:** Conceptualization, Funding acquisition, Investigation, Writing – review & editing. **Telzer Eva H.:** Conceptualization, Funding acquisition, Investigation, Supervision, Writing – original draft.

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.

Data availability

Individual behavioral and neural data from this study are unavailable for access, but codes and outputs for longitudinal whole-brain analyses are available on GitHub.

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Data Statement

Individual behavioral and neural data from this study are unavailable for access because study participants did not consent to the public use of their data, so supporting data is not available. However, codes and outputs for longitudinal whole-brain analyses are available on GitHub (https://github.com/sehjookwon/BFStability_3dlmer).

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