Decision-making Across Development: The Impact of Ambiguity and Social Context

by

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Dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Department of Psychology & Neuroscience in the Graduate School of Duke University

2017
ABSTRACT

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Abstract

Public health data show that many everyday reckless behaviors reach a developmental peak in adolescence, with adolescents engaging in more reckless behaviors than both children and adults. In contrast, most studies of decision-making across development do not find laboratory risk-taking to peak in adolescence. Here, I focus on two factors that contribute to the discrepancy between public health and laboratory findings: ambiguity and social context. Everyday decisions tend to involve ambiguous decisions (choices with unknown probabilities), while previous laboratory studies have largely focused on risky decisions (choices with known probabilities). Consequently, little is known about the ambiguity preferences of young children. Across three behavioral studies, I show that ambiguity aversion is absent in 5-year-old children (Chapter 2) and 8- and 9-year-old children (Chapter 3) but present in 15- to 18-year-old adolescents (Chapter 4) and adults (Chapters 2 to 4). The results of Chapters 2 through 4 indicate that the willingness to take ambiguous gambles, like the willingness to take risky gambles, does not peak in adolescence. Everyday decisions also often occur in social contexts when friends are present and outcomes can be shared, whereas most laboratory studies occur in social isolation. In Chapter 5, I use functional magnetic resonance imaging to show that neural response to reward for self and for friend are similar in a sample of young adults (ages 18 to 28), and that neural response to reward
linearly decreases with age when participants are watched by their friends but not when they are alone. In Chapter 6, I use behavioral modeling to show that adults value rewards similarly for themselves and for their friend. Adolescents, in contrast, value their own rewards more than those of their friend, but the presence of their friend reduces this valuation difference. The results of Chapters 5 and 6 indicate that the presence of friends prompts adolescents and young adults to engage in behavior that benefits both themselves and their friends. Collectively, the results in this dissertation demonstrate the need to consider contextual influences on decision-making in order to better capture everyday decision behavior in the laboratory.
Dedication

To my parents, who gave me life and a love of learning.
Contents

Abstract ................................................................................................................................. iv

Dedication ............................................................................................................................... vi

Contents ................................................................................................................................... vii

List of Tables .......................................................................................................................... xii

List of Figures ........................................................................................................................ xiii

Acknowledgements ............................................................................................................... xviii

1. Introduction: Development of decision-making ................................................................. 1

   1.1 Dual-systems models ...................................................................................................... 2

       1.1.1 Dual-systems models: Support from neural findings .............................................. 3

       1.1.2 Dual-systems models: Mixed support from behavioral findings .............................. 5

       1.1.3 Dual-systems models: Mixed support from public health data .............................. 8

       1.1.4 Dual-systems models: Summary ........................................................................... 10

   1.2 Decision-making and information availability ............................................................... 11

       1.2.1 Decision-making under ambiguity ......................................................................... 11

   1.3 Decision-making and social context ............................................................................. 14

       1.3.1 Decision-making for and with peers ..................................................................... 17

2. Five-year-olds do not show ambiguity aversion in a risk and ambiguity task with
   physical objects .................................................................................................................. 18

   2.1 Introduction ................................................................................................................... 18

   2.2 Method .......................................................................................................................... 22

       2.2.1 Participants ............................................................................................................ 22
2.2.2 Materials .................................................................................................................. 22
2.2.3 Procedure.................................................................................................................. 23
2.3 Results .......................................................................................................................... 24
2.4 Discussion..................................................................................................................... 27
2.4.1 Conclusions............................................................................................................. 30
3. Children do not exhibit ambiguity aversion despite intact familiarity bias .............. 31
   3.1 Introduction.................................................................................................................. 31
   3.2 Materials and methods ............................................................................................. 34
      3.2.1 Participants.......................................................................................................... 34
      3.2.2 Bar Stimuli and Training ................................................................................... 35
      3.2.3 Tasks.................................................................................................................... 38
         3.2.3.1 Bar Choice .................................................................................................... 39
         3.2.3.2 Willingness to Pay (WTP) ........................................................................... 40
         3.2.3.3 Bar Probability ............................................................................................ 41
         3.2.3.4 Familiarity Bias ............................................................................................ 42
   3.3 Results ....................................................................................................................... 43
      3.3.1 Bar Choice .......................................................................................................... 43
      3.3.2 Willingness to Pay (WTP) ................................................................................ 45
      3.3.3 Bar Probability ................................................................................................... 46
      3.3.4 Familiarity Bias ................................................................................................. 47
   3.4 Discussion.................................................................................................................... 48
      3.4.1 Conclusions ........................................................................................................ 52

4.1 Introduction........................................................................................................................................... 53

4.2 Method .................................................................................................................................................. 58

4.2.1 Participants........................................................................................................................................ 58

4.2.2 Tasks .................................................................................................................................................. 59

4.2.2.1 Risk/ambiguity aversion .............................................................................................................. 59

4.2.2.2 Loss aversion ................................................................................................................................ 60

4.2.2.3 BART .......................................................................................................................................... 61

4.2.2.4 Questionnaires ............................................................................................................................ 63

4.2.2.5 Principal components analysis..................................................................................................... 64

4.3 Results .................................................................................................................................................. 65

4.3.1 Risk/ambiguity aversion ................................................................................................................. 65

4.3.2 Loss aversion .................................................................................................................................... 67

4.3.3 BART ................................................................................................................................................ 70

4.3.4 Consistent preferences across behavioral task measures ............................................................... 70

4.3.5 Questionnaires ............................................................................................................................... 71

4.3.6 PCA.................................................................................................................................................. 73

4.4 Discussion ............................................................................................................................................ 78

5. Reward-related neural responses for self and for friend are affected by friend presence ................................................................................................................................. 83

5.1 Introduction......................................................................................................................................... 83

5.2 Methods .............................................................................................................................................. 88
6.3.2 Alone adolescents compared to Alone adults ........................................... 124
6.3.3 Alone adolescents compared to Watched adolescents ............................. 125
6.3.4 Watched adolescents compared to Alone adults ..................................... 126
6.3.5 Relationships between choice behavior and friendship quality ................ 127
6.3.6 Relationships between choice behavior and age ...................................... 129
6.4 Discussion ................................................................................................. 130

7. Conclusions: Better capturing everyday decision preferences in the laboratory .... 135

7.1 Future directions: Decision-making and information availability .................. 137
7.2 Future directions: Decision-making and social context ............................... 143
7.3 Accounting for varied decision contexts through a flexible dual-systems model ......................................................................................................................... 145

References ........................................................................................................ 149

Biography .......................................................................................................... 168
List of Tables

Table 1: Questionnaire measures and mean scores for adolescents and adults ............... 71
Table 2: Positive and negative contributing measures for the first 8 components .......... 74
Table 3: Model AICs and BICs .................................................................................... 123
List of Figures

Figure 1: The classic dual-systems imbalance model, in which cognitive control develops linearly while reward-processing peaks in adolescence. ................................................................. 3

Figure 2: The importance of investigating behavior in childhood. When childhood is not studied (grey regions), greater reckless behavior in adolescence compared to adulthood could represent one of three developmental trends. ................................................................. 13

Figure 3: Risky versus ambiguous stimuli used to test ambiguity preferences. Participants made a series of binary choices between physical stimuli representing risky (in this example, 3 winning and 3 losing eggs; left) and ambiguous (always containing 6 eggs of unknown colors; right) gambles................................................................. 23

Figure 4: Five-year-old children make consistent and ambiguity neutral choices while adults are ambiguity averse. A) Five-year-olds exhibit no ambiguity aversion, with 50% of children preferring 50-50 risk to ambiguity. B) Adults exhibit ambiguity aversion, with 65.6% of adults preferring 50-50 risk to ambiguity. Shaded grids depict the choices of participants (left vertical axis) at each probability of risky sock (horizontal axis). The overlaid logistic regression line shows each group’s proportion of risky choices at each risky sock (right vertical axis; shaded area around regression line indicates 95% confidence interval). ................................................................. 25

Figure 5: Children and adults exhibit different distributions of ambiguity attitudes, with relatively more adults than children showing weak ambiguity aversion and relatively fewer adults than children exhibiting strong preferences. ................................................................. 26

Figure 6: Stimuli and tasks. Red and blue represent the chance of winning a small (2 tokens) or large (12 tokens) reward. The color representing the large reward was counterbalanced across participants. A) Example risky bars. A total of 11 different risky bars representing different probabilities were used. B) All 4 ambiguous bars used. C) Example Bar Choice trial featuring a risky bar versus an ambiguous bar. Participants indicated with a key press which of the two bars they preferred. D) Example of a Bar Choice “catch” trial. If red represented the bigger win, participants should select the risky bar. If blue represented the bigger win, participants should select the ambiguous bar. E) Example Willingness to Pay (WTP) trial. Each bar was presented on the left of the screen with its endpoints labeled with their associated reward values. Participants used arrow keys to toggle the number on the right up or down until it reached their maximum willingness to pay for the displayed bar. ................................................................. 37
Figure 7: Evidence of ambiguity aversion in adults but not in children and significantly greater ambiguity aversion in adults than in children across three separate measures. A) Frequency of choosing the risky bar on risky bar versus ambiguous bar trials in the Bar Choice task. B) Frequency of choosing the less ambiguous bar on ambiguous bar versus ambiguous bar trials in the Bar Choice task. C) Difference in WTP for risky bars and ambiguous bars in the WTP task. Dotted lines indicate chance performance. * indicates significance at $p < 0.05$. ................................................................. 44

Figure 8: A child-friendly guessing game found significant familiarity bias in children. A) Participants were asked to guess the final word on a random page of a book. Physical copies of a familiar and unfamiliar book were shown, along with a page number and four possible final words for that page. Participants first indicated if they wanted to guess for the familiar book or the unfamiliar book, then indicated their guess from the four possible final words. Correct guesses (e.g. STUFF for the familiar book and COINS for the unfamiliar book) were rewarded with 5 additional tokens. B) Percentage of participants that chose to guess for the familiar book. Dotted line indicates chance performance. * indicates significance at $p < 0.05$; + indicates $p = 0.11$................................. 48

Figure 9: Example stimuli from each task. A) An example risky trial from the risk/ambiguity aversion task, in which participants may choose between a certain 5 points or a 25% chance of 12 points. B) An example ambiguous trial from the risk/ambiguity task, in which participants may choose between a certain 5 points or an unknown chance of 12 points. C) An example gamble from the loss aversion task, in which participants may choose to accept or reject a mixed gamble with a 50% chance of +15 and a 50% chance of -10. D) An example balloon from the BART, in which participants may choose to bank their current 7 points or continue pumping the balloon to win more points but risk popping it and winning 0 points. ................................................................. 62

Figure 10: Adults and adolescents exhibit similar behavior on the risk/ambiguity task. A) Adults’ and adolescents’ proportion of safe choices on risky trials as a function of the ratio between the risky gamble’s expected value and the safe value (binned). B) Adults’ and adolescents’ proportion of safe choices on the ambiguous trials as a function of the ratio between the ambiguous gamble’s expected value (assuming 50% probability) and the safe value. C) There were no significant differences between adults’ and adolescents’ overall proportion of safe choices on the risky and ambiguous trials. D) There were no significant differences between adults’ and adolescents’ parameter estimates for risk aversion or ambiguity aversion in the subset of participants with preferences that could be captured by our models (see text for details). ................................................................. 67
Figure 11: Adults and adolescents exhibited somewhat similar behavior on the loss aversion task, with adults accepting slightly more gambles compared to adolescents. A) Adults’ and adolescents’ proportion of accepted gambles as a function of the gamble’s expected value. B) Adults accepted marginally more gambles compared to adolescents. + indicates $p = 0.05$. C) There were no significant differences between adults’ and adolescents’ parameter estimates for risk aversion and loss aversion in the subset of participants with preferences that could be captured by our model (see text for details).

Figure 12: Behavioral task measures show largely consistent preferences. Lower triangle shows $r$ values for each pairwise correlation. Upper triangle shows correlations that are significant at $p < 0.05$. Color and circle size indicate $r$ values.

Figure 13: Correlation matrix for the 26 questionnaire measures, presented in hierarchical clustering order. Number labels correspond to Table 1. Circle color and size represent $r$ values. Lower triangle depicts all values while upper triangle only shows correlations significant at $p < 0.05$.

Figure 14: Coordinates for component 1 predict gambling behavior on the risk/ambiguity aversion and loss aversion tasks, but not the BART. Grey dots indicate adults, and orange dots indicate adolescents. Coordinates for component 1: A) significantly negatively correlate with the proportion of safe trials chosen on risky trials in the risk/ambiguity aversion task, B) significantly negatively correlate with the proportion of safe trials chosen on ambiguous trials in the risk/ambiguity aversion task, C) significantly positively correlate with the proportion of accepted gambles in the loss aversion task, but D) do not significantly correlate with the mean number of pumps on banked balloons in the BART.

Figure 15: An example Gain trial. White text indicates each trial’s target recipient (here, Rosa) and potential outcome (here, may win). Participants were instructed to make a button press while the white box was on the screen. A successful response yielded the better potential outcome in green text (here, +5), while an unsuccessful response that was too slow yielded the worse potential outcome in red text (here, +0).

Figure 16: Response times were slowest for Neutral cues but generally did not vary by Alone/Watched condition. Cue target significantly affected response times such that Self trials were faster than Peer trials, but cue valence (Gain or Loss) did not affect response time. * indicates $p < 0.05$. 
Figure 17: Neural responses to social Anticipation and Outcome. A) The contrast of (Self Anticipation + Peer Anticipation) > Neutral Anticipation shows significant widespread activation throughout the brain, including in bilateral striatum, anterior insula, and supplementary motor area. B) The contrast of Peer Outcome > Self Outcome shows significant activation in MPFC extending into dorsal MPFC. Images are shown at FWE corrected $p < 0.01$.

Figure 18: Neural results within ROIs. A) In all reward-related ROIs, neural activity for anticipation for Self and Peer are greater than for Neutral but not significant from each other or between Alone and Watched conditions. B) In social cognition-related ROIs, neural activity for outcome for Peer is greater than both Self and Neutral only in MPFC in both Alone and Watched conditions. * indicates $p < 0.05$.

Figure 19: Neural activity for (Self Anticipation + Peer Anticipation) > Neutral anticipation significantly negatively correlated with age in Watched but not in Alone conditions.

Figure 20: The difference between neural activity for Self Anticipation and Peer Anticipation correlated with the difference in response time for Self and Peer in A) Left Striatum, B) Right Striatum, C) Left Anterior and D) Right Anterior Insula. $ps < 0.05$ for A, B, and D; $p = 0.05$ for C.

Figure 21: Example trial offering more points for self (light grey bar) than for partner (dark grey bar). Participants were instructed to move the mouse to YES to accept the displayed offer, or to move the mouse to NO to reject the displayed offer in favor of 5 points for self & 5 points for partner (vertical line reference mark).

Figure 22: Schematic diagrams visualizing how the offer space can be categorized. A) Offers in the diagonally shaded area represent advantageous inequity, while offers in the unshaded area represent disadvantageous inequity. B) Offers in the diagonally shaded area are efficient (total payout from accepting the offer is greater than total payout from rejecting the offer), while offers in the unshaded area are inefficient. C) Offers in each quadrant can be better (+) or worse (-) for self and partner than rejecting the offer in favor of 5 points for self and 5 points for partner. D) The offer space categorized by advantageous/disadvantageous inequity, efficient/inefficient, and better/worse for self/partner.

Figure 23: The proportion of offers accepted at every combination of payout for self and payout for partner for A) Adults completing the task alone, B) Adolescents completing
the task alone, and C) Adolescents completing the task while watched by their partner.

Figure 24: Subjective value of each combination of payout for self and payout for friend is depicted for the average values of $\rho$ and $\sigma$ for A) Adults completing the task alone, B) Adolescents completing the task alone, and C) Adolescents completing the task while watched by their partner.

Figure 25: Mean estimates of $\mu$, $\rho$, and $\sigma$ for each participant group. Comparisons between Adults Alone to the Adolescent groups are t-tests, while comparisons between the Adolescents Alone and Adolescents Watched values are paired t-tests. * indicates $p < 0.05$.

Figure 26: Negative friendship quality does not significantly correlate with A) adults’ Alone $\rho$ but does significantly correlate with B) adolescents’ Alone $\rho$ and C) adolescents’ Watched $\rho$. The inset in C shows the relationship between adolescents’ Watched $\rho$ and negative friendship quality after excluding a participant with an extremely high Watched $\rho$.

Figure 27: The relationship between exact age and alone parameters was significant for A) Alone $\mu$, non-significant for B) Alone $\rho$, and significant C) Alone $\sigma$. Note that the relationship between exact age and Alone $\sigma$ remained significant even after excluding one participant with an extremely low Alone $\sigma$. Blue lines represent linear best fits, and shaded areas represent 95% confidence intervals.

Figure 28: In the proposed flexible model, increasing information/decreasing learning demands changes the slope of the strength of cognitive control to drive advantageous decision making. Increasing color saturation indicates increased information/decreased learning demands in the decision environment.

Figure 29: In the proposed flexible model, decreasing emotional arousal decreases the strength of reward-processing in driving decision-making. Decreasing color saturation indicates decreasing emotional arousal.

Figure 30: In a fully flexible model, the relative strengths of cognitive control and reward-processing in driving decision-making vary based upon information availability/learning demands and emotional arousal in the decision environment (trajectories of intermediate levels of information/learning demands and emotional arousal are faded for visual clarity).
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1. Introduction: Development of decision-making

Adolescence is popularly characterized as a turbulent time period in which raging hormones drive reckless teenagers to engage in risky behaviors. Public health data broadly supports such a characterization, as progressing from childhood to adolescence more than triples one’s likelihood of dying, and the percentage of deaths resulting from accidents and unintentional injuries sharply increases in adolescence before dropping off after early adulthood (Heron, 2013). Prevailing dual-systems models suggest that risk-taking peaks in adolescence because adolescent brains are uniquely imbalanced—cognitive control is overwhelmed by reward-seeking specifically during adolescence (Casey, Getz, & Galván, 2008; Casey, Jones, & Somerville, 2011; Shulman, Smith, et al., 2016; Somerville, Jones, & Casey, 2010; Steinberg, 2010). Laboratory studies, however, have found little evidence that risk-taking peaks in adolescence. Though a meta-analysis of developmental risk-taking studies did find adolescents to take more risks compared to adults, it found no differences in risk-taking between children and adolescents (Defoe, Dubas, Figner, & Aken, 2015), a striking departure from what would be expected based on public health data and dual-systems models’ predictions.

Here, I summarize studies of decision-making across development through the framework of prevailing dual-systems models, discuss how such models fall short, and suggest that previous laboratory studies may have been unable to capture the
developmental patterns seen in public health data because they do not manipulate information availability and social contexts to better approximate everyday decisions.

For the purposes of this summary, I will generally consider adolescence as the teenage years (ages 13 to 19), or approximately the time period between the onset of puberty and the attainment of adult status in Western societies (Crone & Dahl, 2012). These bounds are loosely construed, however, as the literature on the development of decision-making has no clean definitions of when adolescence begins and ends. Thus, whenever possible, I note the age ranges of adolescents, adults, and children when referencing previous studies and generally follow the grouping nomenclature used by each study.

1.1 Dual-systems models

Current prevailing models have taken a dual-systems approach to suggest that adolescence is a developmental time period of peak risk-taking due to three factors: 1) cognitive control and its associated prefrontal cortex (PFC) circuitry develop linearly from childhood to adulthood, 2) reward-processing and its associated limbic neural circuitry (including but not limited to ventral striatum; VS) peak in adolescence, and 3) reward-processing overwhelms cognitive control most prominently in adolescence, thereby driving adolescents to behave more recklessly compared to both adults and children (Casey et al., 2008; Shulman, Smith, et al., 2016; Somerville et al., 2010; Steinberg, 2007; Figure 1). While these dual-systems accounts have fostered much
fruitful research in the fields of developmental cognitive neuroscience and decision-making, their behavioral predictions have not been well-supported by laboratory findings or public health data.

1.1.1 Dual-systems models: Support from neural findings

Support for the linear increase in PFC-mediated control has been found in MRI (magnetic resonance imaging) measures of structure and function. Frontal gray matter volume peaks around age 11 in girls and 12 in boys (Giedd et al., 1999) and exhibits gray matter pruning throughout adolescence (Gogtay et al., 2004) and into adulthood (Sowell et al., 2003). A number of studies have shown PFC activity to become more fine-tuned
and focused as age and performance on executive control tasks increases (Durston et al., 2006; Rubia et al., 2006; see Yurgelun-Todd, 2007 for review). In studies of decision-making, however, PFC-related findings have been mixed. Some studies found PFC activity to decrease with age while behavior did not change, suggesting that with age comes increased efficiency (Barkley-Levenson, Van Leijenhorst, & Galván, 2013; Van Leijenhorst, Gunther Moor, et al., 2010). Other studies, in contrast, found PFC activity to increase with age while behavior remained constant, suggesting that with age comes increased ability to draw upon PFC (Bjork, Smith, Danube, & Hommer, 2007; Chein et al., 2011; Eshel, Nelson, Blair, Pine, & Ernst, 2007; Keulers, Stiers, & Jolles, 2011). Thus, interpretations of developmental differences in PFC activity remain problematic (Pfeifer & Allen, 2012; Poldrack, 2014), though overall findings do point to linear age-related change.

Reward-processing studies have generally found VS activity to take an inverted-U shape across development that peaks in early adolescence around ages 14 to 16 (Braams, van Duijvenvoorde, Peper, & Crone, 2015; Galván et al., 2006; Padmanabhan, Geier, Ordaz, Teslovich, & Luna, 2011; Van Leijenhorst, Gunther Moor, et al., 2010; Van Leijenhorst, Zanolie, et al., 2010). Other studies, however, have found VS activity to linearly increase with age from childhood to adulthood or adolescence to adulthood (Bjork et al., 2004; Bjork, Smith, Chen, & Hommer, 2010; Paulsen, Carter, Platt, Huettel, & Brannon, 2012; see Galván, 2010; Richards, Plate, & Ernst, 2013 for review). Though
the preponderance of evidence suggests that VS response to reward peaks in adolescence (Galvan, 2010; Richards et al., 2013), studies with disparate findings suggest there may be additional factors that differentially mediate VS activity across development.

### 1.1.2 Dual-systems models: Mixed support from behavioral findings

Support for dual-system models’ predictions in behavioral findings have been mixed. Self-reported impulsivity, a proxy for lack of cognitive control, was found to linearly decrease from age 10 to 30 in a cross-sectional sample (Steinberg et al., 2008) and from 12 to 25 in a longitudinal sample (Harden & Tucker-Drob, 2011), and a separate study found self-reported behavioral inhibition to linearly increase from age 14 to 21 (Reyna et al., 2011). In contrast, self-reported sensation-seeking has been found to take an inverted-U shape that peaks between ages 12 and 15 in both a cross-sectional sample (Steinberg et al., 2008) and a longitudinal sample (Harden & Tucker-Drob, 2011). The developmental trajectories of these self-report findings nicely map onto those of PFC and VS. Other studies, however have found peaks in self-reported sensation-seeking to occur later in adolescence, around age 18 (Reyna et al., 2011; Romer & Hennessy, 2007). The peaks of these latter studies are later than the developmental peaks found for VS (see Support from neural findings section above), but they do predict the late adolescence peaks in reckless behavior found in public health data (see Mixed support from public health data section below).
As previously noted, a meta-analysis of laboratory developmental risk-taking paradigms found adolescents (ages 11 to 19) to take more risks compared to adults (ages 20 to 65) but no risk-taking differences between children (ages 5 to 10) and adolescents (Defoe et al., 2015). In fact, only two laboratory studies have found adolescents to take more risks than both adults and children (Braams et al., 2015; Burnett, Bault, Coricelli, & Blakemore, 2010). In the following overview of studies that do not align with dual-systems predictions, I define risk as a formal, decision science term referring to uncertain outcomes with known probabilities (i.e. a 50% chance of winning $5); riskiness, or the amount of risk, as the coefficient of variation (CV; a standardized measure of outcome variability); risk-taking as choosing the option with the greater CV (Weber, Shafir, & Blais, 2004); and advantageous decision-making as choosing the option with the greater expected value (EV; a metric of the average outcome of a gamble).

A number of risky decision-making studies have found that the ability to accurately use EV increases with age, especially in childhood. While children as young as 5 were able to integrate both the probability of winning and win outcome when deciding whether to gamble, 5- and 6-year-olds incorrectly added values. It was not until age 8 that probabilities and outcomes were multiplicatively integrated in decision-making (Schlottmann & Anderson, 1994). In a variety of economic gambling tasks, EV advantageous decision-making has been found to increase with age from 8 to 18 (Crone, Bullens, van der Plas, Kijkuit, & Zelazo, 2008), from 5 to 64 (Harbaugh, Krause, &
Vesterlund, 2002), and from 5 to 11 compared to adulthood (Levin, Weller, Pederson, & Harshman, 2007). In these studies, risk-taking similarly linearly decreased with age, as children were more likely to take risks even when they were disadvantageous. Finally, it is worth noting that one of the two laboratory studies that found adolescents to take more risks than both children and adults also found the advantageous use of EV to linearly increase with age from 9 to 35 (Burnett et al., 2010).

When a gamble’s EV was held constant and CV varied, increasing CV drove children (ages 6 to 8) to take more risks but adults (ages 18 to 32) and adolescents (ages 15 to 16) to take fewer risks. At the highest level of CV, risk-taking was found to decrease with age from childhood to adulthood. At the lowest level of CV, there were no age-related differences in risk-taking (Paulsen, Platt, Huettel, & Brannon, 2011). In another version of this study, children (ages 5 to 8) were found to be riskier than both adults (ages 18 to 35) and adolescents (ages 14 to 16), while adolescents did not differ from adults in risk-taking behavior (Paulsen, Carter, et al., 2012). Taken together, these behavioral findings suggest that when there is no advantageously “correct” choice, risk-taking linearly decreases with age.

A number of studies have also found no differences in gambling and EV use with age (Barkley-Levenson et al., 2013; Keulers et al., 2011; Van Leijenhorst, Gunther Moor, et al., 2010; van Leijenhorst, Crone, & Bunge, 2006). It may be that in some cases, likely when EV differences between options are relatively easy to distinguish, providing
explicit probabilities and outcomes can bring children and adolescents’ abilities to make advantageous decisions on par with that of adults. For example, risk-taking on a Wheel of Fortune task decreased with age from 9 to 40 at the more moderate (7:3 odds) of two levels of risk, but behavior was similar across ages at the more obviously risky 9:1 odds gamble (Eshel et al., 2007). Similarly, a Cake Gambling Task found a linear decrease in gambling with age from 8 to 26 at the lowest risk level when gambles were EV equivalent, but no difference in behavior across ages when the risky gambles were EV advantageous (Van Leijenhorst, Gunther Moor, et al., 2010).

Finally, it should be noted that dual-systems models predict risk-taking to peak when VS response to reward does, around ages 14 to 16, but the meta-analysis of decision-making across development found mid-late adolescents (ages 14 to 19) to take fewer risks than early adolescents (ages 11 to 13; Defoe et al., 2015). Thus, there is a disconnect between the behavioral predictions made by neural evidence supporting dual-systems models and what has been measured in the laboratory using risky decision-making paradigms.

1.1.3 Dual-systems models: Mixed support from public health data

A closer look at public health data indicates mixed support for dual-systems models’ predictions. Accidents/unintentional injuries are the leading cause of death for 15- to 19-year-olds in America (Heron, 2013), a fact that has prompted many researchers to conclude that adolescents are especially likely to engage in everyday reckless
behavior. This statistic alone is misleading, however, as accidents/unintentional injuries are the leading cause of deaths of Americans from age 1 through age 44. Furthermore, while the number of deaths and the death rate due to accidents/unintentional injuries does drastically increase from childhood (ages 10 to 14) to adolescence (ages 15 to 19), the death rate due to accidents/unintentional injuries is similarly high for young adults (ages 20 to 24), and the number of deaths due to accidents/unintentional injuries continues to increase into adulthood (Heron, 2013). Thus, while adolescence marks the onset of preventable deaths that may be due to reckless behaviors, it does not represent a lifespan peak.

Some specific everyday reckless behaviors exhibit an inverted-U shaped function with a peak in late adolescence. In the U.S., illicit drug use (Results from the 2012 National Survey on Drug Use and Health: Summary of National Findings, 2013), the age of onset for drug abuse and drug dependence (Compton, Thomas, Stinson, & Grant, 2007), the arrest rate for various violent crimes and property crimes (Snyder, 2012), and rate of unintended pregnancies for sexually active women (Finer, 2010) all peak around age 18 to 19. Other everyday reckless behaviors have been found to peak even later. In the U.S., cigarette use, heavy drinking, and binge drinking all peak between ages 21 and 25 (Results from the 2012 National Survey on Drug Use and Health: Summary of National Findings, 2013), while smoking and drinking to drunkenness was found to peak between
ages 22 and 24 in an urban Swiss sample, where the legal drinking age is 16 (Brodbeck, Bachmann, Croudace, & Brown, 2013).

Taken together, public health data indicate that everyday behaviors may emerge in early adolescence, but they do not necessarily peak at that time. Instead, many metrics indicate that late adolescence/early adulthood (ages 18 to 24) may be a more accurate measure of when everyday reckless behaviors reach their peak, in contrast to the early adolescent (ages 14 to 16) peak predicted by dual-systems models (see Willoughby, Good, Adachi, Hamza, & Tavernier, 2013 for a thorough review of the developmental timecourse of numerous such behaviors).

1.1.4 Dual-systems models: Summary

Though neural findings tend to align with dual-systems models, the predictive validity of such models have two major shortcomings: while neural evidence predicts risk-taking to peak around ages 14 to 16, laboratory studies generally find that risk-taking decreases or is developmentally constant up to and including the ages of 14 to 16, and public health data suggest that everyday reckless behavior peaks after the ages of 14 to 16.

These discrepancies may be because laboratory studies do not fully account for the various social, affective, and cultural factors that alter behavior in everyday decision contexts. In the following sections, I will highlight two factors – information availability and social context – that alter decision-making across development.
1.2 Decision-making and information availability

The amount of information that is available to the decision-maker can drastically differ between laboratory studies and everyday decisions, making it challenging for the former to accurately predict the latter. Description-based laboratory risky decision-making tasks provide participants with full information about possible rewards and their probability contingencies. This stands in contrast to everyday decisions, in which probabilities are unknown, and potential outcomes and their probabilities must be learned through experience (Paulsen, Platt, Huettel, & Brannon, 2012). Everyday decision preferences can be better captured in the laboratory through paradigms that similarly restrict the amount of information available to participants.

1.2.1 Decision-making under ambiguity

One laboratory method to measure decision preferences in low information conditions is to investigate attitudes towards ambiguous gambles (those with uncertain outcomes and unknown probabilities, such as an unknown chance of winning $5). Previous studies of the development of decision-making have focused on attitudes towards risk – that is, they provided participants with full information about potential outcomes and their probability contingencies – and found developmental trajectories that did not correspond with public health data. In contrast, most everyday decisions are ambiguous, as we rarely know the exact probability contingencies of their potential
outcomes. Though risk attitudes provide insight on the development of decision-making, ambiguity attitudes may be better predictors of everyday behavior.

The first developmental study of ambiguity attitudes found that adolescents (ages 12 to 17) were less ambiguity averse (more willing to take ambiguous gambles) compared to adults (ages 30 to 50), and adolescents’ tolerance for ambiguity predicted their self-reported likelihood of engaging in everyday reckless behaviors (Tymula et al., 2012). This study was taken as supporting evidence for dual-systems predictions of peak reckless behavior in adolescence (Shulman, Smith, et al., 2016) – despite the fact that it only compared adolescents to adults and did not investigate ambiguity preferences of children. Studying only adolescents and adults, however, only goes halfway towards probing the prediction of dual-systems models that adolescents are more reckless than both adults and children. Consequently, it is important to investigate ambiguity preferences of children in order to determine if the developmental difference from adolescence to adulthood represents a peak in adolescence, a linear trend across development, or a trait that is already present prior to adolescence (Figure 2). In fact, a recent study found ambiguity tolerance to linearly decrease with age from 10 to 25, with no evidence for a peak in adolescence (Blankenstein, Crone, van den Bos, & van Duijvenvoorde, 2016).
Figure 2: The importance of investigating behavior in childhood. When childhood is not studied (grey regions), greater reckless behavior in adolescence compared to adulthood could represent one of three developmental trends.

The first aim of this dissertation is to better understand the developmental trajectory of decision-making under ambiguity by comparing ambiguity attitudes of young children, adolescents, and adults. In study 1 (Chapter 2), my colleagues and I developed a novel behavioral paradigm in order to measure ambiguity attitudes in 5-year-old children. In study 2 (Chapter 3), we compared ambiguity attitudes of 8-year-old children to those of adults and investigated whether ambiguity attitudes were related to a preference for betting on the familiar. In study 3 (Chapter 4), we investigated the relationships between ambiguity, risk, and loss aversion attitudes in adolescents (high school students between the ages of 15 and 18) and adults. Taken together, our results suggest that ambiguity tolerance does not peak in adolescence, and that the development of ambiguity attitudes also run counter to dual-systems models’ predictions of peak recklessness in adolescence.
1.3 Decision-making and social context

In addition to varying based on information content, laboratory studies also differ from everyday decisions in that the former tend to occur in isolated testing environments while the latter tend to occur in social contexts. In fact, public health data show that adolescents are especially likely to commit crimes with co-offenders. For several violent and property crimes, the majority of arrests of those under age 18 are with co-offenders, and the rates of arrest with co-offenders in those under 18 are over twice that of those over 24 (Zimring & Laqueur, 2015). Because problematic behavior in adolescents tends to occur when they are with their peers, laboratory paradigms that place participants in social contexts may better capture reckless behavior in adolescents (Albert, Chein, & Steinberg, 2013; Schriber & Guyer, 2015; van Hoorn, Fuligni, Crone, & Galván, 2016).

Studies comparing decision behavior in social and non-social contexts have found that the former increases risk-taking in adolescents. In a between-subjects description-based risk-taking paradigm, adolescents (ages 15 to 17) who believed they were being observed by an anonymous peer accepted more disadvantageous risky gambles compared to adolescents who were not told that they were being observed (A. R. Smith, Chein, & Steinberg, 2014). Another study using a within-subjects design found that adolescents (ages 15 to 17) placed bigger bets (i.e. made higher CV gambles) when they thought they were being observed by a virtual peer compared to when alone, even
when the virtual peer gave advice to place small bets (Van Hoorn, Crone, & Van Leijenhorst, 2016).

Other studies comparing the effects of social context on adolescents versus adults have found adolescents but not adults to change behavior when under observation. The mere presence of peers has been found to greatly increase risk-taking on a simulated driving game in adolescents (ages 13 to 16), moderately increase risk-taking in young adults (ages 18 to 22), and not affect adults (age 24+; Gardner & Steinberg, 2005, but see Ross, Jongen, Brijs, Brijs, & Wets, 2016, which found peer presence to similarly increase risky driving in 17- to 18-year-olds and 21- to 24-year-olds). When the simulated driving game was played while participants underwent fMRI scanning, adolescents (ages 14 to 18) who were watched by peers exhibited increased risk-taking compared to those who performed the task alone, while young adults (ages 19 to 22) and adults (ages 24 to 29) exhibited similar behavior across alone and watched conditions. Furthermore, watched adolescents showed an increase in VS response compared to alone adolescents, and adolescents exhibited a greater VS response to risky compared to safe choices. Both adult groups, in contrast, showed similar VS responses to watched and alone conditions and safe and risky choices (Chein et al., 2011). These neural findings suggest that social contexts increase adolescents’ risk-taking by increasing their response to reward.

This adolescent boost in neural response to reward in social contexts has also been found in simpler reward-receipt tasks. One study found that adolescents (ages 14
to 19) showed greater VS response to monetary reward receipt when watched by peers than when alone, while adults (ages 25 to 35) showed no VS differences in the watched and alone conditions (A. R. Smith, Steinberg, Strang, & Chein, 2015). In another study, in which participants received social rewards in the form of positive social feedback from peers, adolescents (ages 13 to 17) exhibited greater reward-related brain activity in response to positive social feedback receipt compared to both children (ages 8 to 12) and adults (ages 18 to 25; Jones et al., 2014).

These findings have been filtered through the dual-systems lens to suggest that the adolescent increase in response to reward is specific to high arousal settings, such as social contexts. In non-social contexts of low affective arousal, adolescent response to reward is comparable to that of adults and thus does not overwhelm cognitive control to prompt reckless behavior (A. R. Smith, Chein, & Steinberg, 2013; Steinberg, 2010). Through this view, the discrepancy between dual-systems models’ predictions of peak risk-taking in adolescence have not been borne out in laboratory studies because the latter occurred in insufficiently arousing, non-social contexts. Consequently, it is important for laboratory studies to compare behavior in social and non-social contexts in order understand how social contexts alter behavior and to better predict behavior in everyday social settings.
1.3.1 Decision-making for and with peers

Previous studies investigating the effect of peer presence on decision-making have examined reward-processing for oneself. Yet many decisions made in social contexts involve outcomes that affect not only oneself but also others who are present. The second aim of the dissertation is to better understand how peer presence affects reward-processing for self and for peer. In study 4 (Chapter 5), my colleagues and I used fMRI to investigate if reward-related neural activity varied as a function of whether young adults (ages 18 to 28) were anticipating earning money for themselves or for their friend, and whether they were alone or watched by their friend. In study 5 (Chapter 6), we asked adolescents (high school students between the ages of 15 and 18) to make tradeoffs between rewards for themselves and rewards for their friends and compared their behavior when alone to their behavior when watched, and to the behavior of a comparison sample of adults. Our results suggest that peer presence increases young adults’ reward-processing after controlling for age, but that rewards for self and for friend are similarly processed when the two are independently earned. Adolescents, however, prioritize reward for self over reward for friend when one comes at a cost to the other, though this self-reward bias is reduced by peer presence and low friendship conflict.
2. Five-year-olds do not show ambiguity aversion in a risk and ambiguity task with physical objects

Previous studies investigating decision-making under uncertainty in young children have focused on capturing attitudes towards risk (Harbaugh et al., 2002; Levin, Weller, et al., 2007; Paulsen, Carter, et al., 2012; Paulsen et al., 2011) and have neglected to examine young children’s attitudes towards ambiguity. Yet everyday decisions are more likely to be ambiguous than risky, so it is important to understand the developmental trajectory of ambiguity preferences in order to better predict everyday decision-making. Here, we developed a novel paradigm to represent risk and ambiguity to young children and found that 5-year-old children exhibit no evidence of ambiguity aversion.¹

2.1 Introduction

In the field of decision science, economists and psychologists formally distinguish between two types of uncertainty: risk, in which outcomes are uncertain but their probabilities are known (e.g. a 50% chance of winning $10, otherwise $0), and ambiguity, in which outcomes are uncertain and their probabilities are unknown (e.g. some unknown chance of winning $10, otherwise $0). Adult decision makers exhibit ambiguity aversion, or the preference for risky gambles over ambiguous gambles with equivalent potential outcomes. This was first demonstrated in the classic Ellsberg Urn

¹ Please note that this chapter uses material from a coauthored paper that has been submitted for publication (Li et al., submitted)
paradigm (Ellsberg, 1961), in which participants preferred to draw from a physical urn containing 50% winning and 50% losing balls over drawing from an urn containing some unknown ratio of winning to losing balls. Throughout the decades since Ellsberg’s seminal work, ambiguity aversion has been consistently found in adult decision-makers in a variety of different tasks (S. W. Becker & Brownson, 1964; Einhorn & Hogarth, 1986; Fox & Tversky, 1995; Hsu, Bhatt, Adolphs, Tranel, & Camerer, 2005; Yates & Zukowski, 1976; see Camerer & Weber, 1992; Trautmann & van de Kuilen, 2015 for review).

Many everyday decisions are formally ambiguous—even if they are colloquially described as “risky”. For example, a child may know that it is “risky” to climb to the top of the jungle gym, but she doesn’t know the exact probabilities of falling and hurting herself. Consequently, for people’s everyday decisions, ambiguity preferences may be better predictors than risk preferences (i.e., preferences for certain outcomes over economically equivalent risky outcomes). In fact, two studies have found that ambiguity aversion, but not risk aversion, correlates negatively with self-reported everyday reckless behavior in older children, adolescents, and adults (Blankenstein et al., 2016; Tymula et al., 2012). Such correlations, when linked to the finding that adolescents are less ambiguity averse compared to adults (Tymula et al., 2012), have led to the conjecture that the developmental peak in reckless everyday decision-making found in adolescents is driven by their tolerance for ambiguity (Shulman, Smith, et al., 2016) –
which in turn suggests that public health interventions should be tailored to adolescents’ ambiguity attitudes (Tymula et al., 2012).

More recent studies with younger populations, however, have found that ambiguity tolerance is not unique to adolescence. Developmental work has found that 8-year-olds are also less ambiguity averse compared to adults (Li, Brannon, & Huettel, 2015), and a cross-sectional study of participants between the ages of 10 and 25 found ambiguity aversion to linearly increase with age, with no evidence of a quadratic trend or peak in adolescence (Blankenstein et al., 2016). Characterizing ambiguity preferences in young childhood could thus provide insight into its developmental timecourse, allowing better appreciation of later changes in adolescence and suggesting developmentally earlier opportunities for intervention to reduce maladaptive decision-making. For example, the assumption that the adolescent peak in everyday reckless behavior is mirrored by laboratory risk-taking findings has been challenged by studies showing that young children take more risks compared to adolescents (Eshel et al., 2007; Paulsen, Carter, et al., 2012; Paulsen et al., 2011; Weller, Levin, & Denburg, 2011; see Defoe et al., 2015; Paulsen, Platt, et al., 2012 for review) and highlighted the need to investigate broader developmental trajectories in developmental decision-making research.

The few aforementioned currently published developmental studies of ambiguity aversion (Blankenstein et al., 2016; Li et al., 2015; Tymula et al., 2012; Tymula,
Rosenberg Belmaker, Ruderman, Glimcher, & Levy, 2013) used abstract, computerized stimuli to represent risk and ambiguity. Risky stimuli represented by segmented pies or bars depicting probabilities, however, may be challenging for young children to grasp before they receive formal education in probability or proportions. Furthermore, ambiguous stimuli that rely on occluded pies or bars to represent hidden probabilities involve complex verbal explanations of the occluded information – making them even more difficult for young children to comprehend. Accordingly, because the classic Ellsberg Urn paradigm relies upon verbal explanations of each urn’s contents, it would likely tax the limits of young children’s attention spans and working memory. Due to such methodological challenges, no studies to date have evaluated the ambiguity preferences of children younger than eight.

In this study, we developed a novel method of representing risk and ambiguity with physical objects that allowed us to measure 5-year-olds’ ambiguity attitudes. Though previous studies have used physical objects to represent risk to 5-year-olds (Harbaugh et al., 2002; Levin & Hart, 2003; Schlottmann & Anderson, 1994), this is the first study to successfully present ambiguity to young children and measure consistent choice behavior.
2.2 Method

2.2.1 Participants

Thirty-two 5-year-old children and 32 adults were recruited for the study. Two children were not tested after training trials revealed that they did not understand the task (see Procedure), leaving a final sample of 30 children (17 female; range = 5.1-5.8 years; mean age = 5.5 years) and 32 adults (18 female; range = 18.2-31.9 years; mean age = 22.7).

2.2.2 Materials

In classic Ellsberg Urn-style studies, risky and ambiguous stimuli are constructed by placing winning- and losing-colored balls into transparent (risky) and opaque (ambiguous) urns, with the urns’ contents either described or labeled. For our child-friendly risk and ambiguity task, we represented winning and losing balls with plastic Easter eggs of two colors. Children were taught that all eggs of one color contained a sticker while eggs of the other color were empty. Adults were taught that eggs of one color would earn them money towards a bonus payment while eggs of the other color would earn no money. The winning color was counterbalanced across participants.

Risky “urns” were sheer socks containing a row of eggs, such that both the colors and number of eggs was visible. Ambiguous “urns” were opaque socks containing a row of eggs, such that the eggs’ colors were obscured but the number of eggs was visible (Figure 3). This method of representing risk and ambiguity overcomes previous
challenges by allowing participants to immediately see how many eggs are in each “urn” and whether the colors of the eggs are known or unknown.

Figure 3: Risky versus ambiguous stimuli used to test ambiguity preferences. Participants made a series of binary choices between physical stimuli representing risky (in this example, 3 winning and 3 losing eggs; left) and ambiguous (always containing 6 eggs of unknown colors; right) gambles.

2.2.3 Procedure

Participants were first taught the winning (W) and losing (L) color. All participants then passed a binary test of choosing between 1W egg and 1L egg. Next, participants were shown risky socks and taught that the contents of a chosen sock would be placed into an opaque container, from which they would randomly draw one egg and keep its contents. Participants completed a risky/risky training trial (4W-2L/2W-4L)
and a risky/certain training trial (5W-1L/4W-0L). Two children who incorrectly chose 5W-1L over 4W-0L, demonstrating a lack of understanding of the probabilistic nature of the socks, were not further tested. Participants were then shown five example ambiguous socks and taught that they contained eggs of unknown colors, which could be all winning (4W-0L), all losing (0W-4L), or any mix of both colors (3W-1L, 2W-2L, 1W-3L).

Finally, participants completed 7 risky/ambiguous test trials using 6-egg socks. Each possible risk level (6W-0L through 0W-6L) was presented side-by-side with an ambiguous 6-egg sock (also containing 6W-0L through 0W-6L; Figure 3). Left/right placement of the risky/ambiguous socks and the order of the 7 risky socks was presented in one of four randomizations. The order of the 7 ambiguous socks was randomly selected for each session and unknown to both the participant and the experimenter. On each trial, participants’ chosen sock was set aside for resolution at the end of the session. Children kept all stickers that they won by drawing from their chosen socks, while adults exchanged each drawn winning egg for a $0.50 bonus payment. For adults, the amount of bonus per winning egg was not revealed until the end of the session in order to control for individual differences in the valuation of small amounts of money.

2.3 Results

All adults and all but two 5-year-olds made consistent choices that switched from choosing risky to choosing ambiguous at a certain probability of risk, with only 3
preference reversals in the 5-year-olds’ 180 trials (Figure 4). This striking consistency indicates that children understood the task. Moreover, on the 50% risky (3W-3L) versus ambiguous trials analogous to the classic Ellsberg Urn task, exactly 50% of the 5-year-olds chose risk and 50% chose ambiguity (Figure 4A). In contrast, 65.6% of our adult sample chose risk on the 50% risky versus ambiguous trials (Figure 4B), exhibiting levels of ambiguity aversion (one-tailed binomial test vs. chance, $p = 0.055$) similar to those previously reported in physical Ellsberg Urn-style tasks (Compare to 63% reported in Trautmann, Vieider, & Wakker, 2011 and 64.5%, 78.3%, and 70.7% reported in Pulford & Colman, 2008).

Figure 4: Five-year-old children make consistent and ambiguity neutral choices while adults are ambiguity averse. A) Five-year-olds exhibit no ambiguity aversion, with 50% of children preferring 50-50 risk to ambiguity. B) Adults exhibit ambiguity aversion, with 65.6% of adults preferring 50-50 risk to ambiguity. Shaded grids depict the choices of participants (left vertical axis) at each probability of risky sock (horizontal axis). The overlaid logistic regression line shows each group’s proportion of risky choices at each risky sock (right vertical axis; shaded area around regression line indicates 95% confidence interval).
We next categorized participants’ choice preferences as strongly ambiguity seeking (chose risk on 2 or fewer trials), weakly ambiguity seeking (chose risk on 3 trials), weakly ambiguity averse (chose risk on 4 trials), or strongly ambiguity averse (chose risk on 5 or more trials; Figure 5). Both the chi-squared test \( \chi^2(3, N = 62) = 8.37, p = 0.03 \) and Fisher’s exact test \( p = 0.04 \) indicated significantly different preference distributions between children and adults, with relatively more adults than children showing weak ambiguity aversion and relatively more children than adults exhibiting strong ambiguity seeking and ambiguity aversion. Thus, 5-year-olds exhibited no evidence of ambiguity aversion on a task that evoked ambiguity aversion in adults.

![Pie charts showing preference distributions](image)

**Figure 5:** Children and adults exhibit different distributions of ambiguity attitudes, with relatively more adults than children showing weak ambiguity aversion and relatively fewer adults than children exhibiting strong preferences.

We note that adults were not significantly more ambiguity averse compared to children in their proportion of risky choices across all trials \( t(60) = 0.85, \) one-tailed \( p = 0.20, \) Cohen’s \( d = 0.21 \). This non-significant finding may result from significantly greater
variance in children’s choices compared to those of adults (Bartlett’s test for homogeneity of variances, \( k^2(1) = 13.82, p < 0.001 \)).

### 2.4 Discussion

Using simple physical representations of ambiguity and risk, we found 5-year-old children to exhibit no ambiguity aversion in a task that evoked ambiguity aversion in adults. Nonparametric testing on categorically defined choice preferences showed that children and adults exhibited significantly different distributions in their choice preferences. Nearly all adults exhibited weak preferences, with the majority expressing weak ambiguity aversion. The children, on the other hand, were equally likely to be ambiguity averse and ambiguity seeking, and their preferences were distributed across all categories of weak and strong ambiguity aversion and ambiguity seeking.

In our final sample, all children made correct probability-based choices in training, and all but two made consistent choices without preference reversals. As a result, we are confident that 5-year-olds understood the stimuli and task, and that their greater variance in choice preferences is not simply random noise. While nearly all adults switched their choice from choosing risky to choosing ambiguous around the 50% risky sock, over one third of our child sample did not. It may be that children, unlike adults, have not developed a choice heuristic based around the 50% risk level, perhaps because children lack formal education in probabilities and proportions.
We note that our task design features only a small number of trials, which is well-suited for small children but does limit the fidelity with which we can determine participants’ indifference points or make statistical comparisons. Because each sock contained only 6 eggs, we can only determine indifference points within a 17% (1/6) range. For example, most of our adults (19/32) switched from preferring risk to preferring ambiguity between the 3W-3L and 2W-4L socks, so we know only that they value the ambiguous socks somewhere between a 50% and 33% chance of winning. Though more fine-grained determinations of individual preferences could be made using longer socks that could fit more eggs, we note that increasing the numerical range of the stimuli (and thus experimental complexity) trades off against the simplicity of the task and its appropriateness for young children.

Our findings indicate that ambiguity aversion is absent in young children; however, additional work is needed to determine the features of ambiguity aversion that change over development. For example, ambiguity aversion can arise when interacting with another person who has more knowledge of outcome probabilities (Fox & Tversky, 1995), such as the experimenter who created the ambiguous stimuli. Adult studies of ambiguity aversion attempt to control for this information asymmetry and potential distrust in the experimenter by allowing participants to choose which stimulus condition leads to winning outcomes (e.g., the winning ball color; see Trautmann & van de Kuilen, 2015). The physical nature of our stimuli precluded participants from
choosing their own winning color because stickers were embedded in the winning eggs (though we reiterate that we did counterbalance winning color across participants). Accordingly, our children’s lack of ambiguity aversion may indicate a greater willingness to trust the experimenter. Previous work has shown that three- to five-year-old children quickly adapt their decision-making to distrust an unreliable experimenter who promises but does not deliver toys and stickers (Kidd, Palmeri, & Aslin, 2012), so future studies could manipulate experimenter trustworthiness to determine if that affects children’s ambiguity preferences.

Ambiguity aversion could also be considered a form of pessimism, such that one assumes worse than even odds for the unknown gamble. Work with older children (ages 9 and up) has found that the ability to learn from negative feedback and worse than expected outcomes increases with age (Cauffman et al., 2010; Moutsiana et al., 2013). Thus, ambiguity aversion may develop as children increasingly interact with an uncertain environment, within which they become better at learning from, and thus increasingly expect, negative outcomes.

Finally, future work is needed to understand how ambiguity preferences of young children relate to their everyday behavior. It may be that ambiguity tolerant young children may be just as prone to reckless behavior as adolescents, but they do not present a public health problem because of sociocultural factors restricting their freedom and access to potentially dangerous situations (Willoughby et al., 2013). Yet, if ambiguity
tolerance is present prior to adolescence, interventions to reduce maladaptive decision-making by changing ambiguity attitudes could also be targeted towards children.

Alternatively, it may be that ambiguity preferences observed in economic tasks are independent from ambiguity preferences in other domains such as health and safety or social interactions (Paulsen, Platt, et al., 2012; Weber, Blais, & Betz, 2002). If so, then future work should evaluate a wider range of decision-making domains in which ambiguity aversion is expressed.

2.4.1 Conclusions

The current study finds that children do not exhibit ambiguity aversion at 5 years of age in a task that evokes ambiguity aversion in adults. Additional research is needed to test why ambiguity aversion is absent in young children, how it emerges over development, and how it interacts with everyday decision-making.
3. Children do not exhibit ambiguity aversion despite intact familiarity bias

In Chapter 2, we established that 5-year-old children do not exhibit ambiguity aversion. Here, we investigate the ambiguity preferences in slightly older 8- and 9-year-old children to further map out the developmental trajectory of ambiguity attitudes. Using three measures derived from behavior on computerized tasks, we find no evidence of ambiguity aversion in 8- and 9-year-old children and significantly less ambiguity aversion in children compared to adults.²

3.1 Introduction

Economists and psychologists distinguish between two types of decision-making under uncertainty: risky decisions feature uncertain outcomes with known probabilities (i.e. a 50% chance of winning $5), while ambiguous decisions feature uncertain outcomes with unknown probabilities (i.e. an unknown chance of winning $5; Ellsberg, 1961; Knight, 1921). Notably, while decision makers are averse to both types of uncertainty, decision makers tend to be even more averse to ambiguity than they are to risk – at least when tested as adults. For example, when offered the chance to win a prize by drawing a red ball from a risky urn of 50% red, 50% black balls or an ambiguous urn with an unknown mix of red and black balls, adults prefer to draw from the risky urn (Ellsberg, 1961). Adults are also willing to pay more for the chance to draw from a risky urn than

² Please note that this chapter uses material from a coauthored paper that has been published in Frontiers in Psychology (Li et al., 2015)
from an ambiguous urn (Eisenberger & Weber, 1995). Ambiguity aversion has been consistently found in studies of adult decision-making behavior (see Camerer & Weber, 1992 for review) – and it shares at least some similarities with risk aversion (Lauriola, Levin, & Hart, 2007).

Evidence suggests, however, that risk and ambiguity engage distinct processes as well (Lauriola et al., 2007). Adults’ behavioral risk preferences have been found to be correlated with their ambiguity preferences only under certain conditions (Lauriola & Levin, 2001) or not at all (Hogarth & Einhorn, 1990; Levy, Snell, Nelson, Rustichini, & Glimcher, 2010). Studies using neuroimaging techniques have found risky and ambiguous decision-making to share some neural processes in reward-related brain regions (Levy et al., 2010) but also to engage distinct circuitry elsewhere in the brain (Bach, Seymour, & Dolan, 2009; Hsu et al., 2005; Huettel, Stowe, Gordon, Warner, & Platt, 2006; Krain, Wilson, Arbuckle, Castellanos, & Milham, 2006). Because assessments of risk and ambiguity have been found to be both behaviorally and neurally distinct, a complete understanding of decision-making under uncertainty must include both risky and ambiguous decision-making.

Several studies have investigated the development of risk preferences in children (Eshel et al., 2007; Harbaugh et al., 2002; Levin & Hart, 2003; Levin, Hart, Weller, & Harshman, 2007; Levin, Weller, et al., 2007; Paulsen, Carter, et al., 2012; Paulsen et al., 2011; Rakow & Rahim, 2010; Weller et al., 2011) with the ultimate goal to predict and
prevent real-world maladaptive reckless behavior. Decisions made outside of the laboratory, however, are more likely to be ambiguous than risky, as individuals rarely know the exact probability contingencies of such decisions. Because preferences for ambiguity may better predict real-world decision-making than do preferences for risk, an understanding of the development of ambiguity preferences is important for guiding policies to promote advantageous decision-making. Yet there is a paucity of studies investigating how ambiguity aversion emerges and changes across development. Just one study has compared adolescents (12- to 17-year-olds) to adults and found reduced ambiguity aversion in adolescents relative to adults in the gain domain (Tymula et al., 2012) but similar levels of ambiguity neutrality in adolescents and adults in the loss domain (Tymula et al., 2013). Another study found ambiguity aversion in adolescents (10- to 18-year-olds) but did not include an adult comparison group (Sutter, Kocher, Glätzle-Rützler, & Trautmann, 2013). To the best of our knowledge, there have been no prior studies comparing ambiguity aversion in children to that of adults.

In the current study, we characterized attitudes towards risk and ambiguity in 8- and 9-year-old children and a comparison group of 19- to 27-year-old adults. Were children to treat ambiguity in the same manner as adults, we would find ambiguity aversion in both age groups. Instead, we found no evidence for ambiguity aversion in children, significant evidence for ambiguity aversion in adults, and significantly greater ambiguity aversion in adults than in children. Because different methods for measuring
preferences can elicit inconsistent valuations of the same gamble (Lichtenstein & Slovic, 1971), we used multiple tasks in order to minimize the chance that our conclusions were specific to a particular task. Our results were consistent across multiple tasks and independent measures, indicating that our findings were robust to different methods of preference measurement. We additionally evaluated whether differences in ambiguity aversion between children and adults might, instead, reflect a relative preference for familiar stimuli – as advanced as a potential explanation for ambiguity aversion in adults (Fox & Tversky, 1995; Fox & Weber, 2002; Heath & Tversky, 1991). We measured children’s preference for betting on items that provided an illusion of greater knowledge in a child-friendly familiarity bias task, and found that children (like adults) exhibited a significant familiarity bias. Our findings indicate that ambiguity aversion emerges over the course of development from childhood to adulthood but disconfirm the alternative explanation that this emergence results from a delayed familiarity bias.

3.2 Materials and methods

3.2.1 Participants

Forty-two children (21 female; mean age = 8.7 years; range = 8.1 to 9.9 years) and forty young adults (17 female; mean age = 22.4 years; range = 19.2 to 27.8 years) were recruited from the Raleigh-Durham-Chapel Hill area of North Carolina. We chose children of this age range because they are the youngest age that could comprehend all task instructions, are just beginning to receive formal education in fractions (“Common
Core State Standards Initiative,” 2015), and are starting to make complex, accurate assessments of probability (Falk, Yudilevich-Assouline, & Elstein, 2012). Informed consent was collected from adult participants and parents of child participants, and written assent was collected from child participants under a protocol approved by the Institutional Review Board of Duke University. Children’s parents were paid $10 for their child’s participation, plus $10-15 for travel expenses. Child participants received toys of their choice. Adult participants were paid $10, plus a cash bonus that was based on the outcome of a randomly selected Bar Choice trial, a randomly selected Willingness to Pay trial, and their accuracy on the Familiarity Bias task (see Tasks below).

3.2.2 Bar Stimuli and Training

Participants were informed that they would be playing games to win tokens, with the goal to win as many tokens as possible. Children were informed that the tokens could be used to purchase prizes (toys and stickers) at the end of the study, while adults were informed that the tokens would be exchanged for a cash bonus at the end of the study. In order to minimize differences in subjective reward valuation between participants or age groups (Geier & Luna, 2012), the exchange rates for the tokens were not revealed to participants until the end of the experimental session. Children’s exchange rates were set on an individual basis so that all children could “purchase” one high quality toy or two medium quality toys. The exchange rate for adults was $0.25 per token.
Stimuli consisted of bars divided into red and blue portions (Hayden, Heilbronner, & Platt, 2010; Levy et al., 2010), in which the colors represented the chance of winning a small (2 tokens) or large (12 tokens) reward. The color representing the large reward was counterbalanced across participants. The red portion of the bars always appeared above the blue portion. Eleven risky stimuli (Figure 6A) representing 10%, 25%, 33%, 40%, 45%, 50%, 55%, 60%, 67%, 75%, and 90% chances of winning were used with all of the adults and 32 of the children (ten children used a subset of 7 risky stimuli representing 10%, 25%, 33%, 50%, 67%, 75%, and 90% chances of winning; after initial testing in those ten children revealed drastic preference shifts between 33% and 50% or between 50% and 67% chances of winning, additional levels of risk were added to capture more subtle changes in preference). Ambiguous stimuli (Figure 6B) featured a gray occluder centered at the midpoint of a risky bar. The size of the occluder varied across trials to determine the level of ambiguity (33%, 50%, 80%, and 100%). The ambiguous bars revealed equivalent amounts of red and blue at the endpoints.
Figure 6: Stimuli and tasks. Red and blue represent the chance of winning a small (2 tokens) or large (12 tokens) reward. The color representing the large reward was counterbalanced across participants. A) Example risky bars. A total of 11 different risky bars representing different probabilities were used. B) All 4 ambiguous bars used. C) Example Bar Choice trial featuring a risky bar versus an ambiguous bar. Participants indicated with a key press which of the two bars they preferred. D) Example of a Bar Choice “catch” trial. If red represented the bigger win, participants should select the risky bar. If blue represented the bigger win, participants should select the ambiguous bar. E) Example Willingness to Pay (WTP) trial. Each bar was presented on the left of the screen with its endpoints labeled with their associated reward values. Participants used arrow keys to toggle the number on the right up or down until it reached their maximum willingness to pay for the displayed bar.

All participants were trained in the experimental stimuli and tasks before data collection. Children were trained one-on-one by an experienced experimenter. Adults read the instructions independently and then completed training trials under an experimenter’s supervision. The reward value (2 or 12 tokens) represented by the bars’ colors (red and blue) was explicitly stated to participants. The ambiguous bars were
explained via animations in which the occluder moved laterally off a 50% ambiguous bar to reveal what colors were beneath it. All different combinations of red and blue (i.e. all red, all blue, half red and half blue, more red than blue, and more blue than red) were shown to underscore that the occluder could be hiding any probability. Both children and adults had to correctly answer questions about the stimuli and procedures before they were allowed to begin the experimental session. For example, to demonstrate their understanding of the risky stimuli, participants had to correctly explain which of several risky bars represented the greatest chance of winning the most tokens. To demonstrate their understanding of the ambiguous stimuli, participants had to correctly explain which risky bars could and could not be under an ambiguous bar’s gray occluder. Children were asked and answered the questions verbally while adults answered the same questions on a worksheet. If participants did not answer a question correctly, the experimenter repeated the training instructions until the participants could answer the question correctly. Average training time was approximately 15 minutes for children and 10 minutes for adults.

3.2.3 Tasks

Participants performed four tasks in the following order: 1) Bar Choice (approximately 15 minutes), 2) Willingness to Pay (approximately 10 minutes), 3) Bar Probability (approximately 5 minutes), and 4) Familiarity Bias (approximately 5
minutes). Total session time was approximately 50 minutes for children and 45 minutes for adults.

3.2.3.1 Bar Choice

In the Bar Choice task, participants were asked to choose which of two bars they preferred (Figure 6C). Participants were shown all possible pairings of risky versus ambiguous bars (28 trials for the 10 children who used the limited set of risky stimuli; 44 trials for all other participants) and ambiguous versus ambiguous bars (6 trials for all participants). The bars remained on the screen until participants indicated their preference using a left or right key press. After a key press was made, a box highlighted the chosen bar, and participants were given the opportunity to change their response. A second key press was required to confirm the highlighted choice in order to minimize impulsive responding. The inter-trial-interval was 1-second.

Left and right positions of the risky and ambiguous bars were counterbalanced across trials. The order of trials was randomized across participants. Participants received no outcome feedback during the task. Instead, they were told that one trial would be selected at random at the end of the session, and they would be paid according to the outcome of their selected bar on that trial.

Six of the risky versus ambiguous trials served as “catch” trials because they featured a choice with an objectively correct answer. On these trials the switch from red to blue in the risky bar occurred within the portion of the bar that was not occluded in
the ambiguous bar (Figure 6D; 10% win-33% ambiguous, 10% win-50% ambiguous, 90% win-33% ambiguous, 90% win-50% ambiguous, 25% win-33% ambiguous, and 75% win-33% ambiguous). The risky bar therefore clearly contained either a greater or smaller amount of the winning color than the ambiguous bar. These catch trials served as exclusion criteria for the Bar Choice task: a participant was excluded from analyses if s/he missed one or more of these “catch” trials. Catch trials were excluded from reported results and analyses.

Data from seven children and 1 adult were excluded from the Bar Choice task on the basis of these criteria, leaving a final Bar Choice sample of 35 children (17 female; mean age = 8.7 years) and 39 adults (16 female; mean age = 22.4 years).

3.2.3.2 Willingness to Pay (WTP)

In the Willingness to Pay (WTP) task, participants were endowed with 12 tokens. They were then shown each risky and ambiguous bar with the red and blue ends labeled with their respective reward values. Participants were asked to press arrow keys to toggle a number up or down until the number reached their maximum WTP for the chance to play that bar (Figure 6E). An additional key press confirmed the WTP value selection.

The order of trials was randomized across participants, and each trial’s WTP start value was randomized to start at 2 or 12. Participants were informed that one trial would be selected at random at the end of the session and a price would be randomly
selected for that trial. If participants’ WTP was greater than or equal to the randomly selected price, they would pay that price from their endowment to “buy the bar” and then be paid according to the outcome of their purchased bar. If their WTP was less than the randomly selected price, they would pay nothing and receive nothing (G. M. Becker, Degroot, & Marschak, 1964).

Data from the 7 children and 1 adult whose data were excluded from Bar Choice task for failing to understand the bar stimuli, as noted above in Tasks: Bar Choice, were also excluded from WTP. Data from an additional child was excluded from WTP because her WTP for the risky bars did not increase with the probability of winning, indicating a failure to understand the WTP task. All other participants’ WTP for the risky bars increased with the probability of winning, leaving a final WTP sample of 34 children (16 female; mean age = 8.7 years) and 39 adults (16 female; mean age = 22.4 years).

3.2.3.3 Bar Probability

In the Bar Probability task, participants were shown each risky and ambiguous bar and were asked to predict how many times the bar would result in red and blue across 100 hypothetical trials. Children verbally gave their responses to an experimenter, while adults indicated their responses on a worksheet.

One child who struggled to produce responses on a scale of 100 trials was asked to give responses out of 10 hypothetical trials. Four children who struggled to produce
responses that summed to 100 trials were permitted to indicate their response for just one color of their choosing rather than for both colors. These modifications allowed children with limited mathematical skills to perform the task while reducing frustrations.

3.2.3.4 Familiarity Bias

In order to measure familiarity bias, participants were given the chance to win additional tokens by correctly guessing the final word on a random page in either a familiar book or an unfamiliar book. Participants were asked to select one of two books for which they would be asked to solve a multiple-choice question with four possible answers (Figure 8A). If they guessed the correct answer (25% chance), they would win an additional 5 tokens. The order of presentation of the books was counterbalanced across participants. Children received verbal directions and indicated their responses verbally or by pointing, while adults received written directions and indicated their response on a worksheet.

Forty-one children completed the Familiarity Bias task (one male 8.3-year-old did not complete this task due to lack of time). For children, the familiar book was always the U.S. Edition of *Harry Potter and the Sorcerer’s Stone* (HP-US) by J.K. Rowling. The unfamiliar book was either the corresponding U.K. Edition of the same book, *Harry Potter and the Philosopher’s Stone* (HP-UK), or *Hammer of Witches* (HoW) by Shana Mlawski. For the 27 children who recognized the physical HP-US book but did not
recognize the physical HP-UK book, the unfamiliar book was HP-UK. These children were told that both books were the same story about Harry Potter and his first year at magic school, but one was sold in the U.S. while the other was sold in the U.K. These children were shown and read the opening of Chapter 4 in both books in order to underscore that both books featured the same text but different page numbers.

The remaining 14 children either recognized the Harry Potter character but not the physical HP-US book or recognized both the HP-US book and the HP-UK book. For these children, the unfamiliar book was HoW. None of these children recognized HoW. These children were told that HP-US was “a story about a boy who can do magic and has adventures in his first year of magic school”, while HoW was “a story about a boy who can do magic and has adventures in his first time on a sailing ship”.

Adults did the Familiarity Bias task with HP-US and HP-UK. Thirty-two of 40 adults indicated having read either HP-US or HP-UK (12 female; mean age = 22.2 years). Their responses were coded with the edition that they had previously read serving as the familiar book. Familiarity bias data were not analyzed for the remaining 8 adults who reported having read neither Harry Potter book.

3.3 Results

3.3.1 Bar Choice

On the risky versus ambiguous trials, we found evidence of 1) ambiguity aversion in adults but not in children and 2) significantly greater ambiguity aversion in
adults than in children. Children chose the risky and ambiguous bars equally often on non-catch trials (chose risk 51.1% of the time; compared to 50% chance, \( t(34) = 0.41 \), 2-tailed \( p = 0.69 \)). Adults chose the risky gambles 59.5% of the time on non-catch trials, significantly more often than chance \((t(38) = 5.29, 2\text{-tailed } p < 0.001)\) and significantly more often than the children did \((t(72) = 2.69, 2\text{-tailed } p = 0.01; \text{Cohen’s } d = 0.60; \text{see Figure 7A})\). These results still held when excluding the 10 children who saw only 7 levels of risk (children compared to 50% chance, \( t(24) = 0.68, 2\text{-tailed } p = 0.51 \); children compared to adults \( t(62) = 2.11, 2\text{-tailed } p = 0.04; \text{Cohen’s } d = 0.53 \)).

![Figure 7: Evidence of ambiguity aversion in adults but not in children and significantly greater ambiguity aversion in adults than in children across three separate measures. A) Frequency of choosing the risky bar on risky bar versus ambiguous bar trials in the Bar Choice task. B) Frequency of choosing the less ambiguous bar on ambiguous bar versus ambiguous bar trials in the Bar Choice task. C) Difference in WTP for risky bars and ambiguous bars in the WTP task. Dotted lines indicate chance performance. * indicates significance at \( p < 0.05 \).](image)

On the ambiguous versus ambiguous trials, we found qualitatively similar results. Children were equally likely to choose the more and less ambiguous bars (chose less ambiguous 56.67% of the time; compared to 50% chance, \( t(34) = 1.11, 2\text{-tailed } p = 0.28 \)). Adults, in contrast, chose the less ambiguous option 72.2% of the time, significantly more often than chance \((t(38) = 4.42, 2\text{-tailed } p < 0.001)\) and significantly
more often than the children did ($t(72) = 2.00$, 2-tailed $p = 0.05$, Cohen’s $d = 0.46$; see Figure 7B). For both children and adults, the likelihood of choosing risky on risky versus ambiguous trials significantly correlated with the likelihood of choosing the less ambiguous bar on ambiguous versus ambiguous trials (children: $r(33) = 0.68$, $p < 0.001$; adults: $r(37) = 0.55$, $p < 0.001$), indicating consistent attitudes towards ambiguity across two different trial types within the task.

### 3.3.2 Willingness to Pay (WTP)

On the WTP task, we again found evidence of 1) ambiguity aversion in adults but not in children and 2) significantly greater ambiguity aversion in adults than in children. Children indicated no difference in WTP for the risky bars (average WTP = 6.51 tokens) and the ambiguous bars (average WTP = 6.68 tokens; paired $t(33) = -0.69$, 2-tailed $p = 0.50$), while adults were willing to pay significantly more for the risky bars (average WTP = 5.53 tokens) than for the ambiguous bars (average WTP = 4.78 tokens; paired $t(38) = 4.67$, 2-tailed $p < 0.001$). The difference in WTP between the risky and ambiguous bars was significantly greater in adults than in children ($t(71) = 3.15$, 2-tailed $p = 0.002$; see Figure 7C).

For both children and adults, the likelihood of choosing risk on risky versus ambiguous bars in the Bar Choice task did not correlate with the difference in their WTP between the risky and ambiguous bars (all $p$s > 0.1). This result is consistent with
previous findings reporting shifts in preferences when comparing forced choice and willingness to pay tasks (Lichtenstein & Slovic, 1971).

### 3.3.3 Bar Probability

All participants included in the Bar Choice sample reported predicted outcomes for the risky bars that correctly scaled with the bars’ actual probabilities. Children’s predicted outcomes linearly fit to the bars’ actual probability with an average slope of 1.06 (range 0.57-1.58), while adults’ predicted outcomes fit with an average slope of 1.04 (range 0.78-1.21). These results indicate that children and adults understood the meaning of the risky bar stimuli and were fairly accurate in perceiving the bars’ proportions of red and blue.

There were no significant differences in children and adults’ reported predicted outcomes for the ambiguous bars: children reported that an average of 50.6% of ambiguous bar outcomes would result in their favorable color (yield a large reward), while adults reported that an average of 51.1% of ambiguous bar outcomes would result in their favorable color ($t(72) = -0.31$, 2-tailed $p = 0.76$). Neither group’s predicted outcomes for the ambiguous bars significantly differed from a 50% chance of resulting in the favorable color (children: $t(34) = 0.64$, 2-tailed $p = 0.53$; adults: $t(38) = 0.88$, 2-tailed $p = 0.38$). Though both children and adults explicitly reported a rational 50-50 estimation of the ambiguous bars’ probabilities in the Bar Probability task, only children also exhibited a rational interpretation of the ambiguous bars on the Bar Choice and WTP
tasks. The discrepancy between adults’ explicitly reported values on the Bar Probability task and their preferences as determined in the Bar Choice and WTP tasks was consistent with past studies finding a disconnect between true probabilities and individuals’ revealed probability weights (Tversky & Kahneman, 1992).

3.3.4 Familiarity Bias

Children exhibited a significant familiarity bias: 75.6% of the children preferred to bet on the familiar book, a proportion significantly greater than chance (2-tailed $p = 0.002$; Figure 8B). This result remained significant when restricted to the 14 children who used HoW as the unfamiliar book (85.7% chose familiar, 2-tailed $p = 0.01$) and was marginally significant when restricted to the 27 children who used HP-UK as the unfamiliar book (70.4%, 2-tailed $p = 0.05$). This result also remained significant when restricted to the 34 children who both did the Familiarity Bias task and were included in the final Bar Choice sample (70.6%, 2-tailed $p = 0.02$).

Adults exhibited a marginally significant familiarity bias: 65.6% of the adults preferred to bet on the book that they reported having previously read (2-tailed $p = 0.11$; Figure 8B). While this is a weaker familiarity bias than what we observed in children, we note that our adult participants, all of whom lived in the US at the time of the experiment, may have recognized the physical HP-US book even if they did not report having read it. When adult analyses were restricted to the 23 adults who reported
having read HP-US, those adults exhibited a significant familiarity bias (78.3%, 2-tailed $p = 0.01$).

**Figure 8:** A child-friendly guessing game found significant familiarity bias in children. A) Participants were asked to guess the final word on a random page of a book. Physical copies of a familiar and unfamiliar book were shown, along with a page number and four possible final words for that page. Participants first indicated if they wanted to guess for the familiar book or the unfamiliar book, then indicated their guess from the four possible final words. Correct guesses (e.g. STUFF for the familiar book and COINS for the unfamiliar book) were rewarded with 5 additional tokens. B) Percentage of participants that chose to guess for the familiar book. Dotted line indicates chance performance. * indicates significance at $p < 0.05$; + indicates $p = 0.11$.

### 3.4 Discussion

Our results demonstrate that children (8-9 years old) and young adults (19-27 years old) hold significantly different attitudes towards ambiguity when making decisions about rewards. This conclusion held across two tasks and three measures. To the best of our knowledge, our study is the first to describe ambiguity preferences in pre-adolescent children.
Our study design allowed us to reject the alternative explanation that children and adults performed differently because children did not comprehend the bar stimuli. All children included in the final sample passed the same rigorous comprehension checks as the adults: 1) correctly answering comprehension questions about the risky and ambiguous bars in training, 2) correctly selecting the favorable bar on all catch trials in the Bar Choice task, and 3) reporting predicted outcomes for the risky bars that correctly scaled with the bars’ probabilities. Additionally, children, like adults, exhibited correlated ambiguity preferences during the Bar Choice task across the two different trial types (risky versus ambiguous; ambiguous versus ambiguous), demonstrating consistent attitudes towards the ambiguous bars. We also note that previous research has successfully used similar stimuli to represent probabilistic gambles with children as young as 4 and 5 years of age (Schlottmann, 2001; Schlottmann & Anderson, 1994).

We cannot, however, rule out that children were simply ignoring the occluders on the ambiguous bars and making their decisions based solely on the visibly equal amounts of red and blue on the ambiguous bars. In fact, such an approach to the ambiguous bars would represent a mathematically rational strategy that follows expected utility theory: if the midpoint-centered occluders could be covering all possible proportions of red and blue, then the average expected proportion would be a 50-50 split. Thus, simply ignoring the ambiguous occluders on the risky versus ambiguous Bar Choice trials would be a strategic, economically rational choice that does not necessarily
indicate a lack of understanding of the ambiguous bars. Future studies could use ambiguous stimuli featuring visibly uneven amounts of red and blue (Peysakhovich & Karmarkar, 2015) to investigate how children use known information when assessing ambiguity.

Our study design also allowed us to probe the role of familiarity bias in causing ambiguity aversion. As adult ambiguity aversion has been theorized to result from a preference to bet on what feels more familiar (Fox & Tversky, 1995; Fox & Weber, 2002; Heath & Tversky, 1991), a natural explanation for children’s lack of ambiguity aversion could be that they are less sensitive to familiarity. Our results argue against that alternative explanation: we found that a significant familiarity bias was present in children, even though ambiguity aversion was absent. Additional studies are needed to determine if other proposed mechanisms of ambiguity aversion in adults (see Camerer & Weber, 1992 for review) are also present in children in order to determine why ambiguity aversion is absent in children. For example, a lack of ambiguity aversion can be interpreted as a sign of optimism or lack of suspicion towards the motives of the experimenter (Kuhberger & Perner, 2003), and the emergence of ambiguity aversion from childhood to adulthood may reflect an increase in pessimism or suspicion towards others that comes with life experiences. Future studies could manipulate experimenter trustworthiness (Kidd et al., 2012) in order to determine if and how children’s expectations of the experimenter interact with their attitudes towards ambiguity.
Our results are consistent with a previous study in which 12- to 17-year-old adolescents exhibited less ambiguity aversion compared to 30- to 50-year-old adults (Tymula et al., 2012). We cannot make direct comparisons between the preferences of our child sample and the adolescent sample of Tymula and colleagues (2012) because we used different tasks to measure ambiguity aversion. We note, however, that the adolescent sample of Tymula and colleagues (2012) exhibited a significant increase in ambiguity aversion as the level of ambiguity increased, while our children were indifferent to ambiguity level on the Bar Choice trials. Thus, ambiguity aversion may increase linearly with age across development, though additional studies directly comparing children, adolescents, and adults are needed to determine if this is the case.

Finally, we note that our findings are restricted to decisions involving potential gains. As adolescents and adults have been found to be similarly ambiguity neutral in the loss domain (Tymula et al., 2013), future studies should compare children’s ambiguity preferences for losses to those of adults.

Our findings that children are surprisingly tolerant of ambiguity have important public health implications, as ambiguous decisions are analogous to most real-world decisions, in which outcome probabilities are not precisely known. In fact, ambiguity tolerance, but not risk tolerance, in adolescents was found to predict their engagement in real-world reckless behavior (Tymula et al., 2012). Many interventions targeted towards reducing real-world reckless behavior focus on adolescents because that age group is
especially vulnerable to preventable morbidity and mortality that results from poor decision-making (Keeney & Palley, 2013). Our findings point to a developmental trajectory for ambiguity tolerance that emerges prior to adolescence, in childhood. Consequently, policies aiming to reduce reckless behavior in adolescents should consider addressing the behaviors and attitudes of children, before they grow into adolescents.

3.4.1 Conclusions

Across three distinct measures in two different tasks, ambiguity aversion was absent in 8- and 9-year-old children but present in adults. When comparing risky gambles to ambiguous gambles, children were equally likely to choose risk or ambiguity while adults preferred risk over ambiguity. When comparing two gambles of varying levels of ambiguity, children were equally likely to choose the more or less ambiguous gamble while adults preferred the less ambiguous gamble. When assigning value to risky and ambiguous gambles, children priced them equally while adults were willing to pay more for risky gambles. We also found that children’s lack of ambiguity aversion was likely not driven by an indifference to familiarity, for children did exhibit a bias to bet on the familiar. Taken together, our results suggest that ambiguity aversion emerges from childhood to adulthood and is not caused by a bias toward familiarity.

In Chapters 2 and 3, we found that children do not exhibit ambiguity aversion in tasks that evoke ambiguity aversion in adults. Here, we further investigate the developmental trajectory of ambiguity preferences using a battery of behavioral tasks and self-report questionnaires to measure decision preferences and personality traits in adolescents (ages 15 to 18) and adults. Additionally, we used principal components analysis to examine the relationships between ambiguity aversion, risk aversion, loss aversion, and self-reported everyday behavior and personality measures. We found risk aversion and ambiguity aversion to be similar between our adolescent and adult groups, while loss aversion was slightly higher in our adolescent group compared to our adult group. Across both groups, we found risk, ambiguity, and loss aversion to be correlated with each other, and with a principal component of our questionnaire measures that included self-reported likelihood of engaging in everyday reckless activities and susceptibility to social influence.

4.1 Introduction

Adolescence is often characterized as a developmental period of peak reckless behavior (Casey et al., 2008; Shulman, Smith, et al., 2016; Somerville et al., 2010; Steinberg, 2007). Experimental studies of decision-making under uncertainty, however, have found conflicting results as to whether adolescents behave especially recklessly in
the laboratory. A meta-analysis of developmental decision-making studies found adolescents to take more risks compared to adults—but only on tasks with immediate outcome feedback. For tasks with delayed outcome feedback, no age group differences were found between adolescents and adults (Defoe et al., 2015). Such discrepant findings highlight how different experimental paradigms may capture different types of decision preferences. Description-based tasks that ask participants to evaluate economic gambles may measure different preferences from experience-based tasks in which participants learn about potential outcomes and their probabilities over the course of completing the task. Additionally, decision preferences regarding economic rewards in the lab may not correspond to everyday decisions involving health and safety risks or social rewards. Consequently, it is important to investigate how decision preferences in different tasks and domains may—or may not—relate to each other.

Developmental studies of decision-making have drawn heavily from behavioral economics paradigms to measure decision preferences. Two commonly measured economic preferences are those for risk (gambles with known probabilities for uncertain outcomes, such as a 50% chance of winning $10) and those for ambiguity (gambles with unknown probabilities for uncertain outcomes, such as an unknown chance of winning $10). Though risk and ambiguity may seem similar, as both involve assessing uncertain outcomes, evidence suggests that risk and ambiguity preferences in adults may only be correlated under certain conditions (Lauriola & Levin, 2001) or are not at related at all.
In developmental work, adolescents have been found to be more risk averse but less ambiguity averse compared to adults (Tymula et al., 2012), and in a cross-sectional study of participants between the ages of 10 and 25, risk-aversion was found to be stable across ages while ambiguity aversion linearly increased (Blankenstein et al., 2016). Furthermore, ambiguity but not risk preferences were found to predict self-reported everyday reckless behavior (Blankenstein et al., 2016; Tymula et al., 2012). Taken together, these studies demonstrate the importance of investigating both risk and ambiguity to more fully examine decision-making across development.

Another commonly measured economic preference is loss aversion, or the degree to which losses are more aversive than numerically equivalent gains are appetitive (Kahneman & Tversky, 1979). One model of adolescent decision-making has posited that adolescents have weak harm-avoidance systems (Ernst, Pine, & Hardin, 2006). Thus, according to this model, adolescents should be less loss averse compared to adults. A previous study comparing adolescents (ages 13 to 17) to adults (ages 25 to 30), however, found no behavioral differences in loss aversion between the two age groups. Furthermore, there was no evidence that loss aversion predicted self-reported engagement in or perception of riskiness of everyday reckless behavior (Barkley-Levenson et al., 2013). It should be noted that loss aversion has, to the best of our knowledge, only been compared between adolescents and adults in this one relatively
small sample (16 adolescents and 19 adults). More data are needed to better understand if loss aversion differs between these two developmental stages.

The development of decision-making has also been measured using dynamic, experience-based tasks. One prominent paradigm is the Balloon Analog Risk Task (BART), in which participants must decide whether to bank points in virtual balloons or continue to pump the balloons, thereby potentially earning more points but running the risk of popping the balloon and losing all points (Lejuez et al., 2002). Behavior on the BART has been found to correlate with self-reported impulsiveness and sensation-seeking in adults (ages 18 to 25; Lejuez et al., 2002), and adolescents (ages 13 to 17; Lejuez, Aklin, Zvolensky, & Pedulla, 2003), and to predict adolescent engagement in everyday reckless behaviors (Aklin, Lejuez, Zvolensky, Kahler, & Gwadz, 2005; Lejuez et al., 2007). Furthermore, a longitudinal study found BART behavior to exhibit a quadratic developmental trend from ages 8 to 28, with a peak in mid-adolescence (Braams et al., 2015). As a dynamic, experience-based task, the BART can yield developmental insights that static, description-based behavioral economics tasks cannot.

Through these various measures of decision-making preferences, participants generally exhibit great individual variation. Even in samples showing aggregate age-related changes, similar behavior can be found in individual participants of different ages (Blankenstein et al., 2016; Burnett et al., 2010). Many studies have tried to relate such variability to individual differences on a variety of self-reported personality traits,
and have yielded inconsistent results. For example, as previously mentioned, behavior on the BART was found to significantly correlate with self-reported impulsivity in two samples (Lejuez et al., 2002, 2003). The same research group, however, did not find that relationship to be significant in other samples (Lejuez et al., 2007; results approached but did not reach statistical significance in Aklin et al., 2005). Furthermore, because null findings are often not reported in published literature, it is difficult to determine how often published individual difference findings are replicated.

One significant challenge to synthesizing developmental research on decision-making is that most studies only use one or two behavioral tasks and only report relationships between their behavioral findings and a small set of self-report measures. Consequently, it is difficult to understand how different behavioral task measures relate to each other and to self-report measures. In the present study, we collected behavioral measures of risk aversion, ambiguity aversion, loss aversion, and BART performance, as well as a battery of self-report measures, in a large sample of adolescents and adults (total N = 147). This allows us to make direct comparisons between different tasks, self-report measures, and age groups. Consequently, we are able to take a more comprehensive look at how different behaviorally-measured decision-making preferences interact with age and self-reported personality scales.
4.2 Method

4.2.1 Participants

Seventy-four adults from the local community and 89 adolescents from a local high school were originally recruited for the study. One adult was excluded for not providing a birthdate, 5 adults and 2 adolescents were excluded for missing too many “catch trials” on the risk/ambiguity task (see Tasks: Risk/ambiguity aversion below), and 8 adolescents were excluded for not completing all questionnaires due to time limitations, leaving a final sample of 68 adults (mean age = 21.4 years; SD = 2.8 years; range = 18.2 to 30.1; 47 female) and 79 adolescents (mean age = 17.2 years; SD = 0.6 years; range = 15.7 to 18.8; 49 female). We note that though there was some age overlap in our two participant groups, we chose to use a cultural definition of when adolescence ends by labeling 18-year-old high-school students as adolescents and 18-year-old undergraduate students as adults (Crone & Dahl, 2012).

Informed consent was collected from adult participants and parents of adolescent participants, and written assent was collected from adolescent participants under a protocol approved by the Institutional Review Board of Duke University. All participants were paid $15, plus an additional bonus based on a randomly selected risk/ambiguity aversion trial, a randomly selected loss aversion trial, and the average points earned per balloon BART. In order to control for varying valuation of money,
points were converted to dollars using a constant exchange rate that was hidden from participants until the end of the session.

4.2.2 Tasks

Participants completed three decision-making tasks (risk/ambiguity aversion, loss aversion, BART; described below), two executive function tasks (not reported here), a computerized demographics form, and a series of computerized self-report questionnaires (described below) in a single, 90-minute session.

4.2.2.1 Risk/ambiguity aversion

Participants completed 165 trials of a risk/ambiguity aversion task, in which they chose between a safe option and a risky gamble (135 trials; Figure 9A), or a safe option and an ambiguous gamble (30 trials; Figure 9B). Risky gambles had 25%, 50%, or 75% chances of winning between 2 and 98 points and were represented by pie charts. Ambiguous gambles were unknown probabilities of winning between 3 and 84 points and were represented by a circle with a question mark. Expected value ratio of the safe to gamble options varied between 0.28 and 2. All participants saw the same risky and ambiguous trials, which were intermixed and presented in a random order.

Fifteen trials (10 risky and 5 ambiguous) were “catch trials”, in which the safe value was greater than or equal to the gamble’s win value, so participants should always choose safe. Two adolescents and 5 adults who missed more than 3 catch trials (failing a binomial test of performing better than chance) were excluded from the study, as their
choices indicated that they did not understand the task or were insufficiently attending to the task. Catch trials were excluded from all further analyses.

Each participant’s risk aversion parameter ($\alpha$) was modeled using the risky trials and a standard utility function, where $U(x)$ indicates a given choice’s utility, $P(\text{win})$ is the probability of winning, and $v$ is the amount that could be won (Equation 4.1). $\alpha = 1$ indicates risk neutrality, $\alpha < 1$ indicates risk aversion, and $\alpha > 1$ indicates risk seeking.

$$U(x) = P(\text{win}) \times v^\alpha$$

(Equation 4.1)

Each participant’s ambiguity aversion parameter ($\beta$) was modeled using the ambiguous trials, the $\alpha$ derived from Equation 4.1 and the risky trials, the below utility function for ambiguous options (Equation 4.2), and Equation 4.1 for safe options (where $P(\text{win}) = 1$). $\beta = 0.5$ indicates ambiguity neutrality (participants treat the ambiguous gamble as a 50% chance of winning), $\beta > 0.5$ indicates ambiguity aversion, and $\beta < 0.5$ indicates ambiguity seeking.

$$U(x) = (1 - \beta) \times v^\alpha$$

(Equation 4.2)

Maximum likelihood estimation was used to separately fit each participant’s $\alpha$ and $\beta$ with the following softmax function (Equation 4.3):

$$P(\text{choice}) = \frac{1}{1 + e^{-\mu(U(\text{chosen}) - U(\text{unchosen}))}}$$

(Equation 4.3)

4.2.2.2 Loss aversion

Participants were endowed with an initial 20 points before completing a loss aversion task in which they could choose to accept or reject mixed gambles consisting of
a 50% chance of winning some points and a 50% of losing some points. All possible combinations of winning 12, 16, 20, 24, 28, 32, 36, and 40 points, and losing 6, 8, 10, 12, 14, 16, 18, and 20 points were shown to participants, for a total of 64 trials. Gambles were depicted using a visual pie chart (Figure 9C).

Each participant’s risk (α) and loss (λ) aversion parameters were modeled using a standard utility function, where U(x) indicates a given gamble’s utility (Equation 4.4). Maximum likelihood estimation was used to fit each participant’s α and λ using the softmax function of Equation 4.3, where the utility of rejecting the gamble was 0. Values of α = 1 and λ = 1 indicate risk and loss neutrality, respectively. An α < 1 indicates risk aversion, an α > 1 indicates risk seeking, a λ > 1 indicates loss aversion, and a λ < 1 indicates loss seeking.

$$U(x) = 0.5 \times \text{gain}^\alpha - \lambda \times 0.5 \times |\text{loss}|^\alpha$$  
(Equation 4.4)

4.2.2.3 BART

Participants completed 20 BART trials (Lejuez et al., 2002). On each trial, participants pumped up a “balloon”, represented by a red circle, to earn points (Figure 9D). Each pump increased the physical size and value of the balloon by 1 point but also risked popping the balloon. A popped balloon earned 0 points. Participants could choose to continue pumping the balloon or bank the current balloon’s points and move on to a new balloon.
Participants were not informed that on each pump number, n, the probability of a balloon popping was $1/(64 - n)$, so balloon explosion values would form a normal distribution around 32 pumps. A running total of the number of banked points was displayed at the top of the screen on each trial.

Figure 9: Example stimuli from each task. A) An example risky trial from the risk/ambiguity aversion task, in which participants may choose between a certain 5 points or a 25% chance of 12 points. B) An example ambiguous trial from the risk/ambiguity task, in which participants may choose between a certain 5 points or an unknown chance of 12 points. C) An example gamble from the loss aversion task, in which participants may choose to accept or reject a mixed gamble with a 50% chance of +15 and a 50% chance of -10. D) An example balloon from the BART, in which participants may choose to bank their current 7 points or continue pumping the balloon to win more points but risk popping it and winning 0 points.
4.2.2.4 Questionnaires

Participants completed the below standardized questionnaires, which are briefly described below and listed in Table 1.

Three questionnaires related to numeracy and probability: an Objective Numeracy Scale (Weller et al., 2012), which measures math and probability fluency; the Subjective Numeracy Scale (Fagerlin et al., 2007), which measures subjective ratings of math and fraction/percentage fluency; and the Gambling Related Cognitions Scale (Raylu & Oei, 2004), which measures gambling-related cognitions such as beliefs about controlling probabilistic outcomes and compulsive gambling behaviors.

Four questionnaires related to social cognition: the Reading the Mind in the Eyes Test (child version; Baron-Cohen, Wheelwright, Spong, Scahill, & Lawson, 2001), which measures the ability to infer emotional states from images of eyes; the Multidimensional Scale of Perceived Social Support (Zimet, Dahlem, Zimet, & Farley, 1988), which measures perceived social support from family and friends; Peer Pressure, Popularity, and Conformity Scale (Santor, Messervey, & Kusumakar, 2000) which measures susceptibility to peer pressure, attitudes towards popularity, and tendency to conformity; and the Resistance to Peer Influence Scale (Steinberg & Monahan, 2007), which measures the ability to resist peer pressure.

Three questionnaires relating to behavioral tendencies: the mini-DOSPERT (Domain-Specific Risk-Taking), an adolescent version of the DOSPERT measuring
likelihood of engaging in and perceived riskiness of everyday behaviors in various
domains (Figner, Kim, Galván, Van Duijvenvoorde, & Weber, in prep.); the Behavioral
Inhibition Scale/Behavioral Activation Scale (BIS/BAS; Carver & White, 1994), which
measures motivations to avoid (BIS) and approach (BAS); and the Abbreviated
Impulsiveness Scale (Coutlee, Politzer, Hoyle, & Huettel, 2014), which measures
impulsiveness in the domains of inattention (ABIS Attention), spontaneous action (ABIS
Motor), and lack of planning (ABIS Nonplanning).

4.2.2.5 Principal components analysis

An exploratory principal components analyses (PCA) was performed on the
questionnaire measures using the R package “FactoMineR” (Lê, Josse, & Husson, 2008).
Data were scaled to unit variance prior to performing the PCA. This PCA allowed us to
reduce the complexity of our many questionnaire measures into fewer dimensions,
which reduces our likelihood of Type I error by reducing the number of questionnaire-
related results to analyze.

Participants’ individual coordinates for each component were compared between
the adult and adolescent groups using two-tailed t-tests. Across all participants,
individual coordinates for each component were compared to exact age and behavioral
risk-taking results using linear regression. Because the parameter estimates for the
risk/ambiguity aversion and loss aversion tasks contain noise from the model fitting
procedure, and because using parameter estimates would mean excluding additional
participants with parameters that could not be captured by our models (see Results below), we instead compared participants’ component coordinates to simpler aggregate measures of behavior: the proportion of choosing safe on risky trials, the proportion of choosing safe on ambiguous trials, and the proportion of accepting loss aversion gambles. For the BART, we selected the average number of pumps on banked balloons (Aklin et al., 2005; Lejuez et al., 2002, 2007, 2003) as the behavioral metric to compare to component coordinates.

4.3 Results

4.3.1 Risk/ambiguity aversion

For illustrative purposes, Figure 10A depicts adolescents’ and adults’ proportion of safe choices on risky trials as a function of the ratio of risky gamble expected value (EV) to safe value (divided into 6 bins), and Figure 10B depicts participants’ proportion of safe choices on ambiguous trials at each ratio of ambiguous gamble EV to safe value (assuming 50% probability for ambiguous gambles). There were no significant age-group differences in the overall proportion of safe choices on risky trials (mean adult = 0.44, mean adolescent = 0.45; \( t(145) = -0.44, p = 0.66 \)) or the overall proportion of safe choices on ambiguous trials (mean adult = 0.62, mean adolescent = 0.63; \( t(145) = -0.20, p = 0.84 \); Figure 11C). Across participants, age did not significantly correlate with the proportion of safe choices on risky trials (\( r(144) = -0.05, p = 0.56 \)) or the proportion of safe choices on ambiguous trials (\( r(144) = -0.03, p = 0.76 \)).
Seven adults and 9 adolescents had extreme or inconsistent preferences that could not be captured by our models. After excluding these participants, the remaining 61 adults and 70 adolescents still exhibited no significant differences in the proportion of safe choices on risky trials (mean adult = 0.44, mean adolescent = 0.42; $t(129) = 0.55, p = 0.59$) or the proportion of safe choices on ambiguous trials (mean adult = 0.62, mean adolescent = 0.58; $t(129) = 0.80, p = 0.43$). There were also no significant age-related differences in risk aversion (adult mean $\alpha = 0.81$, adolescent mean $\alpha = 0.65; t(129) = 1.62, p = 0.11$) or ambiguity aversion (adult mean $\beta = 0.68$, adolescent mean $\beta = 0.69; t(120) = -0.11, p = 0.91$; Figure 10D), nor any significant relationships between age and risk aversion ($r(128) = 0.13, p = 0.16$) or age and ambiguity aversion ($r(128) = 0.06, p = 0.51$).
Figure 10: Adults and adolescents exhibit similar behavior on the risk/ambiguity task. A) Adults’ and adolescents’ proportion of safe choices on risky trials as a function of the ratio between the risky gamble’s expected value and the safe value (binned). B) Adults’ and adolescents’ proportion of safe choices on the ambiguous trials as a function of the ratio between the ambiguous gamble’s expected value (assuming 50% probability) and the safe value. C) There were no significant differences between adults’ and adolescents’ overall proportion of safe choices on the risky and ambiguous trials. D) There were no significant differences between adults’ and adolescents’ parameter estimates for risk aversion or ambiguity aversion in the subset of participants with preferences that could be captured by our models (see text for details).

4.3.2 Loss aversion

For illustrative purposes, Figure 11A depicts adults’ and adolescent’s proportion of accepted gambles at each gamble EV. Overall, adults accepted a marginally
significantly greater proportion of gambles compared to adolescents (adult mean = 0.67, adolescent mean = 0.61; $t(145) = 1.98, p = 0.05$; Figure 11B). Across participants, age significantly correlated with the proportion of accepted gambles ($r(144) = 0.23, p = 0.005$).

Twelve participants (5 adults and 7 adolescents) had extreme or inconsistent preferences that could not be captured by our model. After excluding these participants, the remaining 63 adults still accepted a marginally significantly greater proportion of gambles compared to the remaining 72 adolescents (adult mean = 0.66, adolescent mean = 0.60; $t(133) = 1.82, p = 0.07$), but there were no significant differences in mean parameter estimates for risk aversion (adult mean $\alpha = 0.92$, adolescent mean $\alpha = 0.96; t(133) = -0.25, p = 0.80$) or loss aversion (adult mean $\lambda = 1.47$, adolescent mean $\lambda = 1.75; t(133) = -1.54, p = 0.13$; Figure 11C). Loss aversion did, however, marginally correlate with participant’s exact age ($r(133) = 0.24, p = 0.10$).
Figure 11: Adults and adolescents exhibited somewhat similar behavior on the loss aversion task, with adults accepting slightly more gambles compared to adolescents. A) Adults’ and adolescents’ proportion of accepted gambles as a function of the gamble’s expected value. B) Adults accepted marginally more gambles compared to adolescents. + indicates $p = 0.05$. C) There were no significant differences between adults’ and adolescents’ parameter estimates for risk aversion and loss aversion in the subset of participants with preferences that could be captured by our model (see text for details).
4.3.3 BART

On the BART, there were no significant group differences between adults and adolescents on the mean number of pumps on banked balloons (adult mean = 17.7, adolescent mean = 16.4; $t(145) = 1.26, p = 0.21$) or the number of busted balloons (adult mean = 4.78, adolescent mean = 5.42; $t(145) = -1.39, p = 0.17$). Adults did, however, bank marginally significantly greater total points across the 20 balloons of the task (adult mean = 267.24, adolescent mean = 245.35; $t(145) = 1.86, p = 0.07$). The mean number of pumps on banked balloons, the number of busted balloons, and the total points earned exhibited no significant correlations with age (all $ps > 0.1$).

4.3.4 Consistent preferences across behavioral task measures

Participants’ choice preferences significantly correlated across all simple aggregate measures from the behavioral tasks. The two measures of safe behavior were positively correlated (proportion of safe choices on risky trials and ambiguous trials of the risk/ambiguity aversion task; $r(145) = 0.52, p < 0.001$), as were the two measures of gambling behavior (proportion of accepted gambles in the loss aversion task and mean number of pumps on banked balloons; $r(145) = 0.17, p = 0.04$). Correlations between all paired combinations of the aforementioned safe and gambling behaviors were all significant and negative ($ps < 0.01$). Figure 12 shows the correlation matrix for the behavioral tasks’ simple aggregate measures and parameter estimates.
Figure 12: Behavioral task measures show largely consistent preferences. Lower triangle shows $r$ values for each pairwise correlation. Upper triangle shows correlations that are significant at $p < 0.05$. Color and circle size indicate $r$ values.

4.3.5 Questionnaires

Mean scores of the 26 questionnaire measures used in the PCA are reported in Table 1. Figure 13 shows the correlation matrix of those measures.

Table 1: Questionnaire measures and mean scores for adolescents and adults

<table>
<thead>
<tr>
<th>Questionnaire</th>
<th>Measure/Subscale (if applicable)</th>
<th>Adolescent Mean (SE)</th>
<th>Adult Mean (SE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Objective Numeracy</td>
<td>-</td>
<td>6.14 (0.15)</td>
<td>5.56 (0.20)</td>
</tr>
<tr>
<td>2. Subjective Numeracy</td>
<td>-</td>
<td>4.40 (0.07)</td>
<td>4.21 (0.10)</td>
</tr>
<tr>
<td>3. Gambling Related Cognitions</td>
<td></td>
<td>2.66 (0.16)</td>
<td>2.16 (0.14)</td>
</tr>
<tr>
<td>4. Reading the Mind in the Eyes</td>
<td></td>
<td>20.24 (0.28)</td>
<td>21.13 (0.50)</td>
</tr>
<tr>
<td>5. Perceived Social Support</td>
<td></td>
<td>65.72 (1.52)</td>
<td>67.57 (1.72)</td>
</tr>
<tr>
<td>6. Peer Pressure, Popularity, &amp; Conformity</td>
<td>Peer Pressure</td>
<td>2.37 (0.09)</td>
<td>2.29 (0.08)</td>
</tr>
<tr>
<td>7. Conformity</td>
<td></td>
<td>2.56 (0.10)</td>
<td>2.39 (0.10)</td>
</tr>
<tr>
<td>Questionnaire</td>
<td>Measure/Subscale (if applicable)</td>
<td>Adolescent Mean (SE)</td>
<td>Adult Mean (SE)</td>
</tr>
<tr>
<td>---------------</td>
<td>----------------------------------</td>
<td>----------------------</td>
<td>----------------</td>
</tr>
<tr>
<td>8</td>
<td>Popularity</td>
<td>3.83 (0.07)</td>
<td>3.75 (0.08)</td>
</tr>
<tr>
<td>9</td>
<td>Resistance to Peer Influence</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Adolescent DOSPERT</td>
<td>Ethical Risk-taking</td>
<td>2.88 (0.11)</td>
</tr>
<tr>
<td>11</td>
<td>Financial Risk-taking</td>
<td>2.19 (0.08)</td>
<td>2.32 (0.12)</td>
</tr>
<tr>
<td>12</td>
<td>Health &amp; Safety Risk-taking</td>
<td>3.33 (0.14)</td>
<td>3.79 (0.14)</td>
</tr>
<tr>
<td>13</td>
<td>Recreational Risk-taking</td>
<td>4.24 (0.15)</td>
<td>4.25 (0.18)</td>
</tr>
<tr>
<td>14</td>
<td>Social Risk-taking</td>
<td>4.56 (0.09)</td>
<td>4.41 (0.11)</td>
</tr>
<tr>
<td>15</td>
<td>Ethical Risk Perception</td>
<td>4.82 (0.11)</td>
<td>4.90 (0.13)</td>
</tr>
<tr>
<td>16</td>
<td>Financial Risk Perception</td>
<td>4.58 (0.12)</td>
<td>4.46 (0.14)</td>
</tr>
<tr>
<td>17</td>
<td>Health &amp; Safety Risk Perception</td>
<td>5.13 (0.10)</td>
<td>4.78 (0.11)</td>
</tr>
<tr>
<td>18</td>
<td>Recreational Risk Perception</td>
<td>3.85 (0.11)</td>
<td>3.90 (0.13)</td>
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<tr>
<td>19</td>
<td>Social Risk Perception</td>
<td>3.73 (0.08)</td>
<td>3.61 (0.11)</td>
</tr>
<tr>
<td>20</td>
<td>Behavioral Inhibition/Behavioral Activation (BIS/BAS)</td>
<td>BAS Drive</td>
<td>2.76 (0.06)</td>
</tr>
<tr>
<td>21</td>
<td>BAS Fun Seeking</td>
<td>3.07 (0.06)</td>
<td>3.08 (0.06)</td>
</tr>
<tr>
<td>22</td>
<td>BAS Reward Responsiveness</td>
<td>3.55 (0.04)</td>
<td>3.51 (0.05)</td>
</tr>
<tr>
<td>23</td>
<td>BIS (Behavioral Inhibition)</td>
<td>3.25 (0.06)</td>
<td>3.02 (0.06)</td>
</tr>
<tr>
<td>24</td>
<td>Abbreviated Impulsiveness Scale (ABIS)</td>
<td>Attention</td>
<td>10.30 (0.35)</td>
</tr>
<tr>
<td>25</td>
<td>Motor</td>
<td>8.56 (0.30)</td>
<td>8.60 (0.27)</td>
</tr>
<tr>
<td>26</td>
<td>Nonplanning</td>
<td>7.16 (0.29)</td>
<td>7.54 (0.33)</td>
</tr>
</tbody>
</table>
Figure 13: Correlation matrix for the 26 questionnaire measures, presented in hierarchical clustering order. Number labels correspond to Table 1. Circle color and size represent $r$ values. Lower triangle depicts all values while upper triangle only shows correlations significant at $p < 0.05$.

4.3.6 PCA

The first 8 components had eigenvalues greater than 1 (Kaiser, 1960) and were probed for further analyses. These 8 components explained a cumulative 68.2% of variance. Each component and its measures with contributions that were numerically
greater than chance (100%/26 measures = 3.85% contribution by chance) are reported in Table 2.

Table 2: Positive and negative contributing measures for the first 8 components

<table>
<thead>
<tr>
<th>#</th>
<th>% variance</th>
<th>Positive Contributing Measures (% contribution)</th>
<th>Negative Contributing Measures (% contribution)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20.6</td>
<td>Health &amp; Safety Risk-taking (9.9) Peer Pressure (9.4) Ethical Risk-taking (8.7) Financial Risk-taking (6.4) ABIS Motor (6.0) Recreational Risk-taking (5.3) Conformity (4.9) ABIS Attention (4.7)</td>
<td>Health &amp; Safety Risk Perception (7.2) Ethical Risk Perception (5.9) Recreational Risk Perception (5.0)</td>
</tr>
<tr>
<td>2</td>
<td>11.0</td>
<td>Conformity (12.6) Social Risk Perception (9.6) Peer Pressure (6.6) BIS (Behavioral Inhibition) (6.6) Ethical Risk-taking (5.5) Gambling Related Cognitions (5.3)</td>
<td>Resistance to Peer Influence (19.2) Social Risk-taking (10.8) Recreational Risk-taking (4.9)</td>
</tr>
<tr>
<td>3</td>
<td>9.2</td>
<td>BAS Reward Responsiveness (20.3) BAS Fun Seeking (14.5) Ethical Risk Perception (11.3) BAS Drive (11.0) Financial Risk Perception (7.6) ABIS Motor (7.1) Health &amp; Safety Risk Perception (6.5)</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>7.5</td>
<td>ABIS Nonplanning (16.1) ABIS Attention (11.4) Recreational Risk Perception (9.6) Reading the Mind in the Eyes (5.7) ABIS Motor (4.4)</td>
<td>Subjective Numeracy (12.1) Objective Numeracy (11.5) Perceived Social Support (7.2) Popularity (6.1)</td>
</tr>
<tr>
<td>5</td>
<td>5.9</td>
<td>BIS (Behavioral Inhibition) (18.9) Popularity (15.5)</td>
<td>BAS Drive (20.3) Financial Risk Perception (6.4)</td>
</tr>
<tr>
<td>#</td>
<td>% variance</td>
<td>Positive Contributing Measures (% contribution)</td>
<td>Negative Contributing Measures (% contribution)</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ABIS Nonplanning (6.7) Recreational Risk-taking (5.4) Gambling Related Cognitions (4.3)</td>
<td>Subjective Numeracy Scale (4.3)</td>
</tr>
<tr>
<td>6</td>
<td>5.6</td>
<td>Subjective Numeracy (24.2) Objective Numeracy (18.5) ABIS Attention (8.2) Gambling Related Cognitions (5.4) Health &amp; Safety Risk Perception (4.3) Ethical Risk Perception (4.1)</td>
<td>Perceived Social Support (8.4) Popularity (6.6) Reading the Mind in the Eyes (4.3)</td>
</tr>
<tr>
<td>7</td>
<td>4.5</td>
<td>Financial Risk-taking (22.7) Social Risk Perception (7.7) Recreational Risk Perception (5.6) Social Risk-taking (5.1) Ethical Risk Perception (4.3)</td>
<td>BAS Reward Responsiveness (14.7) ABIS Attention (5.0) BAS Fun Seeking (4.8) BIS (Behavioral Inhibition) (4.8)</td>
</tr>
<tr>
<td>8</td>
<td>4.1</td>
<td>Reading the Mind in the Eyes (40.3) Social Risk Perception (7.8) ABIS Nonplanning (5.2) Objective Numeracy (4.8)</td>
<td>Social Risk-taking (9.6) BIS (Behavioral Inhibition) (5.1) Recreational Risk Perception (4.5)</td>
</tr>
</tbody>
</table>

Compared to adults, adolescents had significantly higher coordinates for Component 6 (adult mean = -0.30, adolescent mean = 0.26; t(145) = 2.87, p = 0.0046), and this difference remained significant after correcting for the 8 comparisons made (Bonferroni-corrected p = 0.04). Component 6 had numeracy measures as the main positive contributors and social cognition-related measures as the main negative contributors. No other components had significant differences between age groups, and
there were no significant correlations between component coordinates and exact age (all uncorrected \( ps > 0.05 \)).

Only Component 1, with positive contributors of likelihood to take everyday risks and peer pressure susceptibility and negative contributors of everyday risk perception, significantly predicted behavior across our economic gambling tasks. Participants’ coordinates for Component 1 negatively correlated with safe choices on the risk/ambiguity aversion task and positively correlated with gambling on the loss aversion task (proportion chose safe on risky trials: \( r(145) = -0.25, p = 0.002 \), Figure 14A; proportion chose safe on ambiguous trials: \( r(145) = -0.21, p = 0.01 \), Figure 14B; proportion accepted loss aversion gambles: \( r(145) = 0.21, p = 0.009 \), Figure 14C). Component 1 coordinates did not, however, significantly correlate with the number of pumps on banked BART balloons (\( r(145) = 0.03, p = 0.73 \), Figure 14D). Linear regressions adding age group (adolescent or adult) to the behavioral task measures to predict Component 1 coordinates found no significant effects of age group or interactions between age group and behavioral task measure (all \( ps > 0.1 \)). Similarly, linear regressions adding exact age to the behavioral task measures to predict Component 1 coordinates also found no significant effects of exact age or the interaction between exact age and behavioral task measures (all \( ps > 0.1 \)).

Participants’ coordinates for component 3 significantly negatively correlated with the proportion of safe choices on risky trials in the risk/ambiguity task (\( r(145) = -0.25 \), Figure 14A; proportion chose safe on ambiguous trials: \( r(145) = -0.21, p = 0.01 \), Figure 14B; proportion accepted loss aversion gambles: \( r(145) = 0.21, p = 0.009 \), Figure 14C). Component 1 coordinates did not, however, significantly correlate with the number of pumps on banked BART balloons (\( r(145) = 0.03, p = 0.73 \), Figure 14D). Linear regressions adding age group (adolescent or adult) to the behavioral task measures to predict Component 1 coordinates found no significant effects of age group or interactions between age group and behavioral task measure (all \( ps > 0.1 \)). Similarly, linear regressions adding exact age to the behavioral task measures to predict Component 1 coordinates also found no significant effects of exact age or the interaction between exact age and behavioral task measures (all \( ps > 0.1 \)).
0.18, \( p = 0.03 \) but did not correlate with other behavioral task measures. No other components significantly predicted behavioral measures (\( ps > 0.05 \)).

Figure 14: Coordinates for component 1 predict gambling behavior on the risk/ambiguity aversion and loss aversion tasks, but not the BART. Grey dots indicate adults, and orange dots indicate adolescents. Coordinates for component 1: A) significantly negatively correlate with the proportion of safe trials chosen on risky trials in the risk/ambiguity aversion task, B) significantly negatively correlate with the proportion of safe trials chosen on ambiguous trials in the risk/ambiguity aversion task, C) significantly positively correlate with the proportion of accepted
gambles in the loss aversion task, but D) do not significantly correlate with the mean number of pumps on banked balloons in the BART.

4.4 Discussion

In a large sample of adolescents and adults completing a battery of behavioral tasks and self-report questionnaires, we found generally similar behavior across our age groups, with minimal to no detectable differences between adolescents and adults. Within individual participants, we found striking similarities in gambling behavior across our four behavioral tasks, suggesting that the four different measures tapped similar decision-making tendencies. Additionally, we found that participants’ gambling behavior on economic decision-making tasks predicted their scores on a principal component representing self-reported engagement in and attitudes towards everyday reckless behaviors, susceptibility to social influence, and impulsivity. Taken together, our findings suggest that adolescents and adults in our age range (15 to 30) exhibit similar behavior on economic decision-making tasks, which in turn similarly predicts their everyday behavior.

There were no significant age group differences or age-related changes in risk aversion, ambiguity aversion, or BART behavior. Though lack of age differences in risk aversion are consistent with some previous studies (Barkley-Levenson et al., 2013; Keulers et al., 2011; Van Leijenhorst, Gunther Moor, et al., 2010; van Leijenhorst et al., 2006), our lack of age differences in ambiguity aversion and BART behavior are inconsistent with prior studies finding ambiguity aversion to increase and risk-taking on
the BART to decrease in moving from adolescence to adulthood (Blankenstein et al., 2016; Braams et al., 2015; Tymula et al., 2012). It should be noted, however, that our adolescents exhibited similar levels of ambiguity aversion to those reported by Tymula and colleagues (2012), whereas our adults were younger (ages 18 to 30) and exhibited less ambiguity aversion compared to their adult sample (ages 30 to 50). Additionally, the studies by Blankenstein and colleagues (2016) and Braams and colleagues (2015) examined developmental trajectories across a broad age range (ages 10 to 25 and 8 to 28, respectively) rather than comparing between two specific age groups. It is possible that our age range was too narrow to detect an age-related trend.

Our only significant age-related behavioral task results were in loss aversion, in which adults were found to accept marginally more gambles compared to adolescents, and age significantly positively correlated with the proportion of accepted gambles. It should be noted, however, that we found no significant group differences or age-related changes in our estimates of individuals’ loss aversion parameters. Overall, our loss aversion findings clearly ran counter to the notion that adolescents take more risks compared to adults and somewhat differed from previous reports of comparable loss aversion-related behavior between adolescents and adults (Barkley-Levenson & Galván, 2014; Barkley-Levenson et al., 2013).

Our exploratory PCA only yielded one component, Component 6, that differed between age groups. Compared to adults, our adolescents had higher coordinates for
Component 6, which featured positive contributions from numeracy-related measures and negative contributions from social cognition-related measures. Component 6 did not, however, significantly correlate with any of our behavioral task measures, consistent with a previous study that found that numeracy did not predict risk or ambiguity aversion (Tymula et al., 2013). Thus, it is unlikely that our adolescents’ higher numeracy affected their decision preferences or caused them to make more adult-like decisions.

Only one PCA component, Component 1, significantly related to our economic behavioral task measures of risk, ambiguity, and loss aversion (though it did not correlate with BART behavior). Component 1 included positive contributors of likelihood of taking health & safety, ethical, financial, and recreational risks and opposing negative contributors of healthy & safety, ethical, and recreational risk perception. Additional positive contributors of Component 1 were peer pressure susceptibility, conformity, and measures of impulsivity. These findings show that gambling propensity, as measured by description-based economic tasks but not by the experienced-based BART, was positively related to self-reported everyday risk-taking, the desire to conform to peers, and impulsivity. This stands in contrast to previous studies that found only ambiguity attitudes, and not risk attitudes, to predict self-reported everyday reckless behavior (Blankenstein et al., 2016; Tymula et al., 2012). Age group or exact age did not account for any additional variance above economic
gambling preferences in predicting Component 1 coordinates, nor did age group
moderate the relationships between economic gambling preferences and Component 1,
indicating that such relationships were stable across the age range of our sample.

Overall, the general lack of age-related results in our sample is striking. This may
be in part because our two age groups are close in age, with overlap in 18-year-olds. We
chose to use a cultural definition to mark the dividing line between adolescents and
adults (Crone & Dahl, 2012), designating seven 18-year-olds as adolescents because they
were in high school and twelve 18-year-olds as adults because they were college
undergraduates. This may have affected our ability to detect differences between age
groups, though we note that we also did not find behavioral task measures to
significantly correlate with exact age (with the exception of the proportion of accepted
gambles on the loss aversion task). Still, a broader age range and/or an age gap may
have improved our ability to detect age differences, if they exist.

One challenge of testing a broader age range through our approach is the need to
use tasks and questionnaires that can be similarly applied across ages. For example, we
administered the adolescent version of the DOSPERT (Figner et al., in prep.) to all
participants regardless of age. This could mean that we missed capturing adults’
attitudes towards adult-relevant activities that are not included in the adolescent scale.
The adolescent DOSPERT may also be similarly inappropriate for capturing everyday
risk-taking and risk perceptions in young children, who may encounter different
everyday types of risk-taking than do adolescents. Thus, though future studies should include a broad range of ages, care should be taken in selecting measures that are appropriate for all ages, and in interpreting findings that may be due to age-appropriateness of measures rather than to true age differences.

Finally, it should be noted that our questionnaire-related analyses hinged on an exploratory PCA rather than a hypothesis driven approach. Additional data are needed to replicate or test our PCA results in a separate sample in order to test their predictive, rather than descriptive, validity. Despite its exploratory nature, our PCA approach is still valuable because it allows us to examine a large set of variables in a single study and report results for all variables with a reduced number of statistical tests, thereby reducing the likelihood of multiple comparisons issues and publication bias problems in which null findings are not fully reported.

The present study, with its sizeable sample and extensive battery of tasks and questionnaires, presents a multi-faceted look at how decision-making behavior and related personality measures interact and change across development. Our findings sometimes support but other times conflict with previous studies that used fewer behavioral measures at a time, highlighting the importance of taking a comprehensive approach to investigating decision-making across development.
5. Reward-related neural responses for self and for friend are affected by friend presence

Many everyday decisions occur in the presence of peers and feature outcomes that are shared with those peers. Previous studies have independently studied peer presence and reward for others, and they found both to activate reward- and social-processing regions of the brain (see Morelli, Sacchet, & Zaki, 2015; van Hoorn, Fuligni, et al., 2016 for review). It is still unknown, however, how peer presence and reward for peers interact to influence neural activity. Here, we investigate the neural basis of reward for self and reward for friend in the presence and absence of that friend. We find that reward for self and for friend are similarly processed in striatal reward-related regions, and that peer presence similarly increases activity for both, after controlling for the effect of age.

5.1 Introduction

Public health data show many everyday reckless behaviors to peak in adolescence (Heron, 2013), but most empirical studies have not found risk-taking to show a corresponding adolescent peak in the laboratory (Defoe et al., 2015). One possibility for this discrepancy is that adolescents make their everyday decisions in the company of peers, while laboratory studies tend to occur in social isolation (Albert et al., 2013). Thus, many researchers have advocated for the importance of empirically investigating how the presence of peers affects adolescent decision-making (Albert et al.,
Previous studies have found that the mere presence of peers increases adolescents’ but not adults’ neural response to reward in striatal regions (Chein et al., 2011; A. R. Smith et al., 2015). In one study, adolescent (ages 14 to 18) but not adult (ages 19 to 29) increases in ventral striatum activity occurred in the presence of peers and when making risky decisions on a simulated driving game, suggesting that peer presence prompts increased adolescent risk-taking by making the potential rewards of risks more attractive (Chein et al., 2011). Other behavioral work has found that believing that one is being watched by an anonymous peer increases adolescents’ (ages 15 to 17) willingness to accept disadvantageous gambles (A. R. Smith et al., 2014) and causes adolescents (ages 11 to 18) to take more high-risk gambles compared to adults (ages 20-38; Haddad, Harrison, Norman, & Lau, 2014).

Other studies, however, have found peer presence to increase risk-taking and reward-seeking beyond adolescence, into early adulthood. While the risky-driving study of Chein and colleagues (2011) did not find peer presence to affect young adults (ages 19 to 22), an earlier risky-driving study did find peer presence to increase risky driving decisions in 18- to 22-year-old young adults (though the young adults were less affected compared to 13- to 16-year-old adolescents; Gardner & Steinberg, 2005), and another simulated driving study found both adolescents (ages 17 to 18) and young adults (ages 19 to 22) to take more risky driving decisions in the presence of peers (van Hoorn, Fuligni et al., 2016). In order to better understand everyday decision-making behavior.
21 to 24) to increase risky driving when in the presence of peers (Ross et al., 2016), with no differences between age groups. Other work has found that young adults (ages 18 to 20) exhibit an increased preference for smaller immediate rewards over larger delayed rewards when in the presence of peers compared to when alone (O’Brien, Albert, Chein, & Steinberg, 2011), and that this effect holds in adults (ages 18 to 22) who merely believe that their choices are being watched by an anonymous peer who is not physically present (Weigard, Chein, Albert, Smith, & Steinberg, 2013). Finally, neuroimaging studies with adult participants have also found that being in presence of peers, compared to being unobserved, increases activity in striatal regions in a social donation task (mean age 22.7; Izuma, Saito, & Sadato, 2010a) and a social norm rating task (mean age 24; Izuma, Saito, & Sadato, 2010b). These studies suggest that the effect of peer presence may linger beyond adolescence into early adulthood.

Peer presence has also been found to alter social behavior and increase activity in neural regions associated with social cognition in adolescents and adults. An imaging study of participants between the ages of 8 and 23 being watched or anticipating being watched by a peer found that self-reported embarrassment and activity in medial prefrontal cortex (MPFC) increased from childhood to adolescence and persisted into adulthood (Somerville et al., 2013). Another study of adolescents (ages 12 to 16) completing a social trust game found higher donations and greater activity in the social cognition regions of MPFC, bilateral temporal parietal junction (TPJ), bilateral superior
temporal sulcus (STS), and precuneus (PreC) when adolescents thought they were being observed compared to when they thought their choices were private (Van Hoorn, Van Dijk, Güroğlu, & Crone, 2016). Adults (mean age 24) completing a social norm rating task similarly showed an increase in MPFC activity when watched by peers compared to when alone (Izuma et al., 2010b).

In addition to being implicated in peer presence studies, reward- and social cognition-related neural regions have also been implicated in vicarious reward studies, in which participants watch others receive rewards. A meta-analysis of such studies in adult participants found that reward for self, compared to reward for other, elicited greater activity in striatal regions. The reverse contrast, reward for other over reward for self, was associated with activity in social cognition regions such as dorsomedial PFC and STS (Morelli et al., 2015). Vicarious reward has also been studied in a developmental sample of participants (ages 8 to 25) playing a win/loss coin flip guessing task for themselves and for a friend and yielded similar results to the meta-analysis: striatal response to reward was greater for self than for friend, while social cognition regions of bilateral TPJ, PreC, and MPFC exhibited greater responses for friend than for self (Braams, Güroğlu, et al., 2014; Braams, Peters, Peper, Güroğlu, & Crone, 2014). Longitudinal work in the same sample found striatal activity for winning for self to peak in adolescence and decline into adulthood (Braams et al., 2015), the difference in neural activity in bilateral TPJ and PreC between playing for friend and for self to linearly
decrease with age, and the difference between playing for friend and for self to be
developmentally stable in MPFC (Braams & Crone, 2016).

Though vicarious reward and peer presence have been found to affect the same
set of neural regions, to the best of our knowledge, there have been no prior studies
investigating the interaction of vicarious reward and peer presence. In the present study,
participants completed a social Monetary Incentive Delay (MID) task while undergoing
functional magnetic resonance imaging (fMRI). In classic MID paradigms (Knutson,
Westdorp, Kaiser, & Hommer, 2000), participants make rapid button press responses to
win or avoid losing money for themselves. In several studies with adult participants,
this has been found to elicit reward anticipation-related activity in striatal regions and
anterior insula (see Knutson & Greer, 2008 for a meta-analytic review). In our social MID
task, participants played for themselves and for their friend (within-subjects) and either
Alone or while Watched by that friend (between-subjects). We recruited a sample of
young adults between the ages of 18 and 28 in order to probe the developmental
transition period between late adolescence and early adulthood that has previously
yielded conflicting peer presence findings. Thus, our study allowed us to investigate the
effects of peer presence, vicarious reward, and the interactions between peer presence,
vicarious reward, and age.
5.2 Methods

5.2.1 Participants

The reported analyses include data from 37 adults recruited from the Durham area (mean age = 22.8 years, SD = 2.9 years, range = 18.6 to 28.2 years, 19 female). All participants provided written informed consent under a protocol approved by the Duke Medicine Institutional Review Board and were right-handed with no history of neurological disorders.

5.2.2 Task

Each session began with task instructions and brief training outside the scanner, followed by the MRI scans. The MRI scans were comprised of an anatomical scan, three runs of a risky decision-making task (not reported here), and two runs of a social MID task (described below). Immediately following the MRI scans, participants completed a series of questionnaires while alone (not reported here).

All participants arrived at the session with a similarly-aged, same-gendered friend to serve as their peer partner. Eighteen participants were in the Alone condition, in which their peers were taken to a separate room to complete a series of separate tasks and questionnaires (see Chapter 6). Prior to the start of the Alone runs, the experimenter used the scanner intercom to notify the participant that the control room stimuli computer’s monitor would be turned off so that the participant’s task performance would be totally private.
The remaining 19 participants were in the Watched condition, in which they were observed by their peer during the scanning portion of the study. During Watched scanning sessions, the peer watched the participant’s task performance via the stimuli computer in the control room. Prior to each Watched run, the peer used the scanner intercom to verbally notify the participant that the peer was watching the participant’s task performance.

Each trial of the social MID began with a 1000 ms cue indicating the trial’s target recipient and potential outcome in white text on a black screen. On Self trials, the participant’s first name appeared; on Peer trials, the participant’s peer’s first name appeared; and on Neutral trials, the words “No one” appeared. On Gain trials, the words “may win” appeared; on Loss trials, the words “may lose” appeared, and on Neutral trials, the words “just play” appeared. On each of the two runs, participants viewed 10 trials of each cue type (SelfGain, SelfLoss, PeerGain, PeerLoss, Neutral) in a pseudorandom order such that the same cue would not occur more than twice consecutively. Trial cues were followed by a variable fixation cross delay of 2000-2500 ms, after which a target (white square) appeared on the screen.

Participants were instructed to respond before the target disappeared with a rapid button press using their right index finger. Successful Gain trials led to an outcome of “+5” in green text; unsuccessful Gain trials led to an outcome of “+0” in red text; successful Loss trials led to an outcome of “-0” in green text; unsuccessful Loss
trials led to an outcome of “-5” in red text; successful neutral trials led to an outcome of “+0” in green text; and unsuccessful neutral trials led to an outcome of “-0” in red text. Outcomes were displayed on a black screen below the trial’s recipient text (in white text) for 1500 ms immediately following the button press. Each trial was following by a jittered fixation cross interval.

Figure 15: An example Gain trial. White text indicates each trial’s target recipient (here, Rosa) and potential outcome (here, may win). Participants were instructed to make a button press while the white box was on the screen. A successful response yielded the better potential outcome in green text (here, +5), while an unsuccessful response that was too slow yielded the worse potential outcome in red text (here, +0).
The presentation time of the target was determined by an adaptive algorithm based on previous RTs for each cue type, such that participants would be successful approximately 70% of the time.

### 5.2.3 Behavioral Analyses

Early button presses that occurred before the onset of the target were considered unsuccessful trials (misses) for accuracy analyses and excluded from response time analyses. “Lapse” trials, in which participants made no response 1500 ms after target onset, were considered misses for accuracy analyses and also excluded from response time analyses. Finally, trials with response times less than 100 ms were excluded from all behavioral analyses, as they were likely too rapid to be driven by target onset.

Response times were analyzed using linear mixed-effects models using the R package “nlme” (Pinheiro, Bates, DebRoy, Sarkar, & Team, 2017), with participant identity as a random effect and other variables of interest as fixed effects.

### 5.2.4 Image acquisition

Functional MRI data were collected using a General Electric MR750 3.0 Tesla scanner equipped with an 8-channel parallel imaging system. Images sensitive to blood-oxygenation-level-dependent (BOLD) contrast were acquired using a T₂*-weighted spiral-in sensitivity encoding sequence (acceleration factor = 2), with slices parallel to the axial plane connecting the anterior and posterior commissures (repetition time (TR): 1580 ms; echo time (TE): 30 ms; matrix: 64 x 64; field of view (FOV): 243 mm; voxel size:
3.8 x 3.8 x 3.8 mm; 37 axial slices acquired in an ascending interleaved fashion; flip angle: 70°. Prior to preprocessing these functional data, we discarded the first four volumes of each run to allow for magnetic stabilization. To facilitate coregistration and normalization of these functional data, we also acquired whole-brain high-resolution anatomical scans (T1-weighted FSPGR sequence; TR: 7.58 ms; TE: 2.93 ms; voxel size: 1 x 1 x 1 mm; matrix: 256 x 256; FOV: 256 mm; 206 axial slices; flip angle: 12°).

### 5.2.5 Preprocessing

Our preprocessing employed tools from the FMRIB Software Library (FSL Version 5.0.1; http://www.fmrib.ox.ac.uk/fsl/) package (S. M. Smith et al., 2004; Woolrich et al., 2009). We first corrected for head motion by realigning the time series to the middle time point (Jenkinson, Bannister, Brady, & Smith, 2002). We then removed non-brain material using the brain extraction tool (S. M. Smith, 2002). Next, intravolume slice-timing differences were corrected using Fourier-space phase shifting, aligning to the middle slice (Sladky et al., 2011). Images were then spatially smoothed with a 6mm full-width-half-maximum Gaussian kernel. To remove low-frequency drift in the temporal signal, we then subjected the functional data to a high-pass temporal filter with a 100 second cutoff. Finally, each 4-dimensional dataset was grand-mean intensity normalized using a single multiplicative factor. Prior to group analyses, functional data were spatially normalized to the MNI avg152 T1-weighted template (2 mm isotropic...
resolution) using a 12-parameter affine transformation implemented in FLIRT (Jenkinson & Smith, 2001).

**5.2.6 fMRI analysis**

Neuroimaging analyses were conducted using FEAT (FMRI Expert Analysis Tool) Version 5.98 (S. M. Smith et al., 2004; Woolrich et al., 2009). Our first-level analyses (i.e., within-run) utilized general linear models with local autocorrelation correction (Woolrich, Ripley, Brady, & Smith, 2001).

The first-level model included 3 regressors for cue target during the anticipation period between cue offset and target onset (Self Anticipation, Peer Anticipation, Neutral Anticipation), and 3 regressors for outcome target during the 1500ms outcome display period (Self Outcome, Peer Outcome, Neutral Outcome). The first-level model also included nuisance regressors for lapse trials (trials in which participants made no button presses, set to the time between cue offset and miss feedback offset), head motion, and outlier volumes (volumes with root-mean-square amplitude greater than 150% of the interquartile range for all volumes in the run). Except for the head motion and outlier volume nuisance regressors, all regressors were convolved with a canonical hemodynamic response function.

Data from the first run of 2 Watched participants were excluded due to excessive head motion (> 3mm). For the other participants, we combined data across each participant’s 2 runs using a fixed-effects model. Data was then combined across all 37
participants using a mixed-effects model at the third level (Beckmann, Jenkinson, & Smith, 2003; Woolrich, Behrens, Beckmann, Jenkinson, & Smith, 2004). Third level contrasts included a main effect of all participants, as well as group contrasts comparing the effect of participant condition (Alone > Watched and Watched > Alone).

For whole-brain analyses, significance was assessed using Monte Carlo permutation-based statistical testing with 10,000 permutations (Nichols & Holmes, 2002; Winkler, Ridgway, Webster, Smith, & Nichols, 2014). Additionally, we used threshold-free cluster enhancement to estimate clusters of activation that survived a corrected family-wise-error-rate of 1% (S. M. Smith & Nichols, 2009). Statistical overlay images were created using MRicron (Rorden & Brett, 2000). All coordinates are reported in MNI space.

Region of interest (ROI) analyses were also conducted using ROIs drawn around peak voxels reported in published meta-analyses. For reward-related ROIs, 5mm spheres were drawn around peak voxels for left striatum (LStr: [-12, 4, 2]), right striatum (RStr: [12, 10, -2]), left anterior insula (LAIins: [-30, 22, -6]), and right anterior insula (RAIns: [32, 20, -6]) reported by Bartra, McGuire, and Kable (2013). For social cognition-related ROIs, 5mm spheres were drawn around peak voxels for left temporal parietal junction (LTPJ: [-55, -54, 27]), right temporal parietal junction (RTPJ: [55, -54, 27]), precuneus (PreC: [2, -58, 46]), and medial prefrontal cortex (MPFC: [1, 57, 12]) reported
by Van Overwalle & Baetens (2009) and converted to MNI coordinates by Braams & Crone (2016).

5.3 Results

5.3.1 Behavioral results

The proportion of successful responses was similar across cue types (SelfGain mean = 0.71, SelfLoss mean = 0.71, PeerGain mean = 0.70, PeerLoss mean = 0.72, Neutral mean = 0.69), indicating that the adaptive algorithm was generally successful in equating success across cue types.

A model with cue type as a categorical fixed factor found cue types to be significant predictors of response time, such that non-neutral cues had faster response times than neutral cues (all $p < 0.001$). Adding Alone/Watched condition and the interaction of condition and cue type, however, did not improve overall model fit, and condition was not a significant predictor of response time ($p > 0.05$). There was a significant interaction of condition and the SelfGain cue type ($\beta = -0.012, p = 0.04$) and a marginally significant interaction of condition and the PeerGain cue type ($\beta = -0.011, p = 0.06$), both indicating that Watched trials were faster than Alone trials for those specific cues; all other interactions were non-significant ($p > 0.1$).
Figure 16: Response times were slowest for Neutral cues but generally did not vary by Alone/Watched condition. Cue target significantly affected response times such that Self trials were faster than Peer trials, but cue valence (Gain or Loss) did not affect response time. * indicates $p < 0.05$.

Age was found to significantly predict overall response time, such that response time decreased with age ($\beta = -0.002$, $p = 0.0498$). The effect of age and the interactions between age and cue type were also significant in a model with age, cue type, and their interactions (all $ps < 0.05$). Age, however, was not significant in a model with age, Alone/Watched condition, and their interaction (all $ps > 0.1$).

The Self and Peer trials were evaluated using categorical fixed factors for cue target (Self or Peer) and cue valence (Gain or Loss). In a model with just cue target, cue target significantly predicted response time, such that Self trials were faster than Peer trials ($\beta_{\text{self}} = -0.004$, $p = 0.03$). There were no significant predictors in a model with just cue valence, or a model with cue target, cue valence, and their interaction, though the effect
of cue target was still marginally significant in the interaction model ($\beta_{self} = -0.005, p = 0.096$). There were no significant predictors in the following models using the Self and Peer trials to predict response time as a factor of condition (Alone or Watched): a model with only condition; a model with condition, cue target, and their interaction; a model with condition, cue valence, and their interaction; or a model with condition, cue target, cue valence, and their interactions (all $ps > 0.1$).

Age no longer significantly predicted overall response time when analyses were restricted to the Self and Peer trials ($\beta = -0.0015, p = 0.13$), nor were there any significant predictors in the following models using the Self and Peer trials to predict response time as a factor of age: a model with age, cue target, and their interaction; a model with age, cue valence, and their interaction; or a model with age, condition, and their interaction (all $ps > 0.1$).
Figure 17: Neural responses to social Anticipation and Outcome. A) The contrast of (Self Anticipation + Peer Anticipation) > Neutral Anticipation shows significant widespread activation throughout the brain, including in bilateral striatum, anterior insula, and supplementary motor area. B) The contrast of Peer Outcome > Self Outcome shows significant activation in MPFC extending into dorsal MPFC. Images are shown at FWE corrected-$p < 0.01$.

5.3.2 Neural results: Whole-brain

During anticipation, the contrast of (Self Anticipation + Peer Anticipation) > Neutral Anticipation revealed significant widespread activation throughout the brain, including in bilateral striatum, anterior insula, and supplementary motor area (Figure 17A). There was no significant whole-brain activation, however, for Self Anticipation > Peer Anticipation or Peer Anticipation > Self Anticipation, nor were there any significant interactions between the aforementioned contrasts and Alone/Watched condition.

During outcome feedback, the contrast of Peer Outcome > Self Outcome revealed significant activation in MPFC, extending into dMPFC (Figure 17B). There was no
significant whole-brain activation for Self Outcome > Peer Outcome or (Self Outcome + Peer Outcome) > Neutral Outcome, nor were there any significant interactions between the aforementioned contrasts and Alone/Watched condition.

5.3.3 Neural results: Reward-related ROIs

Repeated-measures ANOVA with Alone/Watched condition as a between-subjects factor were used to investigate potential differences in reward-related ROI activity to each cue target (Self, Peer, Neutral) during anticipation. In all reward-related ROIs, the effect of cue target was significant (ps < 0.01), such that Self Anticipation and Peer Anticipation were both significantly greater than Neutral Anticipation (all Bonferroni-corrected ps < 0.01) but not significantly different from each other (all Bonferroni-corrected ps > 0.1). The effect of Alone/Watched condition and the interaction between cue target and condition were not significant in all reward-related ROIs (ps > 0.1; Figure 18A).
Figure 18: Neural results within ROIs. A) In all reward-related ROIs, neural activity for anticipation for Self and Peer are greater than for Neutral but not significant from each other or between Alone and Watched conditions. B) In social cognition-related ROIs, neural activity for outcome for Peer is greater than both Self and Neutral only in MPFC in both Alone and Watched conditions. * indicates $p < 0.05$.

General linear models were used to investigate whether age, Alone/Watched condition, and the interaction between age and condition significantly predicted neural
activity in reward-related ROIs for the contrast of (Self Anticipation + Peer Anticipation) > Neutral Anticipation. There was a significant main effect of condition in RStr ($\beta = 1.22, p = 0.035$) and a marginal effect in LStr ($\beta = 0.97, p = 0.09$), such that neural activity was higher in Watched than in Alone participants after accounting for age and the interaction of age and condition. Furthermore, there was a significant interaction between age and condition in RStr ($\beta = -0.05, p = 0.036$) and a marginal interaction in LStr ($\beta = -0.04, p = 0.09$). Post-hoc testing found significant correlations between age and neural activity for (Self Anticipation + Peer Anticipation) > Neutral Anticipation for participants in the Watched condition in RStr ($r(17) = -0.53, p = 0.02$) and LStr ($r(17) = -0.52, p = 0.02$), but no significant relationship between age and the same neural contrast for participants in the Alone condition in RStr ($r(18) = 0.07, p = 0.79$) or LStr ($r(18) = 0.02, p = 0.94$; Figure 19).
Figure 19: Neural activity for (Self Anticipation + Peer Anticipation) > Neutral anticipation significantly negatively correlated with age in Watched but not in Alone conditions.

There were no significant main effects of age in any reward-related ROI ($p$s > 0.1), nor were there any significant effects of condition or the interaction of age and condition in LAIIns and RAIns ($p$s > 0.1).

Across all participants, the difference between Self and Peer response times significantly correlated with the difference between Self and Peer Anticipation in LStr ($r(35) = -0.44, p = 0.007; $ Figure 20A), RStr ($r(35) = -0.41, p = 0.01; $ Figure 20B), and RAIns ($r(35) = -0.36, p = 0.03; $ Figure 20C), while the relationship was marginal for LAIIns ($r(35) = -0.32, p = 0.05; $ Figure 20D). Thus, participants with faster response times for Self than for
Peer also exhibited greater reward-related neural activation for Self Anticipation than for Peer Anticipation.

Figure 20: The difference between neural activity for Self Anticipation and Peer Anticipation correlated with the difference in response time for Self and Peer in A) Left Striatum, B) Right Striatum, C) Left Anterior and D) Right Anterior Insula. $p < 0.05$ for A, B, and D; $p = 0.05$ for C.

5.3.4 Neural results: Social cognition-related ROIs

Repeated-measures ANOVA with Alone/Watched condition as a between-subjects factor were used to investigate potential differences in social cognition-related ROI activity to each outcome target (Self, Peer, Neutral) during feedback. There were no
significant effects of cue target, Alone/Watched condition, or the interaction between cue
target and condition in LTPJ, RTPJ, or PreC ($ps > 0.1$). In MPFC, however, there was a
significant effect of cue target ($p < 0.01$), such that activity for Peer Outcome was greater
than both Self Outcome (Bonferroni-corrected $p = 0.047$) and Neutral Outcome
(Bonferroni-corrected $p = 0.017$), while Self Outcome and Neutral Outcome were not
significantly different (Bonferroni-corrected $p > 0.1$). The effects of condition ($p = 0.18$)
and the interaction between cue target and condition ($p = 0.67$) were not significant in
MPFC (Figure 18B).

A general linear model found that age, Alone/Watched condition, and the
interaction between age and condition did not significantly predict neural activity in
MPFC for Peer Outcome $>$ Self Outcome ($ps > 0.1$). There was also no significant
correlation between the difference between Self and Peer response times and the
difference between Self and Peer Outcome in MPFC ($r(35) = -0.05$, $p = 0.78$).

5.4 Discussion

In this study, we used a social MID task to compare the effects of anticipating
reward for self and for peer, and the effects of completing the task Alone or while
Watched by that peer. We found that anticipation for Self and Peer were similarly
processed in bilateral striatum and anterior insula, and that being Watched increased
anticipation activity in bilateral striatum only after controlling for the effect of age. Our
social MID elicited greater activity in MPFC for Peer Outcome compared to Self
Outcome, but activity in MPFC or other social cognition regions of bilateral TPJ and PreC were not affected by being Watched.

Our peer presence manipulation exhibited no main effects on participants’ response times, their neural activity in reward-related ROIs during anticipation, and their neural activity in social cognition-related ROIs during outcome. This is in contrast to previous studies that found peer presence to prompt increased impulsivity (O’Brien et al., 2011; Weigard et al., 2013), increased risk-taking (Gardner & Steinberg, 2005; Ross et al., 2016), and increased neural activity in reward- or social cognition-related regions (Izuma et al., 2010a, 2010b; Somerville et al., 2013) in young adults. It does, however, correspond with other work finding no influence of peer presence on risk-taking or neural response to reward in young adults (Chein et al., 2011; A. R. Smith et al., 2015).

Peer presence did significantly interact with age in predicting anticipation-related neural activity in RStr and marginally in LStr, such that neural reward anticipation was higher in the Watched than in the Alone participants, after accounting for the effect of age and its significant interaction with Alone/Watched condition. Neural reward anticipation in bilateral striatum linearly decreased with age in the Watched condition, suggesting that the neural effect of peer presence is age-dependent: it is strongest in late adolescence/early adulthood and declines with increasing age. This corresponds to the behavioral finding of an age-related decline in peer presence prompting increased risky driving (Gardner & Steinberg, 2005).
In contrast, neural reward anticipation in striatum exhibited no significant relation with age in the Alone condition, unlike the longitudinal study of Braams and colleagues (2015) that found striatal activity to decrease over this age range. We note, however, that our study contrasted anticipating reward for self and friend over anticipating no reward, while their study contrasted winning reward for self over losing reward for self. Additionally, previous studies have found striatal response to reward anticipation in MID tasks to increase with age from adolescence (ages 12 to 17) to adulthood (Bjork et al., 2004, 2010). Thus, our divergent findings may result from differences in comparing reward to no reward versus comparing gains to losses, or differences in reward anticipation and reward receipt.

Additionally, we found no significant differences between Self and Peer anticipation at either the whole brain or reward-related ROI level (though the latter was generally numerically higher for Self than for Peer). Though a meta-analysis of vicarious reward studies found reward for Self to be greater than reward for Other in striatal regions, most of the studies included in the meta-analysis did not feature socially-close others (Morelli et al., 2015). Studies comparing reward for self to vicarious reward for close others, such as Latino young adults donating to family members (Telzer, Masten, Berkman, Lieberman, & Fuligni, 2010), adults primed to be interdependent with the friend they played for (Varnum, Shi, Chen, Qiu, & Han, 2014), and adults playing for their best friend (Braams, Güroğlu, et al., 2014), have found no differences in striatal
activity for Self and Close Other. Thus, our participants may have exhibited similarly elevated reward-related activity for Self and Peer relative to neutral trials because the peers they played for were close friends. Furthermore, we note that differences in neural activity for Self and Peer in reward-related regions predicted differences in response times for Self and Peer, indicating that individual differences in relative Self/Peer neural anticipation track individual differences in relative Self/Peer behavioral motivation.

We did find outcome feedback for Peer to elicit greater activity compared to Self and Neutral outcomes in MPFC but not in bilateral TPJ or PreC. While our MPFC result replicates previous findings (Morelli et al., 2015), the lack of significant results in other social-processing regions does not. Furthermore, we found no significant effect of Alone/Watched condition in any of our social cognition ROIs, which runs counter to prior studies finding increased MPFC activity in the presence of unknown peers (Izuma et al., 2010b; Somerville et al., 2013; Van Hoorn, Van Dijk, et al., 2016). We note, however, that prior studies investigating the effect of friend presence did not report any effects in social cognition regions (Chein et al., 2011; A. R. Smith et al., 2015). Thus, it may be that peer presence only increases activity in social cognition regions when the peer is not a close other. As the developmental increase in MPFC activity to being watched mirrors the developmental increase in self-reported embarrassment (Somerville et al., 2013), it may be that observation by strangers induces more self-consciousness and MPFC activity than observation by friends. Future studies could compare the effects of
observation by close friends and strangers in order to determine how peer presence
effects are modulated by social closeness.

Our study’s narrow age range of young adult participants allowed us to focus
our investigation of the effect of peer presence on a developmental time period that has
previously yielded conflicting results, but at the expense of understanding how peer
presence affects behavior and neural activity at other ages. Future studies should
investigate the effect of peer presence, and its interactions with vicarious reward, in a
broader age range so that we can determine the full developmental trajectory of how
reward-processing is affected by social context. That would, in turn, allow us to better
understand how isolated laboratory tasks may reveal different behavioral tendencies
compared to everyday decisions that are made in social contexts.
6. Peer presence increases prosocial behavior in adolescents: A social utility model-based approach

While many studies have focused on the negative effects of peer presence on adolescent decision-making (Chein et al., 2011; Gardner & Steinberg, 2005; Haddad et al., 2014; O’Brien et al., 2011; A. R. Smith et al., 2014; Weigard et al., 2013), peer presence has also been found to increase prosocial behaviors towards unfamiliar peers (Van Hoorn, Van Dijk, et al., 2016; van Hoorn, van Dijk, Meuwese, Rieffe, & Crone, 2016). Little is known, however, about how adolescents’ prosocial behaviors towards close friends are affected by the presence of those friends, or by the quality of their friendships. Here, we use social utility models to compare adolescents’ social preferences when alone or when watched. We found that adolescents increase their prosocial behavior when being observed by their friends, but that watched adolescents are still less prosocial compared to adults making their choices alone.

6.1 Introduction

Many everyday decisions affect not only ourselves but also other people. For example, when we pick up groceries for a shared meal, we may choose to consider the tastes of our dining companions in addition to our own – or not. “Other-regarding preferences”, or preferences regarding others’ payoffs, are thought to be integral to maintaining a functioning, cooperative society (Fehr & Schmidt, 1999). A large body of research, mostly with adult decision-makers interacting with anonymous peers, has
worked to understand these preferences and generally find that adults are egalitarian. That is, adult decision-makers prefer equal payoffs and dislike inequity, with disadvantageous inequity (when payoff for self is less than payoff for other) more disliked than advantageous inequity (when payoff for self is more than payoff for other; see Cooper & Kagel, 2013 for review).

Studies of other-regarding preferences at younger ages have generally found that people move from selfishness (caring only about maximizing one’s own payoff) to egalitarianism to efficiency (caring about maximizing total payoff) across development. One study found nearly all 3- and 4-year-olds to selfishly choose 2-self & 0-other over 1-self & 1-other, while about half of 7- and 8-year-olds preferred the equal split (Fehr, Bernhard, & Rockenbach, 2008). Other work has shown that 6- to 8-year-old children so value egalitarianism that they will throw away a small reward to maintain equity, even if the extra reward would have gone to themselves (Shaw & Olson, 2012). Additional studies using simple one-shot games to track other-regarding preferences generally find that preferences for efficiency over equity (e.g. choosing 1-self & 2-other over 1-self & 1-other) increase with age from childhood to adolescence (Fehr, Glätzle-Rützler, & Sutter, 2013; Meuwese, Crone, de Rooij, & Güroğlu, 2015; Steinbeis & Singer, 2013), indicating more complex integration of self and other payoff contingencies with increasing age (Crone, 2013).
Adolescence marks an especially interesting time period to study other-regarding preferences, as both reward-processing (see Galvan, 2010; Richards et al., 2013 for review) and social cognition (see Blakemore, 2008; Blakemore & Mills, 2013 for review) are heightened at this stage of development. Previous studies have shown that the intersection of greater social- and reward-processing in adolescence may cause adolescents to alter reward-related behaviors in social contexts. For example, the presence of friends prompts greater risk-taking and neural response to reward in adolescents but not adults (Chein et al., 2011; Gardner & Steinberg, 2005; A. R. Smith et al., 2015; but see Ross et al., 2016), and peer presence was found to increase prosocial behavior in a sample of adolescents (ages 12 to 16) playing a public goods trust game (Van Hoorn, Van Dijk, et al., 2016). Adolescence also marks a time in which other-regarding preferences begin to consider others’ socially salient traits. Preferential treatment of in-group over out-group emerges in adolescence (Fehr et al., 2013), and 15- and 18-year-olds but not 9- and 12-year-olds show greater prosocial behavior towards friends than towards antagonists, neutral classmates, or anonymous peers (Güroğlu, van den Bos, & Crone, 2014). Consequently, it is especially interesting to investigate how adolescents’ other-regarding preferences interact with the quality of their relationships with others and with whether the other is present.

While previous studies investigating other-regarding preferences in adolescence have largely relied on categorizing simple choices (Fehr et al., 2013; Güroğlu et al., 2014;
Meuwese et al., 2015; Steinbeis & Singer, 2013), to the best of our knowledge no prior studies have formally modeled adolescents’ social preferences using the same social utility models that are commonly applied to adult behavior (Charness & Rabin, 2002; Fehr & Schmidt, 1999). Furthermore, prior studies have not investigated whether adolescents’ other-regarding preferences are affected by being watched by the “other” that they are making decisions for. In the present study, we investigate adolescents’ other-regarding preferences using a Reward Allocation Task (RAT) in which adolescents must choose to accept or reject offers with different reward amounts for self and for friend. We collected data from adults completing the RAT alone and adolescents completing the RAT alone and while watched by their friend (within-subjects). This allows us to compare adolescents’ behavior to that of adults and investigate how being watched by friends alters adolescents’ behavior. Finally, by sampling participant choices in a large offer space, we can formally model participants’ other-regarding preferences and make quantitative utility parameter comparisons across different age groups and social context conditions.

6.2 Methods

6.2.1 Participants

Fifty-eight adolescent high school students and 26 adults (mean age = 23.0 years; range = 18.4 to 28.4 years; SD = 2.8 years; 11 F) participated in the study. One adolescent who missed too many catch trials (see Task below) was excluded from the study,
resulting in a final adolescent sample of 57 participants (mean age = 17.2 years; range = 15.7 to 18.8 years; SD = 0.56 years; 38 F). We note that though there was some age overlap in our two participant groups, we chose to use a cultural definition of when adolescence ends by labeling 18-year-old high-school students as adolescents and 18-year-old undergraduate students as adults (Crone & Dahl, 2012).

Adolescent participants enrolled in the study with a same-gendered friend who also completed the study, resulting in 29 adolescent dyads. Adult participants enrolled in the study with a same-gendered friend who completed a separate task (see Chapter 5), so adults’ data cannot be analyzed in dyads. All participants and parents of adolescent participants gave written informed consent in a protocol approved by the Duke University Institutional Review Board.

6.2.2 Procedure

Adolescent participants completed the study over the course of two separate days (1 to 9 days apart) and always in the same order. On the first day of testing, adolescent dyads arrived to the testing site together and in separate rooms completed a demographics questionnaire and the Friendship Qualities Scale (FQS; Bukowski, Hoza, & Boivin, 1994), as well as three decision-making tasks and two executive function tasks as part of a larger study (see Chapter 4).

On the second day of testing, adolescent dyads arrived to the testing site together and each completed one 300-trial run of the RAT in separate rooms (Alone condition).
Next, both adolescents of the dyad were moved into the same testing room (Watched condition). One adolescent of each dyad (task-doer) completed a second 300-trial RAT run while his or her partner (task-watcher) watched from a nearby chair. Finally, if time permitted, adolescents in each dyad switched roles, such that the adolescent who was the task-watcher became the task-doer, and vice-versa. During such Watched runs, the task-watcher was asked to record on a private worksheet how much he or she agreed with the task-doer’s choices. This was implemented to ensure that the task-watcher remained engaged, and that the presence of the task-watcher remained salient for the task-doer.

We note that while adolescents signed a consent form on the first day of testing that indicated they may be watched by their friend at some point during the study, they were never explicitly told ahead of time when that friend observation would happen. In other words, when participants completed the Alone run, they were not told that they would next participate in a Watched run. Similarly, when dyads completed their first Watched run, they were not explicitly told that they would next switch places and complete a second Watched run.

In 19 dyads, both adolescents each completed a full Alone and a full Watched run (300 trials/run). In 7 dyads, one adolescent completed a full Alone and a full Watched run while the other completed a full Alone run and some trials of a Watched run (mean = 208 trials; range = 131-262 trials). In 2 dyads, one adolescent completed a
full Alone and a full Watched run while the other completed only a full Alone run. Finally in 1 dyad, one participant completed a full Alone and a full Watched run, while his partner’s runs were excluded for missing too many catch trials (see Task below).

Adult participants completed the study in a single session. Adults arrived to the testing site with a partner. While the partner completed a separate study (Chapter 5), adults completed a single 300-trial run of the RAT, as well as a demographics questionnaire and the FQS. All adults completed the RAT Alone.

6.2.3 Task

On each run of the RAT, participants used a computer mouse to make choices to accept or reject point allocations for themselves and their partner. Each trial began with the display of a box containing the word “START” at the bottom center of a black screen. When participants clicked “START”, the screen went black. Once participants began moving the mouse, the current offer appeared in the center and boxes containing “YES” and “NO” appeared in the top corners of the screen. Left/right location of YES/NO was randomly counterbalanced across trials. Participants were instructed to move their mouse to “YES” to accept the displayed offer or to “NO” to reject the displayed offer and instead receive 5 points for themselves and 5 points for their partner (5-self & 5-partner).

Offers were graphically depicted using colored bars of varying lengths to represent points for self (light grey) and points for partner (dark grey), with full bars
representing 10 points. A vertical line was drawn at the halfway mark to represent the reference “reject” allocation of 5-self/5-partner (Figure 21). Top/bottom position of the self and partner bars was randomly counterbalanced across trials.

![Image](image_url)

Figure 21: Example trial offering more points for self (light grey bar) than for partner (dark grey bar). Participants were instructed to move the mouse to YES to accept the displayed offer, or to move the mouse to NO to reject the displayed offer in favor of 5 points for self & 5 points for partner (vertical line reference mark).

The distribution of potential offers included every combination of 0 to 10 points for self and 0 to 10 points for partner in half-point increments, with the exclusion of offers of 5-self & 5-partner and 0-self & 0-partner (Figure 22). Offers were pseudorandomly drawn from the distribution of potential offers such that a person of average preferences (as determined by pilot testing with 10 adults) would be close to indifferent on 1/3 of trials, readily accept 1/3 of trials, and readily reject 1/3 of trials. Trials in which self and partner had equal payouts were treated as catch trials, such that
participants should always accept catch trials in which the self/partner payouts were greater than 5 (e.g. 8-self & 8-partner) and reject catch trials in which the self/partner payouts were less than 5 (e.g. 4-self & 4-partner). Because offers were pseudorandomly drawn from the potential offer distribution, participants received between 2 and 19 catch trials per run. One adolescent participant who missed more than 1 catch trial per run and did not have enough correct catch trials to pass a binomial significance test was excluded. Catch trials were not included in subsequent analyses.

For incentive compatibility, participants were told that one randomly selected trial from each completed run would be paid out for real. In order to control for differences in valuation of money, participants were told that their points would be converted to dollars using a predetermined exchange rate, but that exchange rate would not be revealed until the end of the session.
Figure 22: Schematic diagrams visualizing how the offer space can be categorized. A) Offers in the diagonally shaded area represent advantageous inequity, while offers in the unshaded area represent disadvantageous inequity. B) Offers in the diagonally shaded area are efficient (total payout from accepting the offer is greater than total payout from rejecting the offer), while offers in the unshaded area are inefficient. C) Offers in each quadrant can be better (+) or worse (-) for self and partner than rejecting the offer in favor of 5 points for self and 5 points for partner. D) The offer space categorized by advantageous/disadvantageous inequity, efficient/inefficient, and better/worse for self/partner.
6.2.4 Choice modeling

We used maximum likelihood estimation to fit participants’ choices on each run to 4 different social utility models and then used AIC and BIC for model comparison. For every completed trial, the value of the offer was set relative to the rejection (5-self & 5-partner) by subtracting 5 from the values of what was offered for self and for partner. The value of the rejection was thus set to 0. A sigmoid function (Equation 6.1) was used to translate the value difference between acceptance and rejection into a probability of acceptance. The temperature parameter $\mu$ represents the sensitivity (steepness) of the sigmoid function, or with higher values indicating greater choice consistency.

$$P(choice) = \frac{1}{1 + e^{-\mu(U(chosen) - U(unchosen))}} \quad (\text{Equation 6.1})$$

Each social utility model is briefly described below, where $x_s$ denotes the payout for self, $x_p$ denotes the payout for partner, and $U(x)$ denotes the participant’s utility for the trial.

*Fehr-Schmidt Model* (Fehr & Schmidt, 1999): An individual’s utility is a function of his/her own payout, advantageous inequity aversion ($\beta$), and disadvantageous inequity aversion ($\alpha$). This model assumes that people dislike disadvantageous inequity more than they dislike advantageous inequity, and that people dislike advantageous inequity to a limited extent (Equation 6.2).
\[ U(x) = x_s - \alpha \max[x_p - x_s, 0] - \beta \max[x_s - x_p, 0] \]  
(Equation 6.2)

\[
\begin{align*}
assume \, \alpha \geq \beta \, and \, 0 \leq \beta \leq 1
\end{align*}
\]

**Unbound Fehr-Schmidt Model**: The Fehr-Schmidt model’s assumption that disadvantageous inequity aversion is always higher than advantageous inequity aversion was initially developed for cases in which participants made choices for unknown strangers. Because our participants played for known friends, this model removes the restriction that people dislike disadvantageous inequity more than they dislike advantageous inequity and only restricted both types of inequity aversion to be positive (Equation 6.3).

\[ U(x) = x_s - \alpha \max[x_p - x_s, 0] - \beta \max[x_s - x_p, 0] \]  
(Equation 6.3)

\[
\begin{align*}
assume \, 0 \leq \alpha \, and \, 0 \leq \beta
\end{align*}
\]

**Unbound Fehr-Schmidt Model with partner parameter**: This model adds a parameter (\(\gamma\)) to the Unbound Fehr-Schmidt Model to account for the partner’s raw payout (Equation 6.4).

\[ U(x) = x_s - \alpha \max[x_p - x_s, 0] - \beta \max[x_s - x_p, 0] + \gamma(x_p) \]  
(Equation 6.4)

\[
\begin{align*}
assume \, 0 \leq \alpha \, and \, 0 \leq \beta
\end{align*}
\]

**Charness-Rabin Model** (Charness & Rabin, 2002): An individual’s utility is a function of two parameters, \(q\) and \(\sigma\), that vary depending on whether the individual
receives more or less than their partner, respectively. When \( q = \sigma = 0 \), an individual is purely self-interested at all times, and when \( q = 1 \) and \( \sigma = 0 \), an individual only cares about whoever is behind. \( q = 0.5 \) indicates that self and partner payouts are equally valued when one is ahead. A negative \( \sigma \) indicates that one is willing to sacrifice some of their own payoff to hurt their partner when their partner is ahead, a positive \( \sigma \) indicates that one is willing to sacrifice some of their own payoff to help their partner even when their partner is ahead, and \( \sigma = 0 \) indicates a disregard for the partner’s payoff when the partner is ahead (Equation 6.5).

\[
U(x) = (\rho r + \sigma s)x_p + (1 - \rho r - \sigma s)x_s
\]

(Equation 6.5)

\[
r = 1 \text{ if } x_s > x_p, \text{ otherwise } 0; s = 1 \text{ if } x_s < x_p, \text{ otherwise } 0
\]

### 6.3 Results

Figure 23 depicts the proportion of offers accepted at every combination of payout for self and for partner. Adults accepted nearly all offers that improved payouts for both self and partner, while adolescents in both the Alone and Watched conditions rejected some such offers when there was inequity. Adults also overall accepted more efficient offers compared to adolescents in both conditions, especially for offers of disadvantageous inequity. Compared to adults, Alone adolescents were more likely to accept inefficient advantageous inequity, but this adolescent tendency to accept advantageous inequity was reduced when Watched.
Figure 23: The proportion of offers accepted at every combination of payout for self and payout for partner for A) Adults completing the task alone, B) Adolescents completing the task alone, and C) Adolescents completing the task while watched by their partner.

6.3.1 Model comparisons

Table 3 displays the mean AIC and BIC for each of the four utility models in each participant type. Because the Charness-Rabin Model (Equation 6.5) had significantly lower AICs and BICs compared to the other utility models (paired t-tests, all ps < 0.001), subsequent results will use the ρ and σ parameters fit by the Charness-Rabin Model to
compare behavior between age groups and adolescent Alone and Watched conditions.

Figure 24 displays the subjective value estimates for the offer space based on the mean $\varphi$ and $\sigma$ parameters for each age group/condition.

Table 3: Model AICs and BICs

<table>
<thead>
<tr>
<th>Model</th>
<th>Adults Alone</th>
<th>Adolescent Alone</th>
<th>Adolescents Watched</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fehr-Schmidt</td>
<td>290.2</td>
<td>223.5</td>
<td>219.1</td>
</tr>
<tr>
<td>Unbound Fehr-Schmidt</td>
<td>240.3</td>
<td>185.3</td>
<td>164.5</td>
</tr>
<tr>
<td>Unbound Fehr-Schmidt w/ partner parameter</td>
<td>143.5</td>
<td>154.0</td>
<td>122.3</td>
</tr>
<tr>
<td>Charness-Rabin</td>
<td>140.4</td>
<td>149.6</td>
<td>118.2</td>
</tr>
</tbody>
</table>
Figure 24: Subjective value of each combination of payout for self and payout for friend is depicted for the average values of ρ and σ for A) Adults completing the task alone, B) Adolescents completing the task alone, and C) Adolescents completing the task while watched by their partner.

### 6.3.2 Alone adolescents compared to Alone adults

Adults (who only completed the task alone) and Alone adolescents did not exhibit significantly different ρs ($t(81) = 0.57, p = 0.57$). Adults, however, exhibited significantly greater σs ($t(81) = 3.09, p = 0.003$) and μs ($t(81) = 3.17, p = 0.002$; Figure 25) compared to the Alone adolescents. The difference in μ means that adults exhibited
more consistent choices compared to Alone adolescents. The difference in $\sigma$ means that adults, compared to Alone adolescents, were more willing to accept disadvantageous inequity, including taking a cost to their own payouts, if it maximized total payout (Figure 24A & Figure 24B).

6.3.3 Alone adolescents compared to Watched adolescents

Adolescents exhibited significantly smaller values for all three parameters when Alone compared to when Watched ($\mu$: paired $t(54) = -4.04$, $p < 0.001$; $\rho$: paired $t(54) = -3.52$, $p < 0.001$; $\sigma$: paired $t(54) = -3.69$, $p < 0.001$; Figure 25). The difference in $\mu$ means that adolescents exhibited more consistent choices when Watched than when Alone. The difference in $\rho$ means that adolescents were more averse to advantageous inequity, especially when it came at a cost to their friends, when Watched than when Alone. The difference in $\sigma$ is more challenging to interpret – a sign change in $\sigma$ from negative when Alone to positive when Watched would indicate that Alone adolescents were more willing to reject offers when their partners are ahead, even when they themselves stand to benefit – but adolescents’ $\sigma$s are not significantly different from 0 in either the Alone or Watched conditions (Alone $t(54) = -0.59$, $p = 0.56$; Watched $t(54) = 1.27$, $p = 0.21$), indicating that adolescents generally did not value their partners’ payouts when their partners are ahead (Figure 24B & Figure 24C).

Within the 26 dyads in which both members completed Watched runs, Watched $\rho$s were significantly correlated ($r(24) = 0.45$, $p = 0.02$), while Alone $\rho$s, Watched or Alone
σs, and Watched or Alone μs were not (all ps > 0.1). The significant correlation in Watched but not Alone ρs could be a sign of reciprocity, in which the participant who completed the Watched run second changed their behavior to make choices similar to what s/he observed in the partner’s Watched run. The difference in adolescent ρs between Watched and Alone runs was numerically greater for those who completed the Watched run second (after watching their partner complete a run; mean Δρ = 0.40) than for those who completed the Watched run first (mean Δρ = 0.15), though this difference did not achieve statistical significance (t(53) = 1.64, p = 0.108).

6.3.4 Watched adolescents compared to Alone adults

When comparing the adults (who only completed the task alone) to the Watched adolescent runs, there was no significant difference in ρ (t(79) = -1.13, p = 0.26) and μ (t(79) = 0.19, p = 0.85). The adults, however, had significantly greater σs (t(79) = 2.66, p = 0.009; Figure 25) compared to the Watched adolescents, indicating that adults cared about their partners’ payouts even when their partners were ahead, and were more willing to accept disadvantageous inequity, including taking a cost to their own payouts if it maximized total payout (Figure 24A & Figure 24C).
Figure 25: Mean estimates of $\mu$, $\rho$, and $\sigma$ for each participant group. Comparisons between Adults Alone to the Adolescent groups are t-tests, while comparisons between the Adolescents Alone and Adolescents Watched values are paired t-tests. * indicates $p < 0.05$.

### 6.3.5 Relationships between choice behavior and friendship quality

Two measures of interest were derived from the FQS: positive friendship quality, which was the average of all items measuring positive friendship quality (all items except those from the Conflict subscale), and negative friendship quality, which was the Conflict subscale reporting how often friends argue (Bukowski et al., 1994). Adolescents and adults reported similar levels of positive friendship quality (adolescent mean = 3.72 out of 5, adult mean = 3.83, $t(82) = 0.66$, $p = 0.51$), while adolescents reported marginally greater negative friendship quality than adults (adolescent mean = 2.62 out of 5, adult mean = 2.20, $t(82) = -1.84$, $p = 0.07$). Negative friendship quality significantly correlated
with age across all participants ($r(82) = -0.22, p = 0.047$) but not within age groups.

Positive friendship quality was not significantly correlated with age across participants or within age groups ($ps > 0.1$).

Within the adolescents, positive friendship quality did not significantly predict Alone or Watched $\varrho$, $\sigma$, or $\mu$ (all $ps > 0.09$). Negative friendship quality, however, significantly correlated with Alone $\varrho$ ($r(55) = -0.34, p = 0.009$) and Watched $\varrho$ ($r(53) = -0.36, p = 0.006$) but not Alone or Watched $\sigma$ or $\mu$ (all $ps > 0.1$). The correlations between adolescent $\varrho$s and negative friendship quality remained significant even after controlling for age (Alone $\varrho$ $r(55) = -0.30, p = 0.024$; Watched $\varrho$ $r(53) = -0.34, p = 0.018$). Though the correlation between Alone $\varrho$ and negative friendship quality was no longer significant after excluding one adolescent with an extremely high Alone $\varrho$ and one with an extremely low Alone $\varrho$ ($r(53) = -0.15, p = 0.28$), the correlation between Watched $\varrho$ and negative friendship quality persisted even after excluding an adolescent with an extremely high Watched $\varrho$ ($r(52) = -0.35, p = 0.009$). Within the adults, neither positive nor negative friendship quality significantly correlated with $\varrho$, $\sigma$, or $\mu$ (all $ps > 0.1$; Figure 26).
Figure 26: Negative friendship quality does not significantly correlate with A) adults' Alone $q$ but does significantly correlate with B) adolescents' Alone $q$ and C) adolescents' Watched $q$. The inset in C shows the relationship between adolescents' Watched $q$ and negative friendship quality after excluding a participant with an extremely high Watched $q$.

6.3.6 Relationships between choice behavior and age

While exact age did not correlate with any of the model parameters within the Adults, Alone Adolescents, or Watched Adolescents groups (all $p > 0.1$), it did significantly correlate with Alone $\mu$ ($r(82) = 0.31$, $p = 0.004$) and Alone $\sigma$ ($r(82) = 0.30$, $p = 0.006$) but not Alone $q$ ($r(82) = 0.03$, $p = 0.77$; Figure 27). The significant correlation between exact age and Alone $\sigma$ persisted even after excluding one young adolescent with an especially low Alone $\sigma$ ($r(81) = 0.30$, $p = 0.007$).
Figure 27: The relationship between exact age and alone parameters was significant for A) Alone $\mu$, non-significant for B) Alone $\rho$, and significant C) Alone $\sigma$. Note that the relationship between exact age and Alone $\sigma$ remained significant even after excluding one participant with an extremely low Alone $\sigma$. Blue lines represent linear best fits, and shaded areas represent 95% confidence intervals.

### 6.4 Discussion

We found that the Charness and Rabin (2002) model of other-regarding preferences best fit our participants’ preferences, indicating that participants
incorporated the value of their payoffs and their partners’ payoffs into their decisions rather than just attending to whether they were ahead or behind. By comparing model-fit parameters, we found that adults, when alone, are more prosocial and willing to accept efficient, disadvantageous inequity compared to both Alone and Watched adolescents. This suggests that the developmental increase in accepting efficient, disadvantageous inequity that is found from childhood through adolescence (Fehr et al., 2013; Meuwese et al., 2015; Steinbeis & Singer, 2013) continues to develop beyond adolescence into adulthood. Furthermore, within our sample of 15- to 28-year-olds, we found that age significantly correlated with Alone $\mu$ and Alone $\sigma$ but not Alone $\varphi$, indicating that increasing age predicts increasing choice consistency and integration of payoffs when the partner is ahead. Additional work with a broader age range would be valuable for determining full developmental trajectories of other-regarding preferences.

We also found that in adolescents, but not adults, negative friendship quality within dyads negatively correlated with $\varphi$ in both Alone and Watched conditions (though the correlation in the Alone condition was driven by two outliers, the correlation in the Watched condition remained even after excluding an outlier). Though negative friendship quality did decrease with age across our sample, the relationship between adolescent $\varphi$ and negative friendship quality remained significant even after controlling for age. Thus, in our sample, adolescents but not adults reporting higher friendship conflict behaved more selfishly towards their friends, accepting offers of
advantageous inequity that paid them more and their friends less than the default 5 points. We found no significant relationships between positive friendship quality and behavior captured by any of the other model parameters. Taken together, our findings suggest that adolescents’ other-regarding preferences are more sensitive to the negative aspects of friendship than the positive, whereas adults’ other-regarding preferences remain efficient regardless of friendship quality.

Similar to Van Hoorn and colleagues (2016), we found that the presence of peers increased adolescents’ prosocial behavior. The effect of being watched by a friend, however, only made adolescents more averse to advantageous inequity and did not make them more accepting of disadvantageous inequity. In other words, adolescents were willing to give up some money for themselves in favor of equal payoffs, but they were not willing to give up some money for themselves so that their friends could have more than they did. This suggests that peer influence can be leveraged to facilitate prosocial behavior, but the effect is limited to promoting egalitarianism rather than efficiency.

Within our adolescent dyads, we found that Watched but not Alone qs were significantly correlated. This could indicate reciprocity, in which the adolescent who completed the second Watched run adjusted his/her behavior to match what s/he just observed. An alternative explanation is that dyads have similar other-regarding preferences in social contexts, perhaps due to choosing friends who exhibit similar social
norms or adopting similar social norms within a friendship. Though we found that adolescents who completed the second Watched run exhibited a numerically greater change in $\rho$ as a result of being Watched compared to those who completed the first Watched run, this difference did not reach statistical significance. Thus, given our current sample, we cannot rule out whether dyad behavioral similarity in Watched runs was due to reciprocity or to similar social norms within dyads. Future studies could further disentangle reciprocity from shared social norms by uncoupling the friend that participants watch from the friend that participants play for while watched (i.e. watch Friend A complete the RAT, then complete the RAT while Friend B watches).

This study was also limited in that our adult sample was smaller than our adolescent sample, and that our adult sample did not complete Watched runs or participate in dyads. Future studies should investigate adult behavior when Watched in order to determine if adults’ other-regarding preferences are sensitive to social contexts and investigate whether adult dyads exhibit similar behavior.

Future work could also examine whether other individual difference measures, in addition to friendship quality, predict other-regarding preferences. Adults with self-reported altruistic tendencies were found to pay more attention to others’ outcomes in a reinforcement learning task (Kwak, Pearson, & Huettel, 2014), and adolescents with stable social acceptance histories were more likely to make non-costly prosocial choices than those with a history of chronic rejection (Will, Crone, van Lier, & Güroğlu, 2016).
Thus, it may be that social-cognition and social-status related traits could affect other-regarding preferences, and the degree to which other-regarding preferences are influenced by social contexts.

Early studies of adolescent susceptibility to peer influence generally focused on how peer presence prompted maladaptive risk-taking (Chein et al., 2011; Gardner & Steinberg, 2005; Haddad et al., 2014; A. R. Smith et al., 2014; Van Hoorn, Crone, et al., 2016). Here, we find that peer presence can also increase prosocial behavior in adolescents, especially amongst friends with low friendship conflict. Our findings indicate that, under the right conditions, the presence of peers can be leveraged as a force for societal good (Crone & Dahl, 2012; Do et al., 2016).
7. Conclusions: Better capturing everyday decision preferences in the laboratory

To better understand the differences between developmental trajectories of reckless everyday behavior and risk-taking in laboratory tasks, this dissertation focused on investigating two factors that differ between everyday and laboratory decisions: ambiguity and social context.

The first aim was to examine the developmental trajectory of decision-making under ambiguity using laboratory tasks that provide participants with less than complete information about a decision’s probabilities (just as in everyday decisions). In Chapter 2, we developed a novel method of using physical objects to represent risk and ambiguity to 5-year-old children. We found 5-year-olds to exhibit no evidence of ambiguity aversion while adults were ambiguity averse. In Chapter 3, we found no evidence of ambiguity aversion in 8- and 9-year-old children, and significantly less ambiguity aversion in children compared to adults, through three separate measures of ambiguity aversion. In Chapter 4, we found adolescents and adults to exhibit similar levels of ambiguity aversion, and that ambiguity aversion, along with risk aversion and loss aversion, significantly predicted engagement in and perceived riskiness of everyday reckless behaviors.

Taken together, these studies indicate that ambiguity tolerance does not peak in adolescence and is, instead, highest in early childhood. Thus, though ambiguity
attitudes significantly predict engagement in everyday reckless behaviors, it does not explain why everyday reckless behavior peaks in adolescence.

The second aim was to examine the effect of social context on reward-related neural activity and behavior in adolescents and adults. In Chapter 5, we used fMRI to investigate how reward-related neural activity was affected by whether rewards were earned for self or for friend, and whether rewards were earned while alone or while watched by that friend. We found that reward-related neural activity was similar when earning rewards for self and for friend, and that striatal activity was greater when watched than when alone, after controlling for the effect of age. Striatal activity also linearly decreased with age from 18 to 28 in participants who completed the task while watched but not in participants who completed the task while alone, indicating that the effect of peer presence is strongest for late adolescents/young adults. In Chapter 6, we used behavioral social utility modeling to investigate how adolescents and adults make tradeoffs between rewards for themselves and for a friend, and how adolescents’ tradeoffs are affected by being watched by that friend. We found that, upon being watched, adolescents became less willing to make choices that benefited themselves more than their friends, but they did not become more willing to make choices that benefitted their friends more than themselves. Both alone and watched adolescents, however, were less efficient and more averse to disadvantageous inequity compared to adults.
Taken together, these studies indicate that young adults value rewards for themselves and for their friends similarly, and that their neural reward anticipation increases when watched by their friends. Adolescents, in contrast, value their own rewards more than those of their friends, though this difference in valuation of reward for self and friend is attenuated when the friend is present. Thus, when everyday decisions are made in the presence of friends, adolescents and young adults may be prompted to engage in behaviors that benefit both themselves and their friends.

### 7.1 Future directions: Decision-making and information availability

The finding that adolescents are more ambiguity tolerant compared to adults (Tymula et al., 2012) initially appeared to support dual-systems model predictions of peak recklessness in adolescence. Chapters 2 and 3 showing a lack of ambiguity aversion in young children (Li et al., 2015; Li, Roberts, Huettel, & Brannon, submitted) and other developmental work showing ambiguity aversion to linearly increase with age (Blankenstein et al., 2016), however, indicates that ambiguity aversion does not peak in adolescence. This underscores the importance of including children before drawing conclusions about developmental trajectories and shows that ambiguity attitudes alone are insufficient to explain differences in laboratory and everyday behavior.

If ambiguity attitudes cannot explain the discrepancy between laboratory and public health findings, what other factors could? Another line of research in decision-making under cases of low information availability suggests that learning abilities also
matter. In addition to being ambiguous, most everyday decisions also require learning about potential outcomes and probabilities through experience. The ability to learn from experience has previously been found to vary with age and affect decision-making under uncertainty. A meta-analysis comparing description- versus experience-based laboratory risk-taking paradigms in younger (ages 18 to 35) and older (ages 65 to 85) adults found that learning demands likely explained risk-taking differences between age groups: in described tasks, younger and older adults exhibited similar behavior, while in experienced tasks, risk-taking differences varied depending on how older adults’ poorer working memory and learning abilities interacted with task designs and demands (Mata, Josef, Samanez-Larkin, & Hertwig, 2011).

Though a meta-analysis of risk-taking studies of children, adolescents, and adults did not find that whether a task was experience- or description-based to significantly moderate any age differences (or lack thereof) in risk-taking (Defoe et al., 2015), very few studies have explicitly compared across ages on experience- and description-based versions of the same tasks. The findings of the few studies that do exist suggest that, as with older adults, learning demands affect risk-taking and interact with age. In the experience-based Iowa Gambling Task, children are generally the worst at learning to optimize their decision-making from any type of feedback (positive or negative), adults are the best, and adolescents lie somewhere in between, due to an adolescent tendency to preferentially learn from positive outcomes and not from
negative outcomes (Cauffman et al., 2010; Christakou et al., 2013; Crone & van der Molen, 2004, 2007; Huizenga, Crone, & Jansen, 2007; Prencipe et al., 2011; but see D. G. Smith, Xiao, & Bechara, 2012). When the Iowa Gambling Task was shifted to a description-based task by explicitly labeling payoff contingencies and thereby reducing learning demands, children and adolescents performed better and were able to use more complex advantageous decision strategies (van Duijvenvoorde, Jansen, Bredman, & Huizenga, 2012; van Duijvenvoorde, Jansen, Visser, & Huizenga, 2010).

Thus, the amount of available decision information differentially affects decision-making at different stages of development. When information is held constant in description-based paradigms, or when learning from experience is unavailable or unnecessary, willingness to take ambiguous gambles and choose the riskier of described equal EV options linearly decreases with age (Blankenstein et al., 2016; Crone et al., 2008; Harbaugh et al., 2002; Li et al., 2015, submitted; Paulsen, Carter, et al., 2012; Paulsen et al., 2011). When information is provided via an experimental paradigm, the boost in advantageous decision-making when shifting from experience- to description-based decisions has an inverse relationship with age.

Together, these findings suggest that the recruitment of cognitive control systems in guiding advantageous decision-making may be flexible based upon information availability: In experience-based tasks, the role of cognitive control systems in guiding advantageous decision-making may follow dual-systems imbalance model predictions
and linearly increase with age. In description-based tasks with high information availability or with ambiguous gambles in which information cannot be gained, however, the strength of cognitive control systems may experience a slope change that disproportionately boosts the cognitive control of children relative to adolescents relative to adults, with the shift in slope varying depending on the reduction in learning demands (Figure 28).

Figure 28: In the proposed flexible model, increasing information/decreasing learning demands changes the slope of the strength of cognitive control to drive advantageous decision making. Increasing color saturation indicates increased information/decreased learning demands in the decision environment.

In this flexible dual-systems model, the disparities between neural findings and behavioral predictions of the dual-systems imbalance model can be resolved. Studies
that find no age differences in risk-taking but neural findings consistent with dual-systems imbalance models (Van Leijenhorst, Gunther Moor, et al., 2010) can be explained by a large slope shift that relatively flattens the developmental trajectory of cognitive control, thereby increasing cognitive control above the inverted-U contribution of reward-processing and out of imbalance.

Though plentiful behavioral evidence suggests that the deployment of cognitive control to dictate advantageous decision-making is flexible based upon information availability, the neural basis of this flexible deployment of cognitive control remains speculative. The literature lacks developmental neuroimaging studies directly comparing risky decision-making in tasks of varying information availability. There are, however, developmental neuroimaging studies in high information environments that support the idea of flexible PFC recruitment. When adolescents (ages 13 to 17) and adults (ages 25 to 30) were given the chance to accept or reject described mixed economic gambles, there were no age-related behavioral differences, but adolescents exhibited more activity in frontal pole when choosing to reject trials than adults did, suggesting that choosing to reject gambles required more effort for adolescents (Barkley-Levenson et al., 2013). Similarly, on a described Cake Gambling Task in which participants chose which of two colors to bet on for a reward, children (ages 9 to 12) and adults (ages 18 to 26) performed similarly, but children exhibited greater dACC activity on high-risk (color ratios of 6:3 or 5:4) versus low-risk (color ratios of 8:1 or 7:2) trials,
while adults showed no difference by trial type, suggesting that children required more effort to implement optimal, advantageous decision-making on the more difficult trials (van Leijenhorst et al., 2006). It may be that high information availability boosts children and adolescents’ ability to call on PFC regions, perhaps by reducing learning demands and thus freeing cognitive resources for advantageous decision-making. Future work is needed to fully understand how differences in learning demands interact with age and PFC activity to drive decision-making behavior.

Future work should also investigate how ambiguity attitudes interact with age and the ability to learn from experience. If children are ambiguity neutral but also poor learners, repeated experience with an ambiguous gamble may not alter their starting preferences. In contrast, if adolescents and adults are both ambiguity averse, but adolescents preferentially learn from positive outcomes and adults learn from both positive and negative outcomes, then increased experience with an ambiguous gamble would shift adolescents to optimistic and adults to realistic assessments of the gambles’ underlying probabilities. This interaction between ambiguity attitudes and adolescents’ tendency to learn from the positive could help explain why everyday reckless behavior peaks in adolescence. A better understanding of the interplay between ambiguity attitude and learning abilities across development, and their underlying neural activity, could help design public health interventions to prevent everyday reckless behaviors.
7.2 Future directions: Decision-making and social context

An existing interpretation of the dual-systems imbalance model suggests that reward-processing neural regions are flexibly recruited depending on whether a decision context is affectively arousing (A. R. Smith et al., 2013; Steinberg, 2010; Figure 29). While previous work suggested that the presence of peers is only affectively arousing and increases reward-related neural activity for adolescents and not for adults (Chein et al., 2011; A. R. Smith et al., 2015), Chapter 5 and other studies (Izuma et al., 2010a, 2010b) show that social contexts can also increase reward-related neural activity in young adults, with Chapter 5 showing that the effect of peer presence on striatal activity declines with age from 18 to 28. Thus, there remains uncertainty as to exactly when peer presence stops boosting reward-related neural activity. Furthermore, the effect of peer presence on reward-related neural activity and behavior has not yet been studied in children. As noted in Chapter 1, studying only adolescents and adults only reveals half of the developmental picture. Thus, future work should investigate the influence of peer presence across a broad age range in order to determine its full developmental trajectory and determine whether adolescence truly represents a period of peak sensitivity to peer presence.
Figure 29: In the proposed flexible model, decreasing emotional arousal decreases the strength of reward-processing in driving decision-making. Decreasing color saturation indicates decreasing emotional arousal.

Additionally, it is also important to understand how reward for self and for friend are valued depending on whether those rewards are earned independently, competitively, or simultaneously. We found that both are similarly valued in young adults when reward for self and for friend are independent (Chapter 5) and when they are pitted against each other (Chapter 6), while competition drives adolescents to value their own rewards over those of their friends (Chapter 6). Future work should investigate how reward for self and for friend are processed at different ages and in
different social contexts when their effects are shared or processed simultaneously (e.g. winning $5 for self and for friend). Young adults (mean age 20.6 years) were found to exhibit greater striatal response to reward and report greater excitement when sharing monetary gains with a friend compared to with a stranger or computer (Fareri, Niznikiewicz, Lee, & Delgado, 2012), but it is not yet known how adolescents would respond. As everyday reckless behavior often occurs in social settings in which rewarding experiences are shared with peers, it is also important to understand how shared rewards are processed in social contexts.

### 7.3 Accounting for varied decision contexts through a flexible dual-systems model

A fully flexible dual-systems model allows for cognitive control to vary based on information availability, for reward-processing to vary based on emotional arousal, and for both to differentially vary with age (Figure 30). Moving from a static to a flexible model allows us to account for decision-making under different decision environments and can account for the discrepancies between laboratory findings and everyday behavior.
Figure 30: In a fully flexible model, the relative strengths of cognitive control and reward-processing in driving decision-making vary based upon information availability/learning demands and emotional arousal in the decision environment (trajectories of intermediate levels of information/learning demands and emotional arousal are faded for visual clarity).

As previously noted, the neural underpinnings behind the flexibility of cognitive control and advantageous decision-making remain unexplored, as there have been no developmental neuroimaging studies comparing risk-taking under different learning demands or cases of varying information availability. Additionally, the interactions between cognitive control and reward processing, and the developmental trajectory of those interactions, warrant further exploration. Self-report data suggest that impulse
control and sensation-seeking develop independently (Shulman, Harden, Chein, & Steinberg, 2016), but emotional states have been found to enhance cognitive control performance and increase related neural activity in adults (ages 21 to 25; Cohen et al., 2016). Additionally, adolescent (ages 13 to 17) risk-taking on a simulated driving game was correlated with their performance on a social/emotional cognitive control task but uncorrelated with performance on a nonsocial/nonemotional version of the same cognitive control task (Botdorf, Rosenbaum, Patrianakos, Steinberg, & Chein, 2016). Much more research is needed to unpack if, when, and how control and reward processes interact to influence risky decision-making.

Furthermore, additional work is needed to understand how decision contexts change across development so that laboratory work can better translate to everyday decision-making. Legal access to risky scenarios surely plays a role (Boyer & Byrnes, 2009; Shulman, Smith, et al., 2016), but increasing experience with risky scenarios likely matters as well. It may be that older adolescents/young adults take more everyday risks because they are disproportionately experiencing unfamiliar decision contexts, and risk-taking decreases with age due to increased information gained through experience rather than the passing of peak reward sensitivity. Additional research on the relative strength of the dueling forces of control and reward under various decision-making contexts is necessary to guide public health interventions that would reduce maladaptive adolescent everyday risk-taking.
The relatively young field of developmental risky decision-making has made many important discoveries about the adolescent brain with far-reaching implications for public health (Simpson, 2003) and the law (Steinberg, 2013). Yet much remains to be uncovered. By allowing existing dual-systems imbalance models additional degrees of freedom to vary with decision contexts, we have a more flexible framework for promoting further exploration and understanding of the developmental of risk-taking in a variety of scenarios, from the laboratory to everyday life.
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160

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Biography

Rosa Li was born on September 20, 1987 in Rockville, Maryland. She received her B.A. in 2009 from Yale College, where she graduated cum laude and with distinction in Psychology (neuroscience track). She then spent two years as a lab manager for Dr. Jessica Cantlon’s Kid NeuroLab at the University of Rochester. In the fall of 2011, Rosa enrolled as a graduate student at Duke University via the Cognitive Neuroscience Admitting Program. She later joined the labs of Dr. Scott Huettel and Dr. Elizabeth Brannon and affiliated with the Department of Psychology & Neuroscience at Duke University, from which she received an M.A. in 2014.

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