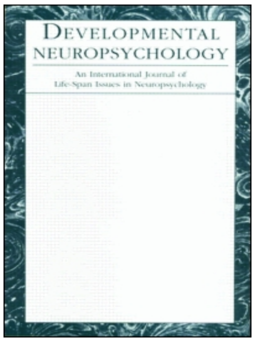

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Dealing With Uncertainty: Testing Risk- and Ambiguity-Attitude Across Adolescence

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ABSTRACT

Attitudes to risk (known probabilities) and attitudes to ambiguity (unknown probabilities) are separate constructs that influence decision making, but their development across adolescence remains elusive. We administered a choice task to a wide adolescent age-range (N = 157, 10–25 years) to disentangle risk- and ambiguity-attitudes using a model-based approach. Additionally, this task was played in a social context, presenting choices from a high risk-taking peer. We observed age-related changes in ambiguity-attitude, but not risk-attitude. Also, ambiguity-aversion was negatively related to real-life risk taking. Finally, the social context influenced only risk-attitudes. These results highlight the importance of disentangling risk- and ambiguity-attitudes in adolescent risk taking.

Adolescence, which encompasses the developmental phase between childhood and adulthood, has often been described as a period of increased risk taking (Crone & Dahl, 2012; Somerville, Jones, & Casey, 2010; Steinberg, 2008). Typically, risk taking is defined as choosing the option with the highest outcome variability (Defoe, Dubas, Figner, & Van Aken, 2015), that is, an action that may lead to greater benefits, but may also lead to negative outcomes, at the expense of certainty. During adolescence engagement in substance abuse, deviant behavior, unprotected sex, and reckless driving increase and peak (Eaton et al., 2008), often accompanied, if not strengthened, by the presence of peers (Chassin et al., 2004; Simons-Morton, Lerner, & Singer, 2005). This potential rise in risk-taking behavior is associated with pronounced neural changes in brain networks including subcortical structures (such as the ventral striatum) and cortical regions (such as the prefrontal cortex). It has been suggested that the different maturational rate of these brain regions, and their connectivity patterns, lead to a "neural imbalance," which may result in increased reward-sensitivity, risk taking, peer susceptibility and attenuated impulse control (Casey, 2015; Crone & Dahl, 2012; Somerville & Casey, 2010; Steinberg, 2008). However, there are large individual differences (not *all* adolescents are risk takers) and contextual influences (adolescents are not *always* risk takers) that are not yet well understood (Casey, Jones, & Hare, 2008; Harden & Tucker-Drob, 2011). The current research examined determinants of risky decision making in adolescence, by testing the role of risk versus ambiguity, and by examining the role of social influence on risk taking. These two contexts have previously been found to play an important role in explaining variance in risk taking (Chein, Albert, O'Brien, Uckert, & Steinberg, 2011; Tymula et al., 2012), but no study to date examined these factors across adolescence in one comprehensive study.

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Risk and ambiguity

Although the *outcomes* of risky prospects are often certain (e.g., you know exactly how much you may win or lose in a gambling game), the probabilities may be presented under different conditions varying in uncertainty (Tversky & Kahneman, 1992). First, risk taking can occur under conditions in which the probabilities are known, reflecting explicit risk (e.g., the probability of heads in a coin toss is 50%). Second, risk taking can occur under conditions in which the probabilities are not known, reflecting ambiguous risk (e.g., the probability of causing an accident when driving through a red light is unknown). Thus, in conditions of risk versus ambiguity the *probabilities* of different outcomes vary in uncertainty. Indeed, real-life often presents ambiguous risks (driving through a red light), rather than explicit risks (a coin toss). Prior developmental studies, however, have often used paradigms that only involve gambles with known probabilities (Braams, Peters, Peper, Guroglu, & Crone, 2014; Burnett, Bault, Coricelli, & Blakemore, 2010; Defoe et al., 2015; van Leijenhorst, Westenberg, & Crone, 2008), or used paradigms that start out ambiguous but in which the ambiguity is reduced over time via learning or experience (Chein et al., 2011; Crone & van der Molen, 2004; Lejuez, Aklin, Zvolensky, & Pedulla, 2003; van Duijvenvoorde, Jansen, Bredman, & Huizenga, 2012) and therefore cannot distinguish between these two elements of risk taking. Individuals' risk-taking behavior may be driven by both one's attitude toward risk (i.e., a taste for risk, known probabilities) and one's attitude toward ambiguity (i.e., a tolerance for uncertainty, unknown probabilities) (Tversky & Kahneman, 1992), indicating the importance of disentangling these attitudes in studies on adolescent risk taking.

Previous research showed that adults tend to dislike both risk (von Gaudecker, van Soest, & Wengström, 2011) and ambiguity (Ellsberg, 1961) indicating that generally, adults are risk- and ambiguity-averse. However, risk and ambiguity attitudes are correlated weakly at best (Levy, Snell, Nelson, Rustichini, & Glimcher, 2010; Tymula, Rosenberg Belmaker, Ruderman, Glimcher, & Levy, 2013), suggesting that these attitudes indeed reflect different elements of risk taking. Most importantly, a recent study found pronounced differences in these elements of risk taking in adolescents (12–17 years) and adults (30–50 years). Tymula et al. (2012) showed that although both age groups were risk- and ambiguity-averse, adolescents were less ambiguity-averse, and unexpectedly more risk-averse, than adults (Tymula et al., 2012). Also, ambiguity-attitude, but not risk-attitude, was related to indices of adolescent real-life risk taking, particularly the frequency of reckless behavior. These results highlight a relatively higher tolerance to ambiguity in adolescence that may relate to the increased risk taking observed in adolescence compared to adulthood (see Defoe et al., 2015). Additionally, a recent study comparing children (8–9 years) with adults (19–27 years) (Li, Brannon, & Huettel, 2014), observed that despite an intact bias towards the familiar (e.g., preferring known books over unknown books), ambiguity-aversion was not yet present in childhood. This indicates that adolescence may be the start of developing ambiguity-aversion as observed in adulthood, or may show unique risk- and ambiguity-tolerance relative to children and adults. Thus, the exact developmental trajectory of risk- and ambiguity-aversion remains unknown.

Here, we aim to further address this question by testing whether risk- and ambiguity-attitude follow a linear trajectory (e.g., ambiguity-aversion increases with age) or a quadratic trajectory (e.g., a tolerance to ambiguity peaking in adolescence) into young adulthood. Furthermore, we explicitly aim to link individual differences in risk-and ambiguity-attitude with differences in self-reported real-life risk-taking behavior and reward sensitivity. Self-report measures are an important addition to the current study, as they serve as validation of our paradigm and explain how risk taking in the laboratory reflects risk-taking behavior in real life. Specifically, we were interested in the behavior subscales of the Adolescent Risk-taking Questionnaire (ARQ, frequency of risk-taking behaviors in daily life; Gullone, Moore, Moss, & Boyd, 2000), and the Behavioral Inhibition System/Behavioral Approach System questionnaire (BIS/BAS, reward sensitivity; Carver & White, 1994). These questionnaires have previously been associated with ambiguity-attitude

(Tymula et al., 2012) and risk-taking tendencies in adolescence (Braams, Van Duijvenvoorde, Peper, & Crone, 2015; van Duijvenvoorde et al., 2014), respectively.

Social influence

Besides a rise in risk-taking behavior, adolescents also show a shift in orientation toward peers, and some have suggested that these processes are strongly related (Chein et al., 2011; Gardner & Steinberg, 2005). For instance, risk-taking behavior typically takes place in groups and studies have shown that merely the presence of peers may lead to increased risk taking (Gardner & Steinberg, 2005) and greater activation in reward-sensitive areas in the brain during risk taking (Chein et al., 2011; Steinberg, 2004). Although most studies until now have focused on peer presence, peers may also be a source of information for choice behavior. Consistently, a recent study with adults focused on the influence of observing peers' choices (Chung, Christopoulos, King-Casas, Ball, & Chiu, 2015). Specifically, it was shown that merely observing other people's choice of gambles changes the subjective value of those gambles. Also, in a study with adolescents (12–17 years) and adults (18+ years), advice from an "expert economist" had stronger effects on adolescents than on adults, with the adolescents approaching adult-like (i.e., risk-averse) risk-attitudes in the presence of advice (Engelmann, Moore, Monica Capra, & Berns, 2012). These studies suggest that information retrieved by observing others is integrated in one's own choice process. As a first step to test whether adolescents' risk- and ambiguity-attitude is influenced by a social context, we presented an additional condition in which adolescents were presented with the same gambles, but in which choices from a high risk-taking peer were presented. Here, we focus particularly on the shift in risk- and ambiguity-attitudes between the solo and the social condition.

The current study

Taken together, we aim to study the developmental trajectory of risk-and ambiguity-attitudes across adolescence, and to what extent these attitudes relate to real-life risk-taking behavior. Second, we test the influence of a social context on risk- and ambiguity-attitude across adolescence. Based on the few previous studies we expect that developmental changes in risk-attitude are less pronounced compared to changes in ambiguity-attitude, which may increase or peak particularly in early- to mid-adolescence. Also, we expect that although both risk- and ambiguity-attitude may relate to individuals' real-life risk-taking behavior, this relation may be stronger for ambiguity-attitude given that this more likely reflects real-life risks (i.e., unknown probabilities rather than known probabilities). Finally, we expect that a social context influences participants' risk and ambiguity-attitudes, particularly in early- to mid-adolescence.

To these ends, we developed a wheel-of-fortune gambling task modeled after Tymula et al. (2012) that included risky choices (known risks) and ambiguous choices (unknown risks) that was administered to a wide adolescent age-group (ages 10–25, $N = 162$). A novel aspect of this study was that we applied a model-based approach derived from economics to estimate individual's risk- and ambiguity-attitudes from this specific set of items (Gilboa & Schmeidler, 1989; Tymula et al., 2012). This is a relatively new approach in developmental research (Tymula et al., 2012) and allows to distinguish individuals' subjective, rather than objective, preferences for risky and ambiguous choices, a central question in economic theory (Camerer & Weber, 1992; Knight, 1921). In addition, participants completed questionnaires on their individual level of risk taking in daily-life situations (ARQ) and reward-sensitivity (BIS/BAS). This provides valuable information with respect to validation of our paradigm and how risk taking in the laboratory reflects real-life risky behavior. Moreover, participants played these gambles by themselves (solo) or when choices from an age-matched peer were present (social). Specifically, peer-choices were manipulated to include a more risk-seeking and ambiguity-seeking attitude to investigate to what extent participants' attitudes were swayed.

Method

Participants

One hundred sixty-two participants (85 female) ages 10–25 completed the wheel-of-fortune task. Participants were recruited from a primary school (10–12-year-olds, n = 37), a secondary school (14–16-year-olds, n = 40), higher vocational institutes (17–20-year-olds, n = 31), and universities (21–25-year-olds, n = 52), in the Netherlands. Written informed consents were provided by the participants themselves or by a parent in the case of minors. Recruitment, written informed consent, and procedures were approved by the local ethics committee. Participants were given a flat rate of 10 Euro (21–25-year-olds) or a small present (10–20-year-olds) for their participation. Additionally, to increase motivation and include a real-life consequence, participants were explained that one trial would be randomly picked out from their choices and that they could win this amount via a lottery in their class. Eventually, one participant from each class won his amount.

Five participants were excluded from all analyses: three because they did not show any variation in choice behavior, making it impossible to estimate risk- and ambiguity-attitudes, and two for violations of stochastic dominance in more than 50% of the trials. Stochastic dominance violations occur when one option is better than another option in all respects, but the suboptimal option is chosen (Birnbaum & Navarrete, 1998). In the current task, dominated choices occurred when presented with a 5 Euro safe choice and a 5 Euro gamble (see task description). Choosing the gamble would be a violation of stochastic dominance, as it is impossible to benefit from the gamble compared to the safe option. Consistently violating stochastic dominance may indicate a limited understanding of the task. These exclusion criteria have been applied before in Tymula et al. (2012, 2013). The final sample therefore included 157 individuals (84 female, M_{age} = 17.04 years, SD_{age} = 4.58, range = 10.00–25.63 years), evenly distributed over four continuous age groups (10–12 years: n = 37, 19 female; 14–16 years: n = 39, 21 female; 17–20 years: n = 31, 12 female; 21–25 years: n = 50, 32 female). A χ^2-test indicated no significant gender differences between age groups (χ^2 (3, N(157) = 5.01, p = .17). IQ was estimated for the three youngest age groups using a short version of the Raven Standard Progressive Matrices (SPM; Raven, Raven, & Court, 1998). The average estimated IQ scores were within the normal range (M = 102.11, SD = 12.81), but correlated with age (r = -.22, p = .023). However, adding IQ as a covariate in the subsequent analyses did not result in any significant effects of IQ nor changed the results, indicating that intelligence did not influence behavior on the task.

Wheel-of-fortune task

In a wheel-of-fortune task (see Figure 1), mimicked after Ernst et al. (2004) and Tymula et al. (2012), participants were asked to make a series of choices between pairs of wheels. One consistent option was a sure wheel that would always yield a gain of 5 Euro. The other option was a gambling wheel that could yield higher gain-amounts, but also entailed a chance to win nothing (0 Euro), depicted with blue (winning) and red (not winning) parts. The gain-amount, gain-probability, and ambiguity-level associated with the gambling wheel varied from trial to trial, allowing to estimate participants risk-attitude (to known probabilities) and ambiguity-attitude (to unknown probabilities). The amount of gain varied between 5, 8, 20, and 50 Euro. In risky trials, the gain-probability of risky gambling wheels (i.e., wheels with known probabilities) varied between 0.125, 0.25, 0.375, 0.50, 0.625, and 0.75. In ambiguous trials, the gambling wheel was obscured by a grey lid that covered more or less of the gambling wheel. The ambiguity-level of ambiguous gambling wheels (i.e., wheels with unknown risks) varied between 25%, 50%, 75%, and 100% (see Figure 1C). In these ambiguous wheels, the visible parts always included the same relative size of red and blue parts. Combining all gain-amounts and gain-probabilities resulted in 24 unique risk trials, and combining all gain-amounts and ambiguity-levels resulted in 16 unique ambiguous trials.

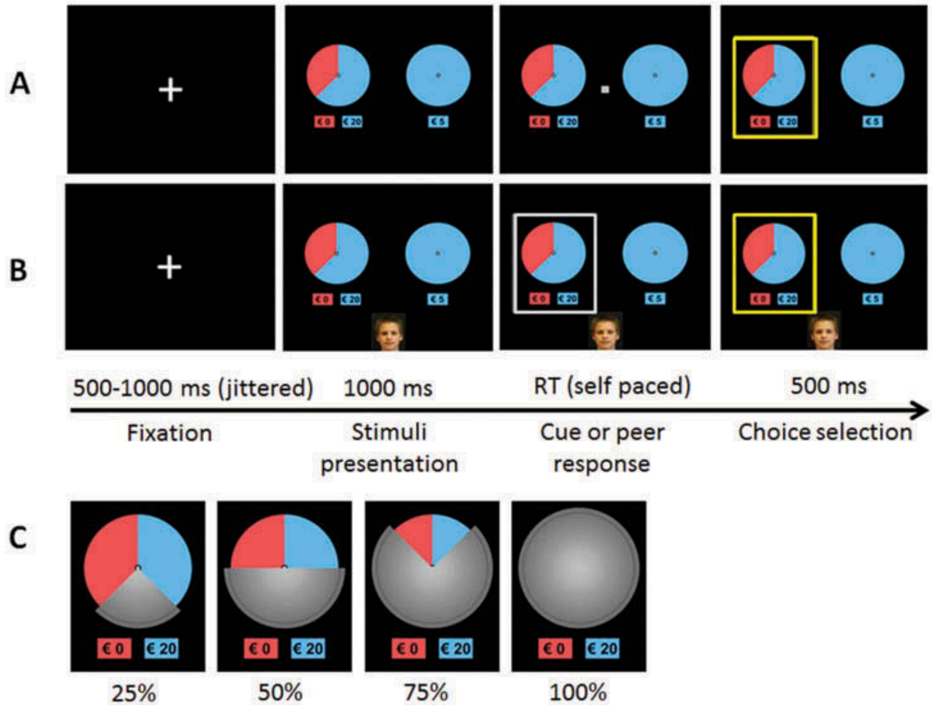

Figure 1. A. Example of a risk trial in the solo condition. Participants were presented with a jittered fixation cross between 500–1,000 msec (with increments of 100 msec), after which the wheels appeared (a gambling wheel varying in gain-probability, gain-amount, and ambiguity-level) and a sure wheel (a consistent gain of 5 Euro). After 1,000 msec a centered cue appeared, allowing the participants to respond. A yellow selection frame (500 msec) confirmed the participant's choice. B. Example of a risk trial in the social condition. The timing of social trials was similar to the solo condition. In addition to the gambling wheel and the sure wheel, an anonymous peer (matching the participant's gender and age) appeared. After 1,000 msec this peer's response appeared, allowing the participants to respond. A yellow selection frame (500 msec) confirmed the participant's choice. C. Examples of the ambiguous gambling wheels. The lid could cover a varying proportion of the wheel.

Risky wheels were explained to the participants as wheels with winning (and not winning) parts that could vary in size, indicating that the chance of winning (and not winning) could also vary. Ambiguity levels were explained to the participants as a lid that could vary in size and hence cover more or less of the gambling wheel. To ensure that participants understood that the blue and red parts under the ambiguous lids could vary randomly, participants were explicitly shown all possible wheels that could lie beneath each type of lid during instruction of the task.

The wheel of fortune task was played in a solo (Figure 1A) and a social condition (Figure 1B). Participants played three repetitions of all unique risky and ambiguous trials in each condition, resulting in a total of 240 trials (120 per condition).

In the solo condition, participants indicated their responses with a left or right button press, without a maximum response time. After their decision a yellow selection frame appeared around the chosen wheel. The social condition (Figure 1B) was similar to the solo condition, except that a picture of a peer was included on screen (matching the participant's age group and gender) during each choice. Before the participant's own choice, the choice of the peer was presented by a grey selection frame around one of the wheels. Subsequently, the participants were able to indicate their choice irrespective of the peer's choice. For each age group and gender a set of 10 standardized pictures were used (Gunther Moor, Crone, & Van der Molen, 2010). For each participant one of these pictures was randomly drawn, matched for age group, and presented throughout the social condition. Participants were explicitly instructed that the observed peer-choices were from another participant of the same age. In reality, our peer-manipulation was programmed as a risk-taking peer, given that the cutoff of gambling for the peer was set to an objective expected value (EV) > 3 Euro of the gambling wheel (i.e., the EV of the safe option was always 5 Euro), with the exception that the peer did not violate stochastic dominance in the 5 Euro gambling items. These settings resulted in a risk-attitude of the peer of $\alpha = 1.44$ (indicating an extreme risk-seeking attitude), and an ambiguity-attitude of $\beta = -.85$ (indicating an extreme ambiguity-seeking attitude). As a control measure, we included four additional trials in which the peer did violate stochastic dominance. These trials were added to check if participants would not blindly mimic the peer's choices. However, this rarely happened (i.e., 3.3% of the time).

All participants first played a solo block of trials followed by a social block. To account for order effects, participants subsequently played another solo block followed by a social block, or vice versa (counterbalanced across subjects). Preliminary one-way ANOVAs did not reveal an effect of block order on overall gambling in risk trials ($p = .95$), nor on overall gambling in ambiguity trials ($p = .36$). Last, to control for key preference and effects of attention, we counterbalanced the position of the blue and red parts of the wheels (left, right, bottom, and top of the wheel), and the position of the ambiguous lids (top or bottom of the wheel), across trials. That is, each stimulus had four possible color configurations (except for the 50:50 explicit risky wheels and the 100% ambiguous wheels, which had two possible color configurations), one of which was randomly chosen on each trial. Finally, the different wheels (gamble, safe) were randomly displayed left and right on the screen.

Questionnaires and exit questions

To test for relations between estimated risk- and ambiguity-attitudes and indices of real-life risk taking, participants completed the *behavior* scale of the ARQ (Gullone et al., 2000), a measure of one's real-life risk-taking behavior (as opposed to the *perception* scale of the ARQ, which is a measure of one's perception towards real-life risk taking; Gullone et al., 2000). That is, participants indicated on a 5-point Likert scale the frequency with which they engaged in risky activities (with 1 indicating *never* and 5 indicating *very often*). Examples include "Snow skiing," "Drinking and driving," and "Having unprotected sex." The ARQ *behavior* scales consists of four subscales: Thrill-seeking, Rebellious, Reckless, and Antisocial behavior. The ARQ has been validated in 925 participants between the ages of 11 and 19 years old (Gullone et al., 2000). To test for relations with reward-sensitivity, participants completed the BIS/BAS (Carver & White, 1994), which measures avoidant and appetitive motives for reaching a desirable goal (e.g., reward sensitivity). This questionnaire contains 24 items on a 4-point Likert scale ranging from 1 (*very true for* me) to 4 (*very false for me*). Examples include "When I get something I want, I feel excited and energized" and "I crave excitement and new sensations." The BIS/BAS questionnaire consists of four subscales: BIS, BAS Fun Seeking, BAS Reward Responsiveness, and BAS Drive. Due to class absence, eight participants did not complete the ARQ questionnaire (two 17–20-year-olds and six 21–25-year-olds), and nine participants did not complete the BIS/BAS questionnaire (three 17–20-year-olds and the same six 21–25-year-olds).

Additionally, all participants completed a number of exit-questions about the anonymous peer in the wheel of fortune task. These questions considered the participants' opinion on how much they believed the decisions of the peer, how wise they found the decisions of the peer, how smart they found the peer, and how influenced they were by the decisions of the peer, on a scale from 0 to 9 with anchors *not at all true for me* and *completely true for me*.

Procedure

Participants played the wheel-of-fortune task individually in a quiet space at their school or university. Instructions were delivered individually and before starting the task it was ensured all participants understood the task. Participants were given a number of examples and completed seven practice trials before starting. The wheel-of fortune task took approximately 20 minutes to complete. Participants completed the Raven SPM, and the questionnaires on paper-and-pencil or online using

Qualtrics (www.qualtrics.com) in a separate session from the wheel-of-fortune task. After the experimental procedure, participants were debriefed by explaining that the choices of the peer were computer-generated. Participants reported to modestly believe the decisions of the peer (M = 3.44, SD = 2.18, range 0–9), but this did not correlate with age (p = .96), indicating all participants reported to believe the decisions of the peer to a similar degree.

Data analyses

To check whether all participants had a basic understanding of the task (e.g., are sensitive to increasing probability, ambiguity level, and amount), conventional ANOVAs were used on the task data. These analyses set the stage for testing our hypotheses. For further analyses with model-based estimations of risk and ambiguity-attitudes (hierarchical) multiple regressions were used.

Model-based analysis: Risk and ambiguity

Our main focus was to estimate risk- and ambiguity-attitudes of each participant using a model-based approach and use these attitudes for subsequent analyses. The advantage of such a model-based approach is twofold. First, it is an elegant way of estimating an integrative choice model that simultaneously estimates risk- and ambiguity-attitude. Second, it allows for an explicit comparison with previous studies using a similar model-based approach (Tymula et al., 2012, 2013), which has been successfully applied to a developmental sample (Tymula et al., 2012).

To estimate the risk- and ambiguity-attitudes of each participant, we modeled the subjective value (EU) of the choice option using a widely used power utility function with an additional term to account for ambiguity-attitudes (Gilboa & Schmeidler, 1989; Levy et al., 2010; Tymula et al., 2012):

$$EU(x, p, A) = \left(p - \beta * \frac{A}{2}\right) * x^{a},$$

where x represents the amount of money that could be won, p is the probability, A the ambiguity level, α the risk-attitude, and β the ambiguity-attitude. In the current gain trials, an α = 1 indicates a linear utility function and thus risk neutrality. An α < 1 indicates a concave utility function and thus risk aversion, whereas α > 1 indicates convexity and thus risk seeking.

To obtain subjective value, the utility of an option was multiplied with the probability of outcome. In this specific case, the level of ambiguity was taken into account. That is, p was the objective probability of winning, and β was the individual ambiguity-attitude to be estimated. A is the objective ambiguity-level. An ambiguity-neutral participant would have an estimated $\beta = 0$. An ambiguity-averse participant would behave as if the winning probability was less than the objective 0.5 probability ($\beta > 0$). An ambiguity-seeking participant would behave as if the winning probability was more than the objective 0.5 probability ($\beta < 0$).

We used the simplex algorithm of the general-purpose optimization toolbox (*optim*) in R for model fitting (R Core Team, 2015). To model trial by trial choices we used a logistic choice rule to compute the probability (P_{Gamble}) of choosing the risky/ambiguous option as a function of the difference in subjective value EU_{Gamble} and EU_{Sure}. To account for the observed stochasticity in choice, we also modeled the decisions of participants as susceptible to an error (μ):

$$\Pr(ChoseGamble) = \frac{1}{1 + \exp\left(-\left(EU_{risky} - EU_{sure}\right)/\mu\right)}$$

To account for local minima in estimated parameters this function was refitted using a grid search procedure. The resulting risk- and ambiguity-parameters were used in subsequent analyses using conventional regressions.

Results

Task understanding

In the following analyses we report the data from the solo condition only (but see "Risk- and ambiguity-attitudes in the social condition").

Stochastic dominance violation

To investigate understanding of the choice task, we determined first-order stochastic dominance violations. That is, in some trials, subjects chose between a sure gain of 5 Euro and a gambling wheel that offered a risky or an ambiguous chance of winning 5 Euro. In such trials it is impossible to benefit by choosing the gambling wheel. Thus, an economically rational subject should always choose the certain amount over the gamble (but see Kahneman & Tversky, 1979). The participants (after exclusions, see "Participants") rarely chose this gambling wheel (M = .02, SD = .07). A linear regression revealed no significant age effect on choosing this lottery over the sure gain (p = .28). This indicates that although subjects occasionally violate dominance, this rarely happened in the current task and age-range.

Sensitivity to gain-probability, ambiguity-level, and gain-amount

Next, to investigate understanding of the task, we tested participants' choice behavior in response to changes in level of gain-probability, ambiguity-level, and gain-amount in conventional repeated measures ANOVAs with age group as a between-subjects variable. These revealed significant main effects on choice behavior of gain-probability, ambiguity-level, and gain-amount, with higher gain-probability, lower ambiguity-level, and higher gain-amount leading to an increased likelihood to gamble (all p's < .001). No significant interactions with age group were found (all p's > .09), and visualization of these effects indicated highly similar patterns across the four equally-spaced age groups (see Figure 2). Thus, all participants indicated a basic understanding of the task.

Finally, we compared gambling in the ambiguous items to gambling in the 50:50 explicit risky items. Considering that this is how one should treat an ambiguous gamble (i.e., with a 50% chance of winning, Tymula et al., 2012), less gambling in ambiguous items versus this option would indicate ambiguity aversion. Indeed, participants generally gambled less in the ambiguous items (M = .28, SD = .16), compared to the 50:50 explicit risky items (M = .46, SD = .17), as shown by a paired samples t-test ($t(156) = -14.35$, $p < .001$). This replicates prior studies (Ellsberg, 1961; Levy et al., 2010) and sets the stage for testing our hypotheses on risk- and ambiguity-attitudes.

Risk- and ambiguity-attitude: Model-based analyses

To more formally estimate individuals' risk- and ambiguity-attitude we used a model-based approach (Tymula et al., 2012, 2013), see Methods for further specification. When plotting the individually estimated risk- and ambiguity-attitudes we observed that people were generally risk-

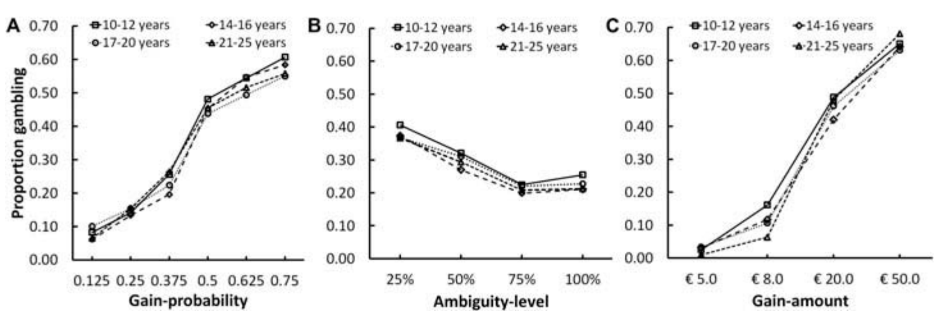

Figure 2. Visualization per age group of the effects of gain-probability (A), ambiguity-level (B) and gain-amount (C), on proportion of gambling.

and ambiguity-averse (see Figure 3A for a visualization of the data). That is, most risk-attitudes (α's) were < 1 (M = .57, SD = .24) and most ambiguity-attitudes (β's) were > 0 (M = .43, SD = .32).

Our main goal was to test for linear and quadratic age effects on risk- and ambiguity-attitudes. Hierarchical multiple regressions, with the linear effect of age as the first predictor and the quadratic effect of age as the second predictor, revealed no significant linear age effect on estimated risk-attitude (p = .25), nor a quadratic effect of age (p-$change$ = .79). To test whether gender would have an effect on risk-attitude, we added gender as a third predictor above age linear and age quadratic. The model with gender explained additional variance (ΔR^2 = .04, F-$change$(1,153) = 4.75, p-$change$ = .031, b = .08, SE = .04), and showed that males (M = .61, SD = .24) were slightly more risk-seeking than females (M = .53, SD = .24). No significant interactions between age (linear or quadratic) and gender were observed.

A similar analysis with estimated ambiguity-attitude showed that ambiguity-aversion increased linearly with age (R^2 = .034, F(1,155) = 5.40, p = .021, b = .01, SE = .006), but did not show a quadratic effect of age (p-$change$ = .41). No significant main effect of gender, nor interactions between gender and age were observed. Thus, ambiguity-attitude, but not risk-attitude, changed significantly with age. A correlation between these attitudes showed that risk- and ambiguity-attitude were not significantly correlated (r = .05, p = .51).

Individual differences

Next, we aimed to test whether the estimated risk- and ambiguity-attitudes were related to indices of self-reported real-life risk taking behaviors (ARQ; Gullone et al., 2000) and reward sensitivity (BIS/BAS; Carver & White, 1994).

First, we observed that self-reported risk taking (ARQ) increased linearly across age for reckless behavior (b = .07, SE = .009, p < .001), rebellious behavior (b = .18, SE = .015, p < .001), and antisocial behavior (b = .06, SE = .01, p < .001). To test which ARQ subscale(s) best explained risk- and ambiguity-attitudes, we performed multiple regressions (using backward selection), with risk- and ambiguity-attitudes as dependent variables and the ARQ subscales as independent variables. To control for age (linear), this variable was always included in the model. We observed that ambiguity-attitude was best explained by the model with age and ARQ Reckless behavior (R^2 = .07, F(2,146) = 5.19, p = .007). As reported above, ambiguity-aversion increased linearly with age (b = .02, SE = .007, p = .002). Interestingly, reckless behavior was negatively related to ambiguity-attitude, with more reckless behavior related to less ambiguity-aversion (b = –.11, SE = .05, p = .041, see Figure 3C). No significant models were observed for risk-attitude.

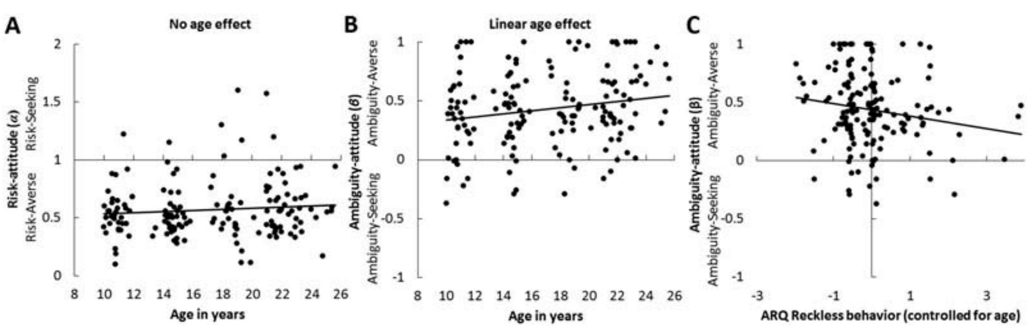

Figure 3. A. Risk-attitude (y-axis) across age (x-axis). α's smaller than 1 indicate risk-aversion, whereas α's larger than 1 indicate risk-seeking. Most subjects across all ages were risk-averse and this did not change with age. B. Ambiguity-attitude (y-axis) across age (x-axis). β's larger than 0 indicate ambiguity-aversion, whereas β's smaller than zero indicate ambiguity-seeking. Most subjects were ambiguity-averse, and this aversion increased linearly with age. C. Relation between the ARQ Reckless behavior scale (controlled for age) and ambiguity-attitude. More reckless behavior was related to less ambiguity-aversion.

Because some of the items of the Reckless behavior scale might not have been applicable to the youngest participants (e.g., "Having unprotected sex"), we inspected the relation between ambiguity-aversion and reckless behavior for participants of 14 years and older (leaving n = 110 participants), using a partial correlation (controlling for age). A similar effect was observed in which risk-taking behavior tended to be related to ambiguity-attitude (r –.18, p = .059), but not to risk-attitude (p = .87).

Second, for self-reported reward-sensitivity (BIS/BAS) we observed that BAS Drive increased linearly with age (b = .14, SE = .035, p < .001). BAS Reward responsiveness showed a quadratic pattern (b = .02, SE = .01, p = .035), which was best described as an emerging pattern of increased reward responsivity in young adulthood. However, the BIS/BAS subscales were not related to either risk- or ambiguity-attitude.

Risk- and ambiguity-attitudes in the social condition

We added a first step in the current study to test for context effects of risk- and ambiguity-attitudes. Particularly we aimed to test to what extent the social condition influenced risk- and ambiguity-attitudes. To this end we calculated risk- and ambiguity-attitudes in the social condition with the same model-based approach as in the solo condition (see Methods for model specification). One participant (a late adolescent) did not complete the social blocks of the task due to time constraints, leading to n = 156 in further analyses on the social condition.

To assess the influence of the social condition on participants' attitudes, we first ran a repeated measures ANOVA on risk-attitudes, with condition (solo, social) as a within factor, and the linear and quadratic effects of age as covariates. With respect to risk-attitude, we observed a significant main effect of condition ($F(1,153) = 5.37$, p = .022, η_p^2 = .034), with participants becoming more risk-seeking in the social condition (M = .59, SE = .02) compared to the solo condition (M = .56, SE = .02). In addition, we observed a significant age (linear)*condition interaction ($F(1,153) = 4.06$, p = .046, η_p^2 = .026), and an age (quadratic)*condition interaction at trend level ($F(1,153) = 3.56$, p = .061, η_p^2 = .023). We have visualized these age effects in Figure 4A, where we have plotted the difference score between risk-attitude in the social condition minus the solo condition. A similar analysis on ambiguity-attitude showed no significant effects of condition, or age (see Figure 4B). When gender was included, this factor did not interact with condition or condition*age effects in

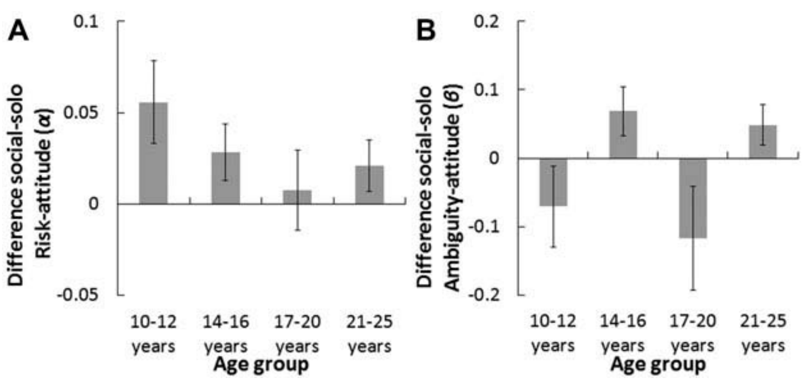

Figure 4. A. Visualization of the difference between the social minus the solo condition for risk-attitude, plotted per age group. Note that a positive score means individuals became more risk-seeking in the social condition compared to the solo condition. Particularly the youngest ages became more risk-seeking in the social compared to the solo condition. B. Visualization of the difference between the social minus the solo condition for ambiguity-attitude, plotted per age group. A positive score means individuals became more ambiguity-averse, wheras a negative score means individuals became more ambiguity-seeking in the social condition compared to the solo condition. There was no significant effect of the social condition. Error bars represent +1/–1 SE around the mean.

both the risk- and ambiguity-attitudes analyses. To control for the self-report rating of peer believability, we added this rating as a covariate in addition to the linear and quadratic effect of age on the ANOVA for risk-attitude. This analysis revealed no significant interaction between the believability rating and condition (p = .424), nor did it change the results, indicating that this rating did not influence the effect of condition that we observed.

Discussion

This study focused on distinguishing determinants of risky choice across adolescence by testing attitudes toward risk (contexts with explicit probabilities) and ambiguity (contexts with unknown probabilities) across adolescence (ages 10–25 years). We observed that ambiguity-attitude, but not risk-attitude, changed with age, with younger adolescents being more ambiguity-tolerant (i.e., less averse) than older adolescents and young adults. Moreover, ambiguity-attitude, but not risk-attitude, was related to self-reported real-life reckless behavior, with less ambiguity-averse attitudes related to more reckless behavior. Finally, we observed an effect with respect to the social condition: risk-, but not ambiguity-attitude, tended to change between the solo and social context, with participants becoming more risk-seeking in the social context. The discussion is organized alongside the line of these main findings.

Risk- and ambiguity-attitudes across adolescence

Age effects

First, we tested for age-related changes in individuals' risk and ambiguity-attitudes. Model fits showed that most participants were risk-averse and ambiguity-averse, as has been observed in adult studies (Ellsberg, 1961; Levy et al., 2010; Von Gaudecker et al., 2011), but note that considerable individual differences were present (see Figure 3A an 3B). Over the course of adolescence, ambiguity-aversion increased monotonically into early adulthood. In contrast, we observed no age-related differences in risk-aversion. These findings highlight a distinct developmental trajectory of risk- versus ambiguity-attitude, which concurs with findings that these attitudes separately drive risk-taking behavior (Tymula et al., 2012) and are uncorrelated (Levy et al., 2010), a pattern we also observe in this study.

The finding that ambiguity-aversion increases with age replicates prior research (Tymula et al., 2012) that showed that adolescents were more ambiguity-tolerant than adults. However, our results extend this finding by showing that ambiguity-tolerance was highest in the youngest ages (10–12 years) and decreases into young adulthood. Prior research found that children (8–9 years) did not yet show ambiguity-aversion (Li et al., 2014). That is, when children and adults were asked which gamble they preferred (a risky or an ambiguous gamble), children were equally likely to choose the ambiguous or the risky option, whereas adults chose the risky option more often. In addition, children were willing to pay as much for betting on an ambiguous gamble versus a risky gamble, whereas adults were willing to pay more for the risky gamble. Both findings highlight that children, in contrast to adults, did not yet distinguish between risk and ambiguity (Li et al., 2014). Possibly, early adolescence is the start of ambiguity aversion in decision making, a question that should be addressed in future research including even younger children.

In contrast, risk-attitudes did not change significantly across adolescence. Previous studies using paradigms with *known* probabilities have generally shown little age differences in overall risk-taking levels (Eshel, Nelson, Blair, Pine, & Ernst, 2007; van Leijenhorst et al., 2008; Wolf, Wright, Kilford, Dolan, & Blakemore, 2013). This absence of age differences has been explained by relatively mature cognitive abilities, and understanding of probabilities, in adolescence (van Duijvenvoorde, Jansen, Visser, & Huizenga, 2010; van Leijenhorst et al., 2008). On the other hand, heightened adolescent risk taking has been shown in explicit risky-choice paradigms when immediate rewards and losses are present, resulting in a "hot" decision context (Burnett et al., 2010; Figner, Mackinlay, Wilkening,

& Weber, 2009). Thus, under conditions of known probabilities, age differences may appear only under higher emotional load, although future research should formally address this hypothesis.

Age-related change may be more pronounced in ambiguous decision-tasks such as the Iowa Gambling Task (IGT; Bechara, Damasio, & Damasio, 2000), the Balloon Analogue Risk taking Task (BART; Lejuez et al., 2003) and the Stoplight task (Chein et al., 2011). A comparison of a non-informed ("ambiguous") and informed (risky) IGT, also observed that particularly in the ambiguous task, choice behavior became more advantageous across adolescence (van Duijvenvoorde et al., 2012). However, most of these ambiguous decision-tasks include immediate feedback, which may result in a heightened emotional load, but also inherently drive learning. Learning may explain some of these age-related changes in decision making (Eppinger, Hämmerer, & Li, 2011; van Duijvenvoorde et al., 2012; van Duijvenvoorde, Jansen, Griffioen, van der Molen, & Huizenga, 2013). The current study is, to our knowledge, one of the first to compare adolescents' risk taking under risky (known) and ambiguous (unknown) decision contexts in a task that does not require learning. Our finding that ambiguity-attitude was driven by age-related change and risk-attitude was not, suggests that ambiguity may differently influence risk taking across adolescence, and is perhaps a better reflection of real-life risk taking, in which age differences are prominent.

Individual differences

This relation between attitudes and real-life risk taking was further tested by relations with self-report risk-taking measures. We observed that with increasing age, reckless behavior (such as drinking and driving) increased. Interestingly, we observed that this scale was related to ambiguity-, but not risk-attitude. Specifically, more ambiguity-aversion was related to less real-life reckless behavior. This finding highlights that ambiguity-attitude may be a characteristic that is particularly driving individuals' real-life risk-taking tendencies, and is consistent with findings in a previous study relating ambiguity-attitudes and self-reported risk taking, particularly reckless behavior (Tymula et al., 2012). Given the relatively modest effect observed in the current study, this relation needs to be replicated in further studies, and extended to adolescent populations with a wider range of risk-taking behaviors (i.e., with less and more extreme risk-taking tendencies).

Prior research has defined reckless behavior as actions that carry strong connotations of serious negative consequences, such as injury and death (Arnett, 1992). Indeed, the ARQ reckless behavior subscale of Gullone et al. (2000) consists of items such as "Drinking and driving," "Speeding," "Having unprotected sex," and "Stealing cars and going for joy rides," all of which can have a strong negative long-term impact, and may be typically framed in the domain of health-safety decisions (Blais & Weber, 2006; Figner & Weber, 2011). Whether ambiguity-attitude specifically relates to behavior in the health-safety domain is an interesting question for further research (e.g., Van Duijvenvoorde, Blankenstein, Crone, & Figner, under review). Tentatively it may be suggested that explicit decision-making tasks reflect real-life risk taking to a lesser degree than ambiguous tasks, because risks in real-life rarely present known probabilities.

Although we did not observe a relation between real-life risk taking and risk-attitude, nor in reward-sensitivity and risk-attitude, there were considerable individual differences in aversion to risk. Whether individual differences in risk-attitudes reflect other aspects of real-life risk taking, or perhaps more cognitive aspects of risk taking (understanding of probability, intelligence, etc.) will need to be determined in future studies.

Social context

Finally, we explored whether risk- and ambiguity-attitude changed between a solo and a social context, in which choices from a high risk-taking peer were presented. The social context tended to only influence risk-attitude, with individuals becoming more risk-seeking in the social context. This shift in risk-attitudes significantly differed with age. When we plotted the difference between the social minus the solo condition, as a measure of the effect of the social condition, we observed the effect was strongest in the youngest age group (10–12 years). Thus these findings indicate an overall sensitivity to peers' choices, but strongest in this age range. Finally, this finding seems to indicate that people are somewhat more swayed by peer behavior in explicit risk compared to ambiguous conditions. This suggest that risk taking may vary under different conditions of social advice. Prior studies have demonstrated peer effects on adolescent risk taking in both ambiguous (Chein et al., 2011; Gardner & Steinberg, 2005) and more explicit risk taking tasks (Smith, Chein, & Steinberg, 2014) although few explicitly compared these risk-taking situations. Future studies will need to confirm whether peers have more, or similar, effects in risky and ambiguous contexts compared to the current study.

When presenting peer's choices it has been suggested that the combination of individuals' behavior and peer behavior may also play an important role in the level of peer influence. That is, a recent study showed that although peer behavior may influence individuals' risk taking, this influence was greater when peer choices were aligned with individual preferences (Chung et al., 2015). That is, for risk-averse individuals the influence of safe peer choices will be greater (i.e., a bias in conforming to safe options) than risky peer choices, and vice versa. Here, we only used risky peer choices (in a relative risk- and ambiguity-averse sample). An interesting next step may be to include both risk-averse and risk-seeking peers. In combination with a model-based approach (see Chung et al., 2015), such a design may disentangle individual differences in adolescents' conformity to peers across risky and ambiguous contexts.

Limitations and future directions

To our knowledge, the current study is the first to compare risk- and ambiguity-attitudes across a wide adolescent age-range, using a validated model-based approach. However, this study also suffered from some limitations that should be addressed in future research. First, we did not have estimates of IQ for the oldest age group. However, we believe it is unlikely IQ would have had an effect on task behavior for the oldest age group, because (1) all age groups showed similar sensitivity to gain-probability, ambiguity-level and gain-amounts and (2) IQ did not appear to influence task behavior in the three younger age groups. Nevertheless, future studies should include an IQ assessment for all participants from all ages.

Second, although a Chi-square test indicated that there were no significant gender differences across the different age groups, gender was not well matched across the two older age groups, with particularly more males than females in the 17–20-year-old group, and more females than males in the 21–25-year-old group. However, when including gender in our analyses, results of age-related changes in risk- and ambiguity-attitude, or the effect of social context, did not change. We observed that in general males were more risk-seeking, but not more ambiguity-seeking, than females. This finding is in line with previous studies showing that generally, males are more risk taking (Byrnes, Miller, & Schafer, 1999; van Leijenhorst et al., 2008). In future studies it is important to have an equal distribution of both genders in each age group to test the role of gender in more detail.

Third, in the current study the self-reported believability of the social manipulation ranged from very low to very high, but was relatively low overall. Including peer-believability as a covariate did not influence our results of the social condition, in which we particularly observed that people became more risk-seeking when presented with a risk-seeking peer. It may be the case that this explicit self-report is not a reliable measure, because it may have resulted in the participants actively questioning the peer, whereas they may not have done this throughout the experiment. Nonetheless, future studies should for instance increase the personal association felt with a social-influence group (e.g., Knoll, Magis-Weinberg, Speekenbrink, & Blakemore, 2015), or perform control experiments to compare social versus non-social influence (e.g., Klucharev, Hytönen, Rijpkema, Smidts, & Fernández, 2009).

Fourth, the current study focused particularly on the gain domain, which may have caused our participants to be particularly risk-averse. That is, individuals tend to be relatively risk-averse when gains are at stake, but risk-seeking when losses are at stake (Tversky & Kahneman, 1992). Future studies could benefit from also including a loss domain, which may provide better insight of risky choice across adolescence under conditions varying in uncertainty.

Finally, we investigated age as an important factor of interest, but we did not include puberty measurements. Puberty typically starts between ages 10–13 and influences structural and functional development of limbic and prefrontal systems (Peper & Dahl, 2013). Pubertal development appears to contribute to increased adolescent sensation-seeking (Forbes & Dahl, 2010) and reward-sensitivity, as shown by heightened neural activation in the nucleus accumbens (Braams et al., 2015). These findings suggest that pubertal development may relate to individual differences in risk- and ambiguity-attitude. Future research may further establish the relation between risk- and ambiguity-attitudes, puberty, and the associated neural development.

Conclusion

The current study highlights the potential of a model-based approach to decompose overt risk-taking levels into underlying determinants of adolescent risk taking: risk- and ambiguity-attitudes. These distinct influences on risk taking were found to have different developmental trajectories, and provide complementary insights into adolescent risky decision making. This study confirmed an emerging ambiguity-aversion across adolescent development, and its relation with risk taking in daily life, and provides suggestions for including a social context in future adolescent risk-taking research. Future studies using neuroimaging methods may allow us to further understand the underlying mechanisms of these separate aspects of risk taking, which may impact adolescent risky decision making in different ways.

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