Journal of Experimental Psychology: General

0096-3445/18/$12.00 http://dx.doi.org/10.1037/xge0000389

Consequences for Peers Differentially Bias Computations About Risk Across Development

Katherine E. Powers
Harvard University

Gideon Yaffe
Yale University

Catherine A. Hartley
New York University

Juliet Y. Davidow
Harvard University

Hedy Kober
Yale University

Leah H. Somerville
Harvard University

Adolescents routinely take risks that impact the well-being of the friends they are with. However, it remains unclear when and how consequences for friends factor into decisions to take risks. Here we used an economic decision-making task to test whether risky choices are guided by the positive and negative consequences they promise for peers. Across a large developmental sample of participants ages 12–25, we show that risky decision computations increasingly assimilate friends' outcomes throughout adolescence into early adulthood in an asymmetric manner that overemphasizes protecting friends from incurring loss. Whereas adults accommodated friend outcomes to a greater degree when the friend was present and witnessing these choices, adolescents did so regardless of whether a friend could witness their decisions, highlighting the fundamentality of adolescent social motivations. By demonstrating that outcomes for another individual can powerfully tune an actor's risk tolerance, these results identify a key factor underlying peer-related motivations for risky behavior, with implications for the law and risk-prevention.

Keywords: adolescence, risk, peer influence, decision-making, development

Supplemental materials: http://dx.doi.org/10.1037/xge0000389.supp

Relative to children and adults, adolescents are more likely to take risks in their everyday lives that directly impact their health and well-being (Boyer, 2006; Steinberg, 2008). This disproportionate rate of risky behavior renders adolescents uniquely vulnerable to injury, death (Miniño, 2010) and engagement with the criminal justice system, underscoring the importance of understanding the factors that contribute to decisions to take risks during this phase of life. Empirical and observational studies have further revealed that adolescent risk-taking occurs most often in social groups: adolescents are more likely to drive recklessly (Gardner & Steinberg, 2005; Simons-Morton, Lerner, & Singer, 2005), commit crimes (Zimring, 1998), and use illegal substances (Chassin, Hussong, & Beltran, 2009) when they are with their friends. In the present study, we examined the influence of a novel feature of the

Katherine E. Powers, Department of Psychology and Center for Brain Science, Harvard University; Gideon Yaffe, Department of Psychology and Yale Law School, Yale University; Catherine A. Hartley, Department of Psychology, New York University; Juliet Y. Davidow, Department of Psychology and Center for Brain Science, Harvard University; Hedy Kober, Department of Psychology and Department of Psychiatry, Yale University; Leah H. Somerville, Department of Psychology and Center for Brain Science, Harvard University.

This work was supported by the Oscar M. Ruebhausen Fund at Yale Law School to Hedy Kober and Gideon Yaffe and a National Science Foundation CAREER award (BCS-1452530) to Leah H. Somerville. We are grateful to Peter Sokol-Hessner for modeling guidance; Erik Kastman for technical assistance; Megan Garrad, Gina Falcone, Nadia Haddara, Hannah Shulman, and Stephanie Sasse for help with participant recruitment and testing; and the Affective Neuroscience and Development Lab at Harvard University for helpful discussion. Portions of these data have been presented at annual meetings of the Social and Affective Neuroscience Society, Flux Developmental Cognitive Neuroscience Congress, Society for Personality and Social Psychology, and the Cognitive Neuroscience Society. Study materials and data can be accessed at osf.io/nsyqc. Hedy Kober and Leah H. Somerville share equal authorship. Gideon Yaffe, Hedy Kober, and Leah H. Somerville designed the research; Katherine E. Powers performed the research; Katherine E. Powers, Juliet Y. Davidow, Catherine A. Hartley, and Leah H. Somerville analyzed the data; Katherine E. Powers and Leah H. Somerville wrote the manuscript; and all other authors provided critical comments and revisions. All authors approved the final version of the manuscript for submission.

Correspondence concerning this article should be addressed to Katherine E. Powers, Department of Psychology, Harvard University, Northwest Science Building Room 290.01, 52 Oxford Street, Cambridge, MA 02138. E-mail: kpowers@fas.harvard.edu

social climate surrounding adolescent risky decision contexts—the consequences that choices hold for friends.

Adolescents' risky decisions rarely impact only the decision-maker, as an individual's choices often stand to help or harm the peers they are with. For example, shoplifting for a friend could simultaneously be risky for the actor and beneficial for the friend. Other decision contexts involve the actor taking a risk that has negative consequence for a friend (e.g., taking a friend's car and getting into an accident). Despite the central role of peers in risk-enabling situations during adolescence (Albert, Chein, & Steinberg, 2013; Steinberg, 2008), research on peer influence has not yet evaluated the impact that friend outcomes exert on decisions to take risks across development. As relationships with peers take on heightened importance and individuals become increasingly concerned with gaining acceptance from peers during adolescence (Brown, 2004; Nelson, Leibenluft, McClure, & Pine, 2005), the valuation of friend outcomes when deciding about risk represents a key factor capable of biasing baseline decision-making strategies.

In the current study, we used a behavioral economics approach to quantify the degree to which an individual's willingness to take a risk is guided by whether a friend stands to benefit or suffer from that choice. A large sample of adolescent and young adult participants brought a friend to the lab and completed an economic decision-making task to characterize attitudes toward risk. For some trials, the participant's friend could win or lose money if the participant selected the risky option (Figure 1A). By testing participants with real-life friends, instead of fictitious or anonymous peers, we were able to gain a more naturalistic understanding of the influence friend outcomes impose on risk calculations. Computational models were used to summarize participants' risk preferences, and group analyses tested the extent to which (a) adolescents and young adults exhibited similar or distinct baseline attitudes toward risk, irrespective of friend outcomes, (b) adolescents and young adults became less willing to take risks if their friend would suffer and more likely if their friend would benefit, and (c) decisions made to accommodate friend outcomes were financially strategic or costly.

We also aimed to tease apart possible motivations underlying why a participant's baseline risk preferences would be impacted by friend outcomes. If choices are guided by a desire to impress peers and build reputational status (Brechwald & Prinstein, 2011; Cohen & Prinstein, 2006), then friend outcomes should infiltrate the decision-making process to a greater degree when the friend is able to directly observe the participant's choices (i.e., is made explicitly aware of the behavior). Conversely, if a more implicit or fundamental motivation is at play, such that valuing friend outcomes does not hinge on reputational benefits, then friend outcomes should factor into individuals' choices regardless of whether the peer can observe the choices. We evaluated these explicit and implicit mechanisms by implementing a between-subjects manipulation of peer observation, where the friend either directly observed the participant's decisions (*friend monitoring*), was in the room but could not see the participant's decisions (*friend present*), or was absent from the room (*alone*; Figure 1B).

Method

Participants

A total of 254 participants took part in this study in pairs (N = 91 adolescent pairs; 48 pairs female and 43 pairs male; ages 12.40–18.38 years; N = 36 young adult pairs; 17 pairs female, 18 pairs male and one pair that identified as neither male nor female; ages 21.82–25.97 years). Interested individuals were asked to identify a friend of approximately the same age and gender to bring to the lab as a co-participant. Male and female pairs were distributed evenly across the age range and members of each pair were close in age, reporting an average age difference of 0.50 (SD = 0.40) years. Behavioral data were collected from N = 175 participants, while the role of N = 79 participants was restricted to serving as the "friend." Of these 175 participants, one adolescent

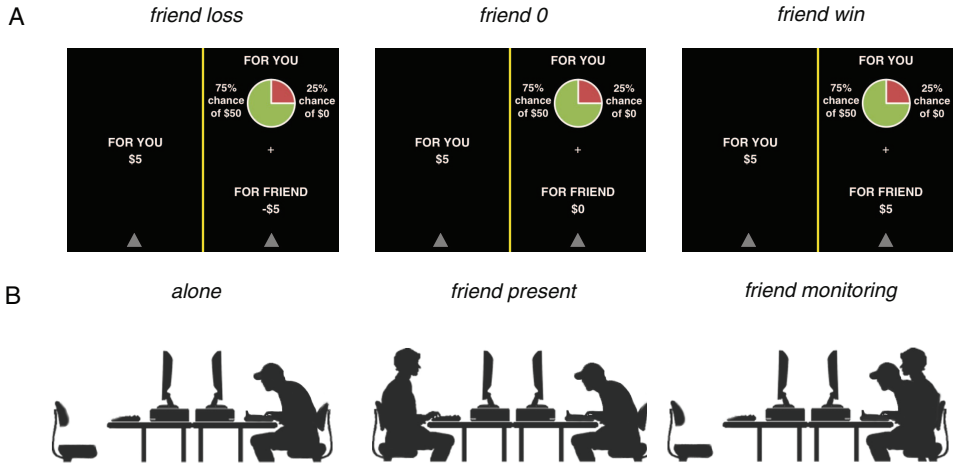

Figure 1. Schematic representation of experimental task. (A) Example trials depicting a choice between a safe option (100% chance of winning $5) and a risky option (75% chance of winning $50, 25% chance of winning $0), with friend loss, friend 0, and friend win outcomes attached to the risky option. (B) Participants were randomly assigned to complete the task in one of three social configurations.

participant was excluded due to failure to understand task instructions and one young adult participant was excluded for failure to complete the task. Additional participants were excluded for issues with model estimation (see Model-Based Estimation of Risk Attitudes). Importantly, these model-based exclusions occurred at a similar rate across the age range. Reported analyses thus reflect data from $N = 145$ participants (103 adolescents and 42 young adults). Sample size was determined prior to data collection based on sample sizes from recent studies assessing differences in risk attitudes between groups of adolescents and adults (Haddad, Harrison, Norman, & Lau, 2014; Jamieson & Mendes, 2016; Tymula et al., 2012) and developmental studies invoking age as a continuous predictor of changes within adolescence (Somerville et al., 2013). While a traditional a priori power analysis could not be conducted because the primary manipulation of friend outcome has not been used in prior work to our knowledge, subsequent power analysis simulations based on parameters of the current study were conducted to quantify observed power (see online supplemental materials). Effect sizes (r) and 95% confidence intervals are reported to guide future work.

In accordance with guidelines specified by the Committee on the Use of Human Subjects at Harvard University, all participants gave informed consent and minor participants also received written permission from a parent or legal guardian prior to participation. Participants received course credit or were paid for their participation. In addition, participants were told that they were playing to earn extra bonus money for both themselves and for their friend, which would total the amount earned on one randomly selected trial at the end of the experiment. In fact, all participants received a fixed amount of bonus money.

Experimental Design and Procedure

Participants completed an economic decision-making task consisting of a series of choices between different monetary options to quantify attitudes toward risk (Chung, Christopoulos, King-Casas, Ball, & Chiu, 2015; Levy, Snell, Nelson, Rustichini, & Glimcher, 2010; Sip, Smith, Porcelli, Kar, & Delgado, 2015; Tymula et al., 2012). This task has been well validated for use in both adolescent (e.g., Tymula et al., 2012) and adult (e.g., Chung et al., 2015; Levy et al., 2010) samples. Each trial presented a choice between a safe option (100% chance of winning \$5) and a risky lottery option (10%, 25%, 50%, 75%, or 90% probability of winning a varying amount of money [\$5, \$10, \$20, \$30, \$40, \$50, \$100]; Tymula et al., 2012). The specific properties of the risky lottery were parametrically varied so that each amount was paired with each probability. A small triangle located below each choice option changed color once a response was made, signaling whether the safe or risky option was chosen. The task was presented using PsychoPy Version 1.80.06.

The task featured two key manipulations designed to examine how social context modulates risk preferences: friend outcome (i.e., friend 0, friend loss, friend win; within-subjects; Figure 1A) and friend observation (i.e., alone, friend present, friend monitoring; between-subjects; Figure 1B). Friend outcome was manipulated by adding a monetary consequence for the coparticipating friend to the risky option presented on each trial, such that if participants selected the risky option, their friend would lose \$5 of bonus money (friend loss), or win \$5 (friend win), with 100% probability. Trials where selecting the risky choice did not impact the friend's bonus money (friend 0) served as a baseline estimate of risk-taking behavior. Participants completed 105 trials (35 trials for friend 0, 35 trials for friend loss, 35 trials for friend win). Trials were presented in a random order, with friend outcomes intermixed, and if a participant did not respond within the time allotted (s) that trial was recycled and presented again at a later time.

Friend observation was manipulated such that pairs of participants were randomly assigned to complete the task in either the alone, friend-present, or friend-monitoring configuration. In the alone configuration, both participants remained in separate testing rooms and completed the task by themselves. In the friend-present configuration, participants were seated in the same testing room, where they completed the task on separate computers, positioned such that neither individual could see the other's computer screen. Behavioral data was acquired from both members of the pair in these conditions. Finally, in the friend-monitoring configuration, participants were seated in the same testing room, and one member of the pair completed the task while the other sat in an adjacent chair, in full view of the computer screen, observing their friend's decisions on the task. In this condition, behavioral data were only acquired from that one member of the pair.

These social configurations were designed based on prior work to isolate two possible motivations underlying peer influence on decision-making. First, if decisions to become riskier are motivated by the goal of building reputational status among peers (Brechwald & Prinstein, 2011; Cohen & Prinstein, 2006), then individuals should show more robust behavioral shifts when being observed by the peer who stands to gain or lose, when they can gain immediate "credit" for their actions relative to conditions in which their choice was not viewable (friend-monitoring effect; friend monitoring compared to friend present and alone). Second, as prior work has shown that adolescents are emotionally reactive to even the most minimal of social evaluative contexts (Somerville et al., 2013), the mere presence of the friend in the room may be sufficient to provoke behavioral changes, even if the friend could not observe the participant's choices. In this case, the mere presence and monitoring conditions (which share the feature of the friend sitting in the room) would evoke greater risky choice than if the participant was alone (friend-presence effect: friend present and friend monitoring compared to alone). When both participants were in the same testing room they were instructed to refrain from talking to each other until the end of the experiment. Detailed instructions and several example trials were presented to all participants at the beginning of the experimental session to ensure comprehension of task parameters and manipulations.

Before beginning the main task, there was a preliminary testing phase in which all participants completed the same choice set in the absence of any social manipulations. This initial set of 35 trials was completed alone in a testing room and did not include friend outcomes, and served to provide an additional, independent assessment of baseline risk preferences to validate the baseline measurements obtained from the friend 0 models. Trials were presented in a random order and if a participant did not respond within the time allotted (16 s), that trial was recycled and presented again at a later time.

At the end of the experimental session, a subset of participants completed a self-report scale measuring risk attitudes (Domain-Specific Risk-Taking Questionnaire; Blais & Weber,

2006) to examine whether knowledge of a friend's risk preferences might modulate choices behavior. These preliminary analyses are presented in the online supplemental materials to guide future work.

Model-Based Estimation of Risk Attitudes

We fit a probabilistic choice model with two free parameters to each participant's choices during the task to quantify individual differences in risk attitudes. Similar risk models have been widely used in prior empirical work to precisely decompose the specific features that give rise to complex decisions (Gilaie-Dotan et al., 2014; Levy & Glimcher, 2011; Levy, Belmaker, Manson, Tymula, & Glimcher, 2012; Levy et al., 2010). The expected utility of each option was modeled using a standard power utility function:

$$\mathrm{EU} = p^{*}v^{\alpha}$$

where v is the dollar amount that can be won, p is the associated probability of winning, and α is the estimated parameter of interest that quantifies the participant's attitude toward risk. In this study, risk is defined as the choice option with the largest variability of outcomes (Kahneman & Tversky, 1984); here, the probabilistic choice depicted by the pie-diagram. People are generally risk averse, displaying a preference for selecting a certain option over a risky option, even if the risky option has a higher potential payoff, or expected value (i.e., combination of monetary value and odds of winning; Glimcher, 2008; Platt & Huettel, 2008). A risk-averse participant, someone who prioritizes certainty over expected value, would have an $\alpha < 1$, and a risk seeking participant, someone who exhibits the opposite preference, would have an $\alpha > 1$. A risk neutral participant would have an $\alpha = 1$, displaying indifference between two options that have the same expected value but different levels of risk.

A maximum likelihood procedure was used to fit each participant's trial-by-trial choice data to a single logistic function, calculating the probability of selecting the risky option based on the estimated expected utilities of the safe and risky options as follows:

$$P(\text{choose risky option}) = \frac{1}{1 + \exp(\mu * (EU_{safe} - EU_{risky}))}$$

where EU_{safe} is the expected utility of the safe option, EU_{risky} is the expected utility of the risky option, and μ is the second estimated parameter which indexes the degree to which a participant's choice behavior reflects rational evaluation of the differential value between the options (i.e., inverse decision noise). Parameter recovery simulations confirmed robust recovery of risk aversion using this model (for model validation and additional model exploration see the online supplemental materials).

Parameters estimating individual attitudes toward risk (α) were estimated from computational models fit to participants' choices for the baseline friend 0 condition and separately for each friend outcome condition (friend loss, friend win). A measure of goodness of fit of the models (pseudo-R^2) was computed by comparing the log-likelihood of the model fit to the observed data against a model fit to a set of random choices, with higher values indicating better fit (Levy & Glimcher, 2011). If a model's R^2 value indicated that participants were choosing randomly and not in a manner consistent with the risk preference model ($n = 21$), or if the model could not fit to the observed data ($n = 3$), individuals were excluded from all analyses (as in Glimcher, 2008; Levy et al., 2010).

The reported modeling procedure characterized behavior well for all participants included in the final sample (median friend 0 models: $R^2 = 0.74$; median friend-loss models: $R^2 = 0.65$; median friend-win models: $R^2 = 0.60$), values consistent with prior work using similar models (Levy & Glimcher, 2011; Levy et al., 2010). Because baseline model fit quality can vary across age and muddy interpretation of developmental differences (Hartley & Somerville, 2015; Van Den Bos, Cohen, Kahnt, & Crone, 2012), we compared fit quality of the friend 0 baseline models across age groups. An independent samples t test conducted on measures of model fit revealed that the models fit adolescent and young adult behavior equally well ($M_{\text{difference}} = 0.05$, 95% CI [−0.01, 0.11]), $t(143) = 1.65$, $p = .102$.

Data Analysis

Analysis of age effects. For all developmental analyses, we tested for age-related changes in risk attitudes specifically within the adolescent sample, utilizing age as a continuous variable to maximize statistical power, following our prior work (Somerville et al., 2013). Then we used the young adult sample as a benchmark comparison group to evaluate whether any observed modulation of friend outcome in the adolescent sample was specific to adolescence or generalized to young adults. Analyses were also conducted within the young adult comparison group to confirm the stability of risky decision-making processes during young adulthood.

Baseline risk attitudes. The friend 0 condition is reported as the baseline against which to evaluate shifts in decision-making that result from considering friend outcomes, as this condition also preserves similarity across the friend observation manipulations. Examining modulation of choice behavior relative to a baseline estimate is important because it allows us to account for individual variation in baseline riskiness. To confirm the suitability of this baseline metric, an additional model was estimated for choices made during the initial testing phase prior to the introduction of any social manipulations. Indeed, choices made during the friend 0 trials were highly consistent with those made during the initial testing phase, evidenced by a strong correlation within participant for estimated α parameters, $r(145) = 0.73$, 95% CI [0.64, 0.80], $p < .001$.

Shifts in risk attitudes evoked by friend outcomes. The key objective of the present study was to determine whether consequences for peers biased computations about risk differentially across development. To evaluate whether individuals become less willing to take risks if their friend would incur a loss, or more willing if their friend would benefit, we computed difference scores for each participant comparing baseline risk aversion parameters (α) to those estimated from the friend-loss and friend-win models. Relative to the participant's baseline risk preferences, negative difference scores demonstrate a shift to greater risk aversion and positive difference scores demonstrate a shift toward risk seeking evoked by potential outcomes for a friend. Examination of the difference scores derived from contrasting baseline α parameters with those estimated in the friend-loss or friend-win conditions revealed data points from four individuals that qualified as

statistical outliers (defined as ±3 *SD* from the mean; Sokol-Hessner, Camerer, & Phelps, 2013). While these scores were outliers in the predicted direction, out of an abundance of caution, these individuals were excluded from all analyses.

Costs to participant. To determine whether these shifts in risky choice yielded tangible financial consequences for the participant, we calculated the total amount of money each participant would have earned based on the expected value of each choice assuming every trial had counted for payment (Tymula, Rosenberg Belmaker, Ruderman, Glimcher, & Levy, 2013) separately for the three friend outcome conditions. Baseline expected earnings were subtracted from expected earnings tabulated for the friend-loss and friend-win trials, again to account for baseline decision-making strategies. These difference scores quantified the financial "costs" of shifting to accommodate friend outcomes, with negative difference scores reflecting money lost and positive difference scores reflecting money gained.

Moderation by friend observation. To evaluate potential motivations underlying these shifts in risk attitudes, a priori contrasts of the social configurations were implemented to directly test for modulatory effects of direct peer observation (friend-monitoring effect: friend monitoring compared to friend present and alone; Brechwald & Prinstein, 2011; Cohen & Prinstein, 2006) and effects for which the mere presence of a peer in the room was sufficient (friend-presence effect: friend present and friend monitoring compared to alone; Somerville et al., 2013). Given the role of these manipulations as moderators of our primary findings, reported results focus on interactions with the age–risk-aversion effects.

Decision strategy guiding friend outcome-based choices. Finally, to complement the model-based analyses of risk attitudes, we conducted additional regression analyses to examine *how* the underlying cognitions about friend outcomes guide decision-making. We hypothesized that outcomes for a friend may infiltrate decision making via representations of a shared expected value. In other words, do participants utilize a *joint expected value* (EV) when considering taking a risk, and does this integration of friend outcome change with age? Two separate trial-by-trial binomial regression models were built for each participant, a *solo-EV model* using the expected value of the risky option to predict choice, and a *joint-EV model* using a recomputed expected value incorporating the friend outcome amount (−$5 or +$5) into the calculation of the risky option to predict choice. We compared estimates of model fit (pseudo-R^2, which is equivalent to the proportion of variance explained by that model relative to a null model; Levy et al., 2012) to assess whether the joint-EV model predicted choice behavior better than the solo-EV model. Difference scores comparing model fits were computed for each participant, with positive scores indicating a better fit of the joint-EV model relative to the solo-EV model, to allow for analyses of age-dependent changes in this decision strategy.

General analysis approach. Because friends were recruited in pairs, all data points in our sample are not fully independent. Although full dyadic data exist for 31 out of 114 pairs (27.2%) included in the final sample due to counterbalancing and exclusions, this dependence between members of a friend pair violates the assumptions that each observation is independent. Hence, we conducted all analyses within the framework of mixed-effects models to account for potential dependencies within dyads. Mixed-effects models were employed using the lme4 and lmerTest packages in R (www.r-project.org; Bates, Maechler, Bolker, & Walker, 2014; Kuznetsova, Brockhoff, & Christensen, 2014; R Core Team, 2014). Separate models were constructed to test for effects of age on changes in (a) risk aversion, (b) expected earnings, and (c) expected value computations. All participants were assigned a dyad number (with members of the same dyad having the same number) and this variable was specified as a random effect. This "nested" data structure appropriately accounted for potential dependencies within dyads. For analyses within either the adolescent or young adult sample testing for continuous age-related changes, age was included as a mean-centered linear predictor. For analyses comparing adolescents to young adults, age group was specified as a between-subjects factor. For secondary analyses examining the modulatory role of the friend observation, friend-monitoring and friend-presence contrasts were entered as between-subjects fixed effects. Parameter estimates (*B*) are reported in unstandardized units.

Results

Baseline Risk Attitudes

Consistent with previous work showing that people typically tend to be averse to risk (Blankenstein, Crone, van den Bos, & van Duijvenvoorde, 2016; Gilaie-Dotan et al., 2014; Kahneman & Tversky, 1979; Levy et al., 2010; Pratt & Zeckhauser, 1987; Tymula et al., 2012), most participants in our sample exhibited a baseline level of risk aversion (average α for all participants = 0.49, *SD* = 0.26). Throughout adolescence, there was an upward shift in baseline risk-seeking ($B = 0.05$, 95% CI [0.02, 0.08], $p < .001$, effect size $r = .33$), with increasing age from 12 to 18 years old associated with less risk aversion (i.e., more tolerance for risk). This uptick in risky choice leveled off into adulthood, indicated by equivalent estimates of risk aversion across the grouped adolescent ($M = 0.490$, $SD = 0.32$) and young adult samples ($M = 0.487$, $SD = 0.23$; $B = 0.003$, CI [−0.09, 0.10], $p = .951$, $r = .005$; Figure S1) and stable estimates of risk aversion within the young adult sample ($B = -0.05$, CI [−0.13, 0.04], $p = .313$, $r = .16$). These findings suggest that while risk tolerance rose during adolescence, overall levels of risk tolerance were comparable across the entire sample.

Analysis of friend 0 expected earnings revealed participants consistently selected options that yielded the greatest payoff (average simulated earnings amounted to $594.86 out of a maximum $662.50 possible). Performance was comparable for adolescents and young adults, indicated by equivalent estimated earnings across age groups ($B = 22.79$, 95% CI [−6.29, 52.07], $p = .128$, $r = .16$). However, the ability to maximize earnings improved from early adolescence through age 18 ($B = 13.12$, 95% CI [5.37, 20.87], $p = .001$, $r = .34$), suggesting that the capacity to choose according to economic expected value improves over the course of development.

Developmental Shifts in Risk Aversion Evoked by Friend Loss

All participants showed heightened levels of risk aversion when faced with the prospect of friend loss relative to baseline levels

($B = -0.25$, 95% CI [−0.30, −0.19], $p < .001$, $r = .48$). The magnitude of this shift toward risk aversion increased throughout adolescence ($B = -0.04$, 95% CI [−0.06, −0.02], $p < .001$, $r = .34$; Figure 2A). Comparison of adolescent and young adult difference scores revealed no differences ($B = -0.003$, 95% CI [−0.07, 0.07], $p = .932$, $r = .007$), indicating that young adults similarly shied away from risk to guard against friend loss. This shift in risk attitudes amounted to adolescents switching their choice to the safe option (relative to the matched friend 0 trial) 20.3% of the time, whereas young adults switched responses at a similar rate, on 18.5% of trials. Moreover, this pattern of decision-making in the young adults was consistent across all ages ($B = -0.01$, 95% CI [−0.07, 0.05], $p = .777$, $r = .05$). Taken together, these findings show that across adolescence, individuals became less likely to take risks if those choices negatively impact a friend, a behavioral tendency that similarly biased young adults' decision-making processes.

Figure 2B shows that participants forfeited a large amount of money to safeguard against friend loss. Analyses of expected earnings revealed that this was a significant monetary loss relative to baseline expected earnings for both the adolescents ($B = -100.22$, 95% CI [−117.67, −82.77], $p < .001$, $r = .62$) and young adults ($B = -95.54$, 95% CI [−127.61, −63.47], $p < .001$, $r = .54$). That is, on average adolescents and young adults gave up \$100.22 and \$95.54, respectively, to protect their friends. This pattern was consistent across development, with no differences within adolescents ($B = -5.91$, 95% CI [−18.98, 7.17], $p = .378$, $r = .09$) or between adolescent and young adult age groups ($B = -4.68$, 95% CI [−40.99, 31.63], $p = .801$, $r = .02$).

We evaluated modulatory effects of direct peer observation (friend-monitoring effect: friend monitoring compared to friend present and alone) by testing for interactions between the effects of age and friend-monitoring condition on changes in risk aversion during friend loss. We did not observe a significant Age × Friend Monitoring interaction within the adolescent sample ($B = 0.009$, 95% CI [−0.04, 0.06], $p = 0.682$, $r = .04$) or when testing for group differences across the adolescents and young adults ($B = 0.06$, 95% CI [−0.09, 0.20], $p = 0.466$, $r = .06$). Likewise, the mere presence of the friend (friend-presence effect: friend present and friend monitoring compared to alone) was not sufficient to modulate age-related shifts in risky choice in the context of friend loss. There was not a significant Age × Friend Presence interaction within the adolescent sample ($B = 0.02$, 95% CI [−0.03, 0.07], $p = 0.403$, $r = .08$) or a significant Age × Friend Presence interaction comparing across adolescent and young adult samples ($B = 0.09$, 95% CI [−0.05, 0.24], $p = 0.201$, $r = .11$). Thus, at all ages participants protected their friends from loss to an equivalent extent irrespective of whether the friend was out of the room, in the room, or actively monitoring the participant's choices. Descriptive statistics summarizing behavior separately for the three friend observation conditions comprising these contrasts (i.e., alone, friend present, and friend monitoring) are provided in the online supplemental materials.

Developmental Shifts in Risk Aversion Evoked by Friend Win

In contrast, the prospect of a friend winning promoted greater overall risk seeking relative to baseline across all participants ($B = 0.22$, 95% CI [0.17, 0.27], $p < .001$, $r = .44$). Figure 3A shows that older adolescents were more willing to take risks relative to baseline preferences when their friend stood to benefit from that choice than younger adolescents ($B = 0.03$, 95% CI [0.01, 0.06], $p = .019$, $r = .25$). Interestingly, this trend became more prominent in young adults, who demonstrated a greater shift toward riskiness than adolescents ($B = -0.22$, 95% CI [−0.32, −0.11], $p < .001$, $r = .32$). Examination of the frequency with which participants switched to select the risky option relative to the safe

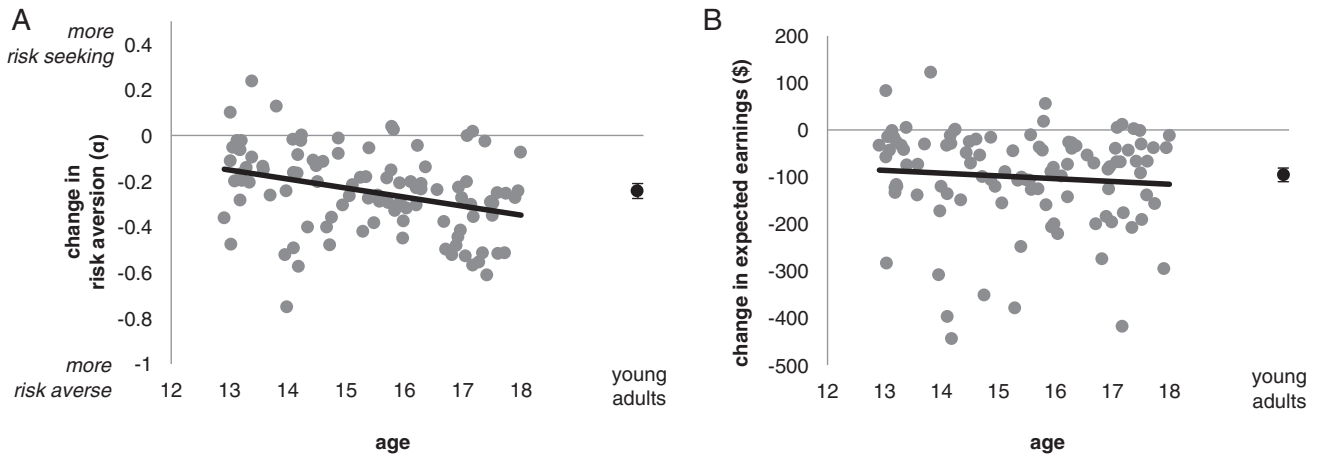

Figure 2. Behavioral shifts in the context of friend loss. (A) Scatterplot depicting shifts toward greater risk aversion in adolescent participants evoked by the prospect of a friend losing, plotted as a function of changes in risk aversion parameters (α) in the friend-loss condition relative to baseline estimates of risk aversion obtained from friend 0 models. Mean young adult behavior is plotted as a single reference point (bars indicate standard error of the mean). (B) Scatterplot depicting the amount of money adolescent participants forfeited to protect against friend loss relative to baseline choices. Mean young adult earnings are plotted as a single reference point (bars indicate standard error of the mean).

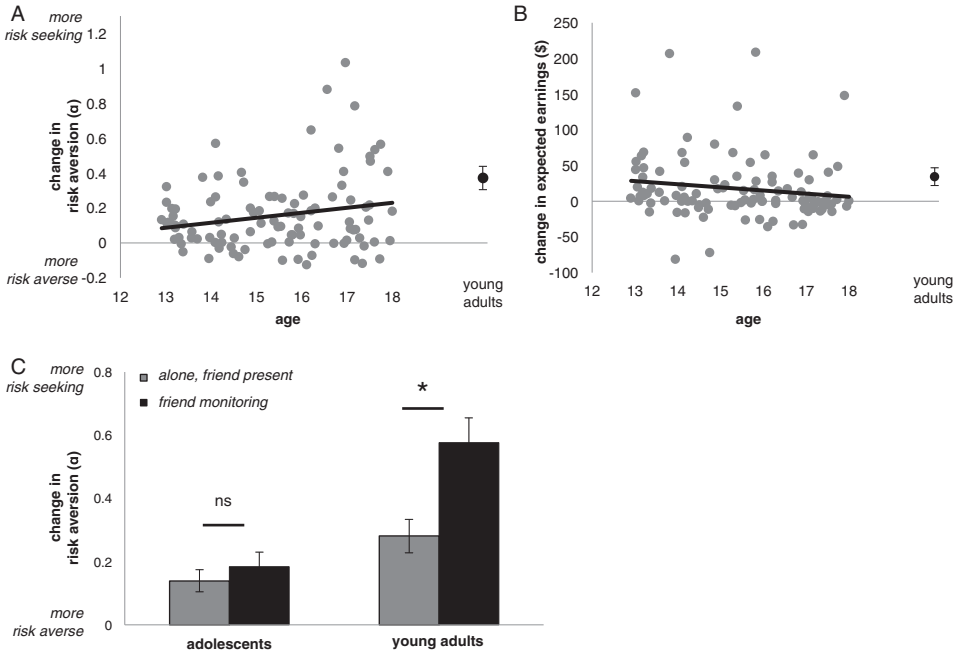

Figure 3. Behavioral shifts in the context of friend win. (A) Scatterplot depicting shifts toward greater risk seeking in adolescent participants evoked by the prospect of a friend winning, plotted as a function of changes in risk aversion parameters (α) in the friend-win condition relative to baseline estimates of risk aversion obtained from friend 0 models. Mean young adult behavior is plotted as a single reference point (bars indicate standard error of the mean). (B) Scatterplot depicting the amount of money adolescent participants gained while facilitating a friend's win, relative to baseline choices. Change in mean young adult earnings is plotted as a single reference point (bars indicate standard error of the mean). (C) Direct peer observation enhanced young adults' risk seeking to facilitate a friend's win, whereas adolescent participants behaved uniformly across peer contexts. Bars indicate standard error of the mean. * $p < .05$.

option on the matched friend-win trials revealed that adolescents and young adults shifted toward the risky option on 14.3% and 19.2% of trials, respectively. Again, no age-related changes were observed within the young adult range ($B = 0.02$, 95% CI [−0.10, 0.14], $p = .742$, $r = .05$).

Figure 3B shows that shifts toward greater riskiness induced by the prospect of a friend winning money was financially profitable for all participants, though the magnitude and prevalence of this change was less robust than in the friend-loss condition. This was a significant monetary increase relative to baseline choices, amounting to an average gain of $17.62 for the adolescents ($B = 17.62$, 95% CI [0.17, 35.07], $p = .049$, $r = .14$) and $34.40 for the young adults ($B = 34.40$, 95% CI [2.33, 66.47], $p = .039$, $r = .23$). When the friend stood to gain we again found no significant age-related differences within the adolescents ($B = -4.29$, 95% CI [−10.03, 1.47], $p = .147$, $r = .15$) or at the group level between the adolescents and young adults ($B = -17.01$, 95% CI [−38.16, 4.05], $p = .117$, $r = .16$). Thus, although participants at different developmental stages demonstrated a difference in their rate of shifting choices to accommodate friends' outcomes, they did so in a way that was equivalent in its impact on their own earnings.

Finally, we tested whether shifts toward greater riskiness to facilitate friend gain were modulated by the friend's presence differentially across development. Including friend-monitoring condition and age as predictors of changes in risk aversion revealed that being observed by a friend (friend-monitoring effect) did not alter decisions when a friend stood to gain for the adolescents (Age × Friend Monitoring interaction: $B = 0.03$, 95% CI [−0.03, 0.09], $p = 0.294$, $r = .11$). However, comparing adolescents to young adults revealed a significant Age Group × Friend Monitoring interaction ($B = -0.25$, 95% CI [−0.47, −0.03], $p = 0.027$, $r = .19$; see Figure 3C). Post hoc comparisons demonstrated that young adults made riskier choices relative to baseline when the friend who stood to benefit witnessed their decisions ($B = 0.29$, 95% CI [0.02, 0.57], $p = 0.040$), whereas adolescent behavior was consistently riskier regardless of the physical location of the friend ($B = 0.04$, 95% CI [−0.05, 0.13], $p = 0.388$; see Figure 3C). Additional targeted post hoc analyses directly comparing behavior across each of the three friend observation conditions (i.e., alone, friend present, and friend-monitoring conditions) yielded the same pattern of results (see the online supplemental materials for descriptive statistics and results). The mere presence of the friend (friend-presence effect) was not sufficient to alter risky choice behavior within the adolescent sample (Age × Friend Presence interaction ($B = 0.03$, 95% CI [−0.03, 0.10], $p = 0.283$, $r = .12$) or across the adolescent and young adult groups (Age Group × Friend Presence interaction: $B = -0.11$, 95% CI [−0.33, 0.10], $p = 0.303$, $r = .09$).

Decision Strategy Guiding Friend Outcome-Based Choices

To determine whether individuals relied on calculations of their own expected value or a joint expected value representation that included friend outcomes, we examined which of these measures better predicted risky choice for each participant using separate binomial regressions. Across the sample as a whole, analysis of model fit parameters (pseudo-R^2) derived from each regression revealed that the joint-EV model explained choice behavior better than the solo-EV model for all participants ($B = 0.07$, 95% CI [0.06, 0.09], $p < .001$, $r = .63$). Figure 4 shows that the improvement generated by the joint-EV model increased with age throughout adolescence ($B = 0.02$, 95% CI [0.01, 0.03], $p = .002$, $r = .31$), although adolescents and young adults overall utilized joint expected value to the same degree ($B = -0.02$, 95% CI [−0.05, 0.01], $p = .221$, $r = .10$). These results show that individuals become more likely to absorb friend outcomes into their expected value calculations to guide choice throughout adolescence, and this strategy persists into adulthood.

To the extent that direct friend observation differentially impacts risky decision making across development, as suggested by the model-based analyses described above, we hypothesized that there might also be age-related differences in the degree to which expected value computations reflect joint outcomes if the friend is watching (friend-monitoring effect). Indeed, analysis of model fits revealed that young adults incorporate friend outcomes into expected value calculations to a greater degree when the friend could see their choices (Trend-Level Age × Friend Monitoring interaction, $B = -0.06$, 95% CI [−0.13, 0.003], $p = .064$, $r = .16$). Post hoc comparisons revealed that the joint-EV model better explained choice behavior for the young adults when the friend was watching ($B = 0.07$, 95% CI [0.005, 0.14], $p = .042$), whereas adolescent value calculations consistently integrated friend outcomes across the friend contexts ($B = 0.01$, 95% CI [−0.02, 0.04], $p = .546$). Within the adolescent sample, the Age × Friend Monitoring interaction was not significant ($B = -0.006$, 95% CI [−0.03, 0.01], $p = .542$, $r = .06$).

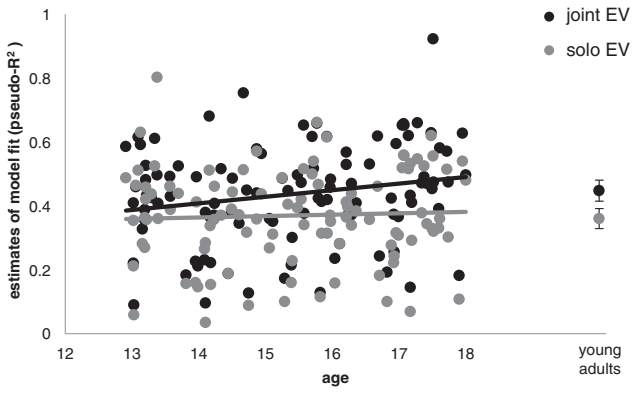

Figure 4. Decision strategy underlying friend-outcome based choices. Scatterplot showing estimates of model fit (pseudo-R^2) derived from regressions using the expected value (EV) of the risky option to predict choice (solo EV) and a recomputed expected value incorporating the friend outcome amount into the expected value calculation of the risky option (joint EV). Each adolescent participant is represented by two points. Mean young adult fits for both models are plotted as single reference points (bars indicate standard error of the mean).

Analysis of Peer Effects on Baseline Risk Attitudes

Though not the primary focus of the present study, features of the design permit tests for replication of basic peer observation effects on adolescent risky-decision making in the absence of friend outcomes, as has been a focus of prior work (e.g., Cavalca et al., 2013; Chein, Albert, O'Brien, Uckert, & Steinberg, 2011; Gardner & Steinberg, 2005; Ouimet et al., 2013). We aimed to replicate prior findings demonstrating that peer monitoring increases risky choices (for oneself) more in adolescents than adults (Chein et al., 2011; Gardner & Steinberg, 2005;). This analysis thus examined whether risk baseline attitudes were modulated by direct peer observation (friend-monitoring effect) or by the mere presence of a peer in the room (friend-presence effect). Risk attitudes were assessed by comparing risk aversion parameters (α) estimated from friend 0 models to those estimated from choices made during the initial testing phase prior to the implementation of any social manipulations, to equate across individual differences.

A mixed-effects model within the adolescent sample using age and friend-monitoring condition to predict changes in risk aversion was conducted to test for moderating effects of direct friend observation (friend-monitoring effect) on risky choice. This analysis did not yield a significant Age × Friend Monitoring interaction ($B = -0.03$, 95% CI [−0.08, 0.02], $p = .322$, $r = .11$). Comparing across adolescent and young adult groups similarly yielded no significant interaction ($B = 0.04$, 95% CI [−0.10, 0.18], $p = .556$, $r = .05$). Likewise, the mere presence of a friend (friend-presence effect) was not sufficient to modulate age-related shifts in baseline risk preferences. There was not a significant Age × Friend Presence interaction within the adolescent sample ($B = -0.02$, 95% CI [−0.07, 0.03], $p = .519$, $r = .08$) or a significant Age × Friend Presence interaction comparing across adolescent and young adult samples ($B = -0.03$, 95% CI [−0.17, 0.11], $p = .672$, $r = .05$). Thus, whether the friend was out of the room, in the room, or actively monitoring the participant's choices had no measurable impact on participants' baseline risk preferences in the present study.

Discussion

Understanding how adolescents reason about and decide to take risks has critical implications spanning scientific, legal and health policy domains. In this study, we applied an economic decision framework to test the hypothesis that outcomes for a friend are a key factor guiding adolescents' decisions to take risks. Computational analysis of trial-by-trial choice behavior revealed that individuals became more attuned to friend outcomes throughout adolescence and into adulthood, folding them into the expected value of their own decisions when choosing whether or not to take a risk.

Recent work leveraging mathematical approaches from behavioral economics to decompose complex decisions into component parts (e.g., Levy et al., 2010; Tymula et al., 2012) has made critical advances in identifying the decision contexts and task features that underlie similarities and differences in risk-taking across ages. Capitalizing on this approach, in the present study we observed an uptick in baseline risky choice throughout adolescence, stabilizing

into adulthood. Although adolescence is commonly characterized as a time of heightened risk taking, prior work assessing developmental differences in risk attitudes has yielded mixed effects. While some studies report adolescent-specific peaks in risky decision-making (Reyna et al., 2011; Van Leijenhorst et al., 2010), others note no differences across ages (Barkley-Levenson, Van Leijenhorst, & Galván, 2013; Van Leijenhorst, Westenberg, & Crone, 2008). Others even show that adolescents are more averse than adults to clearly stated risks (Tymula et al., 2012). Because adolescents may make especially risky choices when immediate feedback about task performance is provided (Defoe, Dubas, Figner, & van Aken, 2015), it is possible that we did not observe an adolescent peak in riskiness in the present study because feedback was withheld until the end of the experiment. Collectively this work underscores the importance of pinpointing the specific psychological features of the decision space that give rise to age-related peaks in risky choice.

Both adolescents and young adults demonstrated robust sensitivity to friend outcomes when evaluating risky choices, becoming less willing to take a risk if their friend might suffer and more willing if their friend might benefit. Although adolescence is characterized as a time of heightened sensitivity to the social environment and increased concern with gaining peer acceptance (Brown, 2004; Somerville, 2013), our findings demonstrate that the prospect of a friend winning or losing is powerful enough to equivalently bias decision-making processes in young adults. This aligns with prior work showing that adults are less willing to make a risky choice if that choice would expose a partner to a monetary loss (Arfer, Bixter, & Luhmann, 2015). The present study thus extends knowledge of how peer outcomes guide risky decision-making across development by highlighting similarity in the degree to which adolescents and young adults are susceptible to weighing both the negative and positive consequences risky choices hold for their friends.

Within adolescence we observed a developmental shift in attunement to peer outcomes, with older adolescents placing adult-like levels of emphasis on the outcomes of a friend when deciding about risk. While younger adolescents tended to make decisions about risk based on evaluation of their own prospects, older teens integrated a friend's outcome into their own calculations of the value of a risk, altering choice. Having established these patterns of behavior, future research will be needed to pinpoint the developmental mechanisms underlying this effect. Here, we offer several possibilities, informed by prior work. One possibility is that increases in mathematical reasoning abilities (Demetriou, Platsidou, Efklides, Metallidou, & Shayer, 1991; Susac, Bubic, Vrbanc, & Planinic, 2014) support the more complex computational demands of factoring in the joint outcomes inherent to the friend win and loss trials. It is also possible that with age, prosocial motivations intensify (Crone & Dahl, 2012; Güroğlu, van den Bos, & Crone, 2014), rendering consequences for friends more salient and motivating to older than younger adolescents. A third possibility is that perspective-taking abilities continue to improve across adolescence (Choudhury, Blakemore, & Charman, 2006; Dumontheil, Apperly, & Blakemore, 2010), supporting richer consideration of a friend's reaction to gains and losses and enhanced incorporation of friend outcomes into one's own choices.

The observed shifts in risk attitudes yielded financial consequences for individuals of all ages, as participants sacrificed their own money to safeguard against friend loss and secured financial gains to help a friend win. Though we observed differences in both the friend win and loss contexts, the magnitude of financial loss when participants shied away from risk to protect a friend was more robust. Research has shown that human behavior reflects a heightened sensitivity to the prospect of losses relative to gains of the same magnitude (Tversky & Kahneman, 1992). These findings suggest that the motivation to protect against friend loss may lower the threshold individuals apply to incurring a personal loss, ultimately leading to choices that are less personally beneficial. In contrast, engaging in risk to help a friend win yielded financial gains. Though these gains were more modest in scope, this result indicates that the motivation to help a friend win is sufficient to nudge individuals to behave in less risk-averse ways that may ultimately yield more optimal outcomes for themselves.

Age-asymmetric patterns were also observed across the two friend outcome contexts, as the shifts toward risk seeking displayed by young adults became more pronounced if a friend would benefit from that choice. That young adults were especially responsive to the prospect of helping a friend win is consistent with research showing robust reward-related neural responses when adults win money for or in conjunction with a friend (Braams, Peters, Peper, Güroğlu, & Crone, 2014; Fareri, Niznikiewicz, Lee, & Delgado, 2012), and higher subjective ratings of excitement for these experiences relative to earning money for an unknown individual (Fareri et al., 2012). Moreover, this boost was particularly robust under direct friend monitoring—when the decision-maker could reap reputational benefits. This tendency suggests that decisions to become more risky in adulthood may derive from a strategic desire to strengthen social bonds or otherwise impress friends (Brechwald & Prinstein, 2011; Steinberg, 2008). Indeed, prior work has shown similar upticks in adult riskiness when a peer is watching in the context of a simulated driving game (Gardner & Steinberg, 2005).

Conversely, adolescents behaved uniformly across all friend observation contexts, suggesting that the motivation to tune risk preferences to maximize peer outcomes is operating even if the friend did not witness the choices. Though speculative, the consistency with which adolescents accommodate their friends' outcomes could reflect "purer" social motivations held by adolescents compared to young adults, who accommodate friends to a greater degree when the friend is watching. From this perspective, adolescents may represent the value of friends' outcomes in a more fundamental way that does not hinge on reputational gains. This mindset could help adolescents skillfully adapt to dynamically evolving social environments and consistently behave in ways that are highly aligned with their goals of social belongingness (Crone & Dahl, 2012; Hartley & Somerville, 2015). More generally, these results illuminate key developmental differences in the strategies underlying decision-making about peer outcomes under risk. Whereas young adults orient toward friend outcomes more strongly in the presence of a friend, adolescents may be implicitly motivated to make decisions that accommodate friend outcomes regardless of whether or not the friend is able to witness their choices in the moment. That young adult value computations are suggestive of greater integration of friend outcomes specifically when the friend is watching, while adolescents exhibit consistent

valuation of friend outcomes across social contexts in their calculations, provides converging evidence in support of this interpretation.

The present study demonstrates that consideration of friend outcomes biases computations about choosing to engage in risk across development. Our results also raise key open questions to guide future work. For example, it will be important to understand how the magnitude of the value of the friend outcome amount interacts with baseline decision-making strategies. Varying the friend outcome amount could also allow for the development of novel computational models aimed at parameterizing the role of peer consequences in risky decisions. In the current study, we chose to use well-validated models as a tool to quantify risk aversion, but future work could aim to incorporate social aspects of the decision context into a model. Related to this idea, Chung and colleagues (2015) recently observed how in adults, knowing how peers would choose between differentially risky options had the power to sway an individual's decisions. However, the psychological processes captured by their social utility parameter—the degree to which observing the choices of peers contributes to the participant's own choice—is conceptually distinct from the value given to the outcome for the peer, the key aspect of peer influence reported in the current study. While it is not yet understood how these various facets of peer influence collectively weigh on decisions to commit risks, the current findings offer a broader framework in which to study different dimensions of peer-related motivations in adolescent decision-making. Moreover, the concept of "peer influence" is conceptualized broadly in the literature, referring to a diverse range of peer-related processes such as displaying risk-permissive norms (Ouimet et al., 2013), providing explicit advice (Van Hoorn, Crone, & Van Leijenhorst, 2017), observing choices (Gardner & Steinberg, 2005; Chein et al., 2011) and inducing social evaluative stress (Jamieson & Mendes, 2016). The similarities and differences of the social factors included across these paradigms underscore the importance of considering the precise functions of peers when evaluating the reliability and specificity of peer effects.

Conducting integrative studies about friend pairs to better understand the dyadic processes and dynamics that give rise to shifts in risk attitudes will also be an important direction for future work. Given recent work emphasizing the interpersonal nature of emotion regulation (Rimé, 2007; Zaki & Williams, 2013) and capacity for physiological convergence with a social partner's emotional state (Waters, West, & Mendes, 2014), it would be interesting to examine emotional coregulation between members of the dyads in risky decision contexts. Relatedly, it is possible that adolescents and adults subjectively experience or interpret the mere presence of friends differently when facing decisions about risk. Collecting data cataloguing these appraisals, for example through targeted posttask interviews or coding of dyadic behaviors via video recordings, could provide key insights into developmental differences in the internal representations of the social elements of decision contexts. Researchers could also collect measures of social preference (e.g., guilt aversion; empathic accuracy) and social status (e.g., relative popularity) to identify the individual and developmental differences that give rise to more prosocial or more individualistic choices when friend outcomes are on the line. Although we did not acquire data to address these questions in the present study, we note that the increased importance of social hierarchies in adolescence relative to adulthood (Cillessen & Rose, 2005) points to the utility of examining power differentials between friend pairs as a factor that may more strongly shape risky decisions that impact friends during adolescence. Finally, as coparticipants in the present study were all friends self-selected by the participants, in contrast to other studies using fictitious online peers or matching participants with unknown same-aged partners, it will be important for future work to evaluate whether the effects reported here extend to other types of peers as well. Humans are known to show generosity toward unrelated individuals and even strangers (Bereczkei, Birkas, & Kerekes, 2010), suggesting that the tendency to factor the outcomes of others into decisions may extend beyond the context of existing friendships. Additional research will be necessary to identify the specific relationship qualities and decision contexts that give rise to peer-oriented decision-making.

The findings of the present study indicate that adolescents' decisions about risk are dependent, in part, on the benefits and costs those choices hold for friends. We show that decision computations increasingly assimilate friends' outcomes with age, in an asymmetric way that emphasizes protecting friends from incurring loss, even at the expense of personal profit. Uncovering the emerging reliance on friend outcomes across development represents a key theoretical advance in characterizing adolescents' underlying motivation to take risks. That adolescents maximize their friends' outcomes even when the friends are not present to witness those choices reveals a unique fundamentality of social motivations in this phase of life. More generally, these findings reveal how outcomes for another individual can powerfully tune an actor's tolerance toward risk.

Context of the Research

In recent years, the Supreme Court has cited adolescents' susceptibility to peer influence as a reason to shield them from the harshest punishments for terrible crimes, assuming that in the presence of peers adolescents make decisions in ways that are different from adults, and imply lessened culpability. This research, a collaboration between psychological scientists and legal scholars, aims to test this assumption through the specification of the motivations that could underlie adolescents' tendency to commit criminal acts in the presence of peers. On the one hand, because older adolescents and adults both factor in friend outcomes when computing risk to a similar degree, this suggests that, in that one respect, the Supreme Court's assumption is false: adolescents are not in this way different from adults. On the other hand, the tendency for adolescents and adults to factor in peer outcomes differed depending on whether the peer was actively monitoring the choice, implying that distinct underlying motivations could drive risky choices when peers are actively monitoring criminal acts. Further work is required to determine whether this difference speaks to lessened culpability on the part of adolescents. Therefore, our findings suggest that further research should proceed with an attitude of openness toward the possibility that social motivations influence risky decisions in adolescents similarly to adults in some situations, but differently in others. Within the justice system, incorporating peers' roles in criminal contexts is too complex to be captured by a simple heuristic.

References

Albert, D., Chein, J., & Steinberg, L. (2013). The teenage brain: Peer influences on adolescent decision making. *Current Directions in Psychological Science, 22,* 114–120. http://dx.doi.org/10.1177/0963721412471347

Arfer, K. B., Bixter, M. T., & Luhmann, C. C. (2015). Reputational concerns, not altruism, motivate restraint when gambling with other people's money. *Frontiers in Psychology, 6,* 848. http://dx.doi.org/10.3389/fpsyg.2015.00848

Barkley-Levenson, E. E., Van Leijenhorst, L., & Galván, A. (2013). Behavioral and neural correlates of loss aversion and risk avoidance in adolescents and adults. *Developmental Cognitive Neuroscience, 3,* 72–83. http://dx.doi.org/10.1016/j.dcn.2012.09.007

Bates, D., Maechler, M., Bolker, B., & Walker, S. (2014). *lme4: Linear mixed-effects models using Eigen and S4* (R package Version 1.1–7). Retrieved from https://cran.r-project.org/web/packages/lme4/index.html

Bereczkei, T., Birkas, B., & Kerekes, Z. (2010). Altruism towards strangers in need: Costly signaling in an industrial society. *Evolution and Human Behavior, 31,* 95–103. http://dx.doi.org/10.1016/j.evolhumbehav.2009.07.004

Blais, A.-R., & Weber, E. U. (2006). A domain-specific risk-taking (DOSPERT) scale for adult populations. *Judgment and Decision Making, 1,* 33–47.

Blankenstein, N. E., Crone, E. A., van den Bos, W., & van Duijvenvoorde, A. C. (2016). Dealing with uncertainty: Testing risk-and ambiguity-attitude across adolescence. *Developmental Neuropsychology, 41,* 77–92. http://dx.doi.org/10.1080/87565641.2016.1158265

Boyer, T. W. (2006). The development of risk-taking: A multi-perspective review. *Developmental Review, 26,* 291–345. http://dx.doi.org/10.1016/j.dr.2006.05.002

Braams, B. R., Peters, S., Peper, J. S., Güroğlu, B., & Crone, E. A. (2014). Gambling for self, friends, and antagonists: Differential contributions of affective and social brain regions on adolescent reward processing. *NeuroImage, 100,* 281–289. http://dx.doi.org/10.1016/j.neuroimage.2014.06.020

Brechwald, W. A., & Prinstein, M. J. (2011). Beyond homophily: A decade of advances in understanding peer influence processes. *Journal of Research on Adolescence, 21,* 166–179. http://dx.doi.org/10.1111/j.1532-7795.2010.00721.x

Brown, B. B. (2004). Adolescents' relationships with peers. In R. M. Lerner & L. Steinberg (Eds.), *Handbook of adolescent psychology* (2nd ed., pp. 363–394). New York, NY: Wiley. http://dx.doi.org/10.1002/9780471726746.ch12

Cavalca, E., Kong, G., Liss, T., Reynolds, E. K., Schepis, T. S., Lejuez, C. W., & Krishnan-Sarin, S. (2013). A preliminary experimental investigation of peer influence on risk-taking among adolescent smokers and non-smokers. *Drug and Alcohol Dependence, 129,* 163–166. http://dx.doi.org/10.1016/j.drugalcdep.2012.09.020

Chassin, L., Hussong, A., & Beltran, I. (2009). Adolescent substance use. In R. M. Lerner & L. Steinberg (Eds.), *Handbook of adolescent psychology: Vol. 1. Individual bases of adolescent development*. Hoboken, NJ: Wiley.

Chein, J., Albert, D., O'Brien, L., Uckert, K., & Steinberg, L. (2011). Peers increase adolescent risk taking by enhancing activity in the brain's reward circuitry. *Developmental Science, 14,* F1–F10. http://dx.doi.org/10.1111/j.1467-7687.2010.01035.x

Choudhury, S., Blakemore, S. J., & Charman, T. (2006). Social cognitive development during adolescence. *Social Cognitive and Affective Neuroscience, 1,* 165–174. http://dx.doi.org/10.1093/scan/nsl024

Chung, D., Christopoulos, G. I., King-Casas, B., Ball, S. B., & Chiu, P. H. (2015). Social signals of safety and risk confer utility and have asymmetric effects on observers' choices. *Nature Neuroscience, 18,* 912–916. http://dx.doi.org/10.1038/nn.4022

Cillessen, A. H. N., & Rose, A. J. (2005). Understanding popularity in the peer system. *Current Directions in Psychological Science, 14,* 102–105. http://dx.doi.org/10.1111/j.0963-7214.2005.00343.x

Cohen, G. L., & Prinstein, M. J. (2006). Peer contagion of aggression and health risk behavior among adolescent males: An experimental investigation of effects on public conduct and private attitudes. *Child Development, 77,* 967–983. http://dx.doi.org/10.1111/j.1467-8624.2006.00913.x

Crone, E. A., & Dahl, R. E. (2012). Understanding adolescence as a period of social-affective engagement and goal flexibility. *Nature Reviews Neuroscience, 13,* 636–650. http://dx.doi.org/10.1038/nrn3313

Defoe, I. N., Dubas, J. S., Figner, B., & van Aken, M. A. (2015). A meta-analysis on age differences in risky decision making: Adolescents versus children and adults. *Psychological Bulletin, 141,* 48–84. http://dx.doi.org/10.1037/a0038088

Demetriou, A., Platsidou, M., Efklides, A., Metallidou, Y., & Shayer, M. (1991). The development of quantitative-relational abilities from childhood to adolescence: Structure, scaling, and individual differences. *Learning and Instruction, 1,* 19–43. http://dx.doi.org/10.1016/0959-4752(91)90017-3

Dumontheil, I., Apperly, I. A., & Blakemore, S. J. (2010). Online usage of theory of mind continues to develop in late adolescence. *Developmental Science, 13,* 331–338. http://dx.doi.org/10.1111/j.1467-7687.2009.00888.x

Fareri, D. S., Niznikiewicz, M. A., Lee, V. K., & Delgado, M. R. (2012). Social network modulation of reward-related signals. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience, 32,* 9045–9052. http://dx.doi.org/10.1523/JNEUROSCI.0610-12.2012

Gardner, M., & Steinberg, L. (2005). Peer influence on risk taking, risk preference, and risky decision making in adolescence and adulthood: An experimental study. *Developmental Psychology, 41,* 625–635. http://dx.doi.org/10.1037/0012-1649.41.4.625

Gilaie-Dotan, S., Tymula, A., Cooper, N., Kable, J. W., Glimcher, P. W., & Levy, I. (2014). Neuroanatomy predicts individual risk attitudes. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience, 34,* 12394–12401. http://dx.doi.org/10.1523/JNEUROSCI.1600-14.2014

Glimcher, P. W. (2008). Understanding risk: A guide for the perplexed. *Cognitive, Affective & Behavioral Neuroscience, 8,* 348–354. http://dx.doi.org/10.3758/CABN.8.4.348

Gonzalez, R., & Wu, G. (1999). On the shape of the probability weighting function. *Cognitive Psychology, 38,* 129–166. http://dx.doi.org/10.1006/cogp.1998.0710

Green, P., & MacLeod, C. J. (2016a). SIMR: An R package for power analysis of generalized linear mixed models by simulation. *Methods in Ecology and Evolution, 7,* 493–498. http://dx.doi.org/10.1111/2041-210X.12504

Green, P., & MacLeod, C. (2016b). *simr: Power analysis for generalised linear mixed models by simulation* (R package Version 1.0.3). Retrieved from https://CRAN.R-project.org/package=simr

Güroğlu, B., van den Bos, W., & Crone, E. A. (2014). Sharing and giving across adolescence: An experimental study examining the development of prosocial behavior. *Frontiers in Psychology, 5,* 291.

Haddad, A. D., Harrison, F., Norman, T., & Lau, J. Y. (2014). Adolescent and adult risk-taking in virtual social contexts. *Frontiers in Psychology, 5,* 1476. http://dx.doi.org/10.3389/fpsyg.2014.01476

Hartley, C. A., & Somerville, L. H. (2015). The neuroscience of adolescent decision-making. *Current Opinion in Behavioral Sciences, 5,* 108–115. http://dx.doi.org/10.1016/j.cobeha.2015.09.004

Hsu, M., Krajbich, I., Zhao, C., & Camerer, C. F. (2009). Neural response to reward anticipation under risk is nonlinear in probabilities. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience, 29,* 2231–2237. http://dx.doi.org/10.1523/JNEUROSCI.5296-08.2009

Jamieson, J. P., & Mendes, W. B. (2016). Social stress facilitates risk in youths. *Journal of Experimental Psychology: General, 145,* 467–485. http://dx.doi.org/10.1037/xge0000147

Kahneman, D., & Tversky, A. (1979). Prospect theory: An analysis of decision under risk. *Econometrica, 47,* 263–291. http://dx.doi.org/10.2307/1914185

Kahneman, D., & Tversky, A. (1984). Choices, values, and frames. *American Psychologist, 39,* 341–350. http://dx.doi.org/10.1037/0003-066X.39.4.341

Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. B. (2014). *lmerTest: Tests for random and fixed effects for linear mixed effects models* (lmer objects of lme4 package; R package Version 2.0–11). Retrieved from https://CRAN.R-project.org/package=lmerTest

Levy, D. J., & Glimcher, P. W. (2011). Comparing apples and oranges: Using reward-specific and reward-general subjective value representation in the brain. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience, 31,* 14693–14707. http://dx.doi.org/10.1523/JNEUROSCI.2218-11.2011

Levy, I., Belmaker, L. R., Manson, K., Tymula, A., & Glimcher, P. W. (2012). Measuring the subjective value of risky and ambiguous options using experimental economics and functional MRI methods. *Journal of Visualized Experiments, 67,* e3724–e3724.

Levy, I., Snell, J., Nelson, A. J., Rustichini, A., & Glimcher, P. W. (2010). Neural representation of subjective value under risk and ambiguity. *Journal of Neurophysiology, 103,* 1036–1047. http://dx.doi.org/10.1152/jn.00853.2009

Miniño, A. (2010). *Mortality Among Teenagers Aged 12-19 years: United States, 1999–2006.* (NCHS data brief no. 37), Atlanta, GA: Centers for Disease Control and Prevention.

Nelson, E. E., Leibenluft, E., McClure, E. B., & Pine, D. S. (2005). The social re-orientation of adolescence: A neuroscience perspective on the process and its relation to psychopathology. *Psychological Medicine, 35,* 163–174. http://dx.doi.org/10.1017/S0033291704003915

Ouimet, M. C., Pradhan, A. K., Simons-Morton, B. G., Divekar, G., Mehranian, H., & Fisher, D. L. (2013). The effect of male teenage passengers on male teenage drivers: Findings from a driving simulator study. *Accident; Analysis and Prevention, 58,* 132–139. http://dx.doi.org/10.1016/j.aap.2013.04.024

Platt, M. L., & Huettel, S. A. (2008). Risky business: The neuroeconomics of decision making under uncertainty. *Nature Neuroscience, 11,* 398–403. http://dx.doi.org/10.1038/nn2062

Pratt, J. W., & Zeckhauser, R. J. (1987). Proper risk aversion. *Econometrica, 55,* 143–154. http://dx.doi.org/10.2307/1911160

R Core Team. (2014). *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing. Retrieved from www.R-project.org/

Reyna, V. F., Estrada, S. M., DeMarinis, J. A., Myers, R. M., Stanisz, J. M., & Mills, B. A. (2011). Neurobiological and memory models of risky decision making in adolescents versus young adults. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 37,* 1125–1142. http://dx.doi.org/10.1037/a0023943

Rimé, B. (2007). Interpersonal emotion regulation. In J. J. Gross (Ed.), *Handbook of emotion regulation* (pp. 466–485). New York, NY: Guilford Press.

Simons-Morton, B., Lerner, N., & Singer, J. (2005). The observed effects of teenage passengers on the risky driving behavior of teenage drivers. *Accident: Analysis and Prevention, 37,* 973–982. http://dx.doi.org/10.1016/j.aap.2005.04.014

Sip, K. E., Smith, D. V., Porcelli, A. J., Kar, K., & Delgado, M. R. (2015). Social closeness and feedback modulate susceptibility to the framing effect. *Social Neuroscience, 10,* 35–45. http://dx.doi.org/10.1080/17470919.2014.944316

Sokol-Hessner, P., Camerer, C. F., & Phelps, E. A. (2013). Emotion regulation reduces loss aversion and decreases amygdala responses to losses. *Social Cognitive and Affective Neuroscience, 8,* 341–350. http://dx.doi.org/10.1093/scan/nss002

Somerville, L. H. (2013). Special issue on the teenage brain: Sensitivity to social evaluation. *Current Directions in Psychological Science, 22,* 121–127. http://dx.doi.org/10.1177/0963721413476512

Somerville, L. H., Jones, R. M., Ruberry, E. J., Dyke, J. P., Glover, G., & Casey, B. J. (2013). The medial prefrontal cortex and the emergence of self-conscious emotion in adolescence. *Psychological Science, 24,* 1554–1562. http://dx.doi.org/10.1177/0956797613475633

Steinberg, L. (2008). A social neuroscience perspective on adolescent risk-taking. *Developmental Review, 28,* 78–106. http://dx.doi.org/10.1016/j.dr.2007.08.002

Susac, A., Bubic, A., Vrbanc, A., & Planinic, M. (2014). Development of abstract mathematical reasoning: The case of algebra. *Frontiers in Human Neuroscience, 8,* 679. http://dx.doi.org/10.3389/fnhum.2014.00679

Tversky, A., & Kahneman, D. (1992). Advances in prospect theory: Cumulative representation of uncertainty. *Journal of Risk and Uncertainty, 5,* 297–323. http://dx.doi.org/10.1007/BF00122574

Tymula, A., Rosenberg Belmaker, L. A., Roy, A. K., Ruderman, L., Manson, K., Glimcher, P. W., & Levy, I. (2012). Adolescents' risk-taking behavior is driven by tolerance to ambiguity. *Proceedings of the National Academy of Sciences of the United States of America, 109,* 17135–17140. http://dx.doi.org/10.1073/pnas.1207144109

Tymula, A., Rosenberg Belmaker, L. A., Ruderman, L., Glimcher, P. W., & Levy, I. (2013). Like cognitive function, decision making across the life span shows profound age-related changes. *Proceedings of the National Academy of Sciences of the United States of America, 110,* 17143–17148.

van den Bos, W., Cohen, M. X., Kahnt, T., & Crone, E. A. (2012). Striatum-medial prefrontal cortex connectivity predicts developmental changes in reinforcement learning. *Cerebral Cortex, 22,* 1247–1255. http://dx.doi.org/10.1093/cercor/bhr198

Van Hoorn, J., Crone, E. A., & Van Leijenhorst, L. (2017). Hanging out with the right crowd: Peer influence on risk-taking behavior in adolescence. *Journal of Research on Adolescence, 27,* 189–200. http://dx.doi.org/10.1111/jora.12265

Van Leijenhorst, L., Gunther Moor, B., Op de Macks, Z. A., Rombouts, S. A., Westenberg, P. M., & Crone, E. A. (2010). Adolescent risky decision-making: Neurocognitive development of reward and control regions. *NeuroImage, 51,* 345–355. http://dx.doi.org/10.1016/j.neuroimage.2010.02.038

Van Leijenhorst, L., Westenberg, P. M., & Crone, E. A. (2008). A developmental study of risky decisions on the cake gambling task: Age and gender analyses of probability estimation and reward evaluation. *Developmental Neuropsychology, 33,* 179–196. http://dx.doi.org/10.1080/87565640701884287

Waters, S. F., West, T. V., & Mendes, W. B. (2014). Stress contagion: Physiological covariation between mothers and infants. *Psychological Science, 25,* 934–942.

Zaki, J., & Williams, W. C. (2013). Interpersonal emotion regulation. *Emotion, 13,* 803–810. http://dx.doi.org/10.1037/a0033839

Zimring, F. E. (1998). *American youth violence*. Oxford, England: Oxford University Press.

Received April 3, 2017
Revision received October 16, 2017
Accepted October 19, 2017 ■