

Distinct Age-Related Differences in Temporal Discounting and Risk Taking in Adolescents and Young Adults

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Age-related differences in temporal discounting (TD) and risk taking, and their association, were examined in adolescents and young adults ($n = 337$) aged 12–27 years. Since monetary rewards are typically used in TD and risk-taking tasks, the association between monetary reward valuation and age and decision making in these tasks was explored as well. TD declined linearly with age, with a particularly sharp decline from 15 to 16 years. In contrast, risk taking was not correlated with age and TD. Reward valuation was not associated with TD and risk taking, and age-related differences in TD remained significant after controlling for reward valuation. Together, these findings suggest that risk taking and TD are two separate constructs with distinct age-related differences in adolescence and young adulthood.

Adolescents frequently engage in impulsive and risky behaviors, such as substance use, unprotected sex, and reckless driving (Hibell et al., 2012). Impulsivity is a multifaceted construct, and has been defined as including both a preference for smaller, immediate rewards over larger, delayed rewards, as well as engaging in risky behaviors (Dalley, Everitt, & Robbins, 2011). Given this definition of impulsivity and the fact that many risky behaviors could also be characterized as impulsive, one might assume that impulsivity and risk taking are positively related constructs in adolescence and young adulthood. However, several studies have suggested otherwise, by showing that impulsive and risky decision making are not correlated in children, adolescents, and young adults (Olson, Hooper, Collins, & Luciana, 2007; Prencipe et al., 2011; Scheres et al., 2006).

At present, little is known about whether age-related differences in both constructs are similar or distinct in adolescence and young adulthood.

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Age-related differences in impulsive and risky decision making are often assessed with tasks in which the delay to a monetary reward or the probability of receiving that reward is systematically varied, respectively. Temporal discounting (TD) tasks, which measure one aspect of impulsivity (i.e., preference for immediate rewards), involve choices between smaller, immediate rewards (e.g., €5 today) and larger rewards that are delivered after a delay (e.g., €10 in 2 weeks). Risk taking, on the other hand, is frequently measured by gambling tasks, in which participants must choose between receiving a small reward with a high probability, or a larger reward with a low probability.

Age-Related Differences in TD

TD refers to the decrease in subjective value (SV) of a reward when the delay to that reward increases. TD tasks measure the preference for immediate rewards (Green & Myerson, 2004), which is a component of impulsivity that is distinct from the failure to inhibit inappropriate behaviors (Solanto et al., 2001). Impulsive individuals typically display an increased preference for smaller, immediate rewards (i.e., increased discounting). Indeed, it has been found that adolescents with attention deficit hyperactivity disorder (ADHD), and adolescent smokers, show relatively steep discounting of delayed rewards (i.e., strong preference

for immediate rewards) in TD tasks (Audrain-McGovern et al., 2009; Demurie, Roeyers, Baeyens, & Sonuga-Barke, 2012a; Reynolds & Fields, 2012; Scheres, Tontsch, Thoeny, & Kaczurkin, 2010).

Although discounting of delayed rewards decreases across the life span (Green, Fry, & Myerson, 1994), findings on age-related differences in TD during childhood, adolescence, and adulthood are limited to a small number of studies, and are inconsistent. Some studies have shown a linear decrease in TD from childhood (6–11 years) to adolescence (12–17 years; Demurie, Roeyers, Baeyens, & Sonuga-Barke, 2012b; Prencipe et al., 2011; Scheres et al., 2006), and from adolescence to young adulthood (18–30 years; Olson et al., 2007; Steinberg et al., 2009). In contrast, others have reported nonlinear age-related differences in TD, with *decreased* discounting in adolescents compared to children and young adults (Scheres, Tontsch, Thoeny, & Sumiya, 2013). Finally, in a longitudinal study, Audrain-McGovern et al. (2009) showed that discounting was stable between the ages of 15 and 20 years.

One explanation for the inconsistent findings on age-related differences in TD might be the use of different TD tasks. Linear decreases in TD with age have mostly been reported by researchers using TD tasks with relatively large monetary rewards (e.g., \$10–100) and long delays (e.g., up to 1 year; Olson et al., 2007; Steinberg et al., 2009; but see Scheres et al., 2006, for an exception). The increased preference for delayed rewards with increasing age observed in these studies could be due to improvements in cognitive control functions during adolescence, such as working memory and response inhibition (Huizinga, Dolan, & van der Molen, 2006; Luciana, Conklin, Hooper, & Yarger, 2005).

Nonlinear age-related differences were reported when all rewards and delays were actually experienced (Scheres, Tontsch, et al., 2013). It may be hypothesized that in TD tasks with real rewards, affective processes, such as reward sensitivity, influence one's preferences more strongly than cognitive processes. As such, differential discounting behavior on real TD tasks by adolescents relative to adults or children could reflect adolescents' heightened reward sensitivity (Casey, Getz, & Galvan, 2008; Crone & Dahl, 2012).

In sum, studies on age-related differences in TD have produced mixed results, and further research is clearly warranted. There is a particular need for studies testing both linear and nonlinear age-related differences in TD. The majority of previous studies were not able to directly compare linear and non-

linear changes, due to including participants from a relatively narrow age range, such as only children and adolescents, or only adolescents (Demurie et al., 2012b; Prencipe et al., 2011; Scheres et al., 2006). Other studies did include individuals with a wide age range, but they did not test or report nonlinear age-related differences (Olson et al., 2007). In this study, we therefore included a large sample from a broad age range (12–27 years) to test both linear and nonlinear age-related differences in TD during adolescence and young adulthood.

Age-Related Differences in Risky Decision Making

Similar to the aforementioned TD studies, findings regarding age-related differences in risky decision making have been mixed. Several studies have reported a linear decrease in risky decisions from childhood to adolescence (Crone & van der Molen, 2007; Hooper, Luciana, Conklin, & Yarger, 2004), and from adolescence to adulthood (Crone & van der Molen, 2004; Mitchell, Schoel, & Stevens, 2008; Steinberg et al., 2008; van Duijvenvoorde, Jansen, Bredman, & Huizinga, 2012). Furthermore, with increasing age, adolescents and young adults are able to use more sophisticated decision rules in risk-taking tasks (Huizinga, Crone, & Jansen, 2007; Jansen, van Duijvenvoorde, & Huizinga, 2012). However, in other studies, no differences in risky decisions were found between adolescents (from age 14 onward) and young adults (Cauffman et al., 2010; Overman et al., 2004). In addition, nonlinear age-related differences in risky decision making have been reported as well, with a peak in risky decisions in (mid) adolescence relative to childhood and adulthood (Burnett, Bault, Coricelli, & Blake-more, 2010; Smith, Xiao, & Bechara, 2012).

Differences in task characteristics might contribute to these inconsistent findings, since it has been found that adolescents made riskier choices than adults in an emotionally arousing version of a risk-taking task, but no age differences were found in a more deliberative version of the same task (Figner, Mackinlay, Wilkening, & Weber, 2009; see also van Duijvenvoorde, Jansen, Visser, & Huizinga, 2010). In addition, many previous studies used (modified versions of) the Iowa Gambling Task (IGT), in which participants must learn to make more advantageous decisions based on feedback during the experiment. While the IGT closely resembles real-life decision making, it also draws heavily upon working memory (van Duijvenvoorde et al., 2012) and other complex executive functions that are still developing during adolescence.

To address this issue, recent studies have employed gambling tasks in which all the information that is required to make a decision is presented visually during each trial. For instance, in the Cake Gambling (CG) task (van Leijenhorst, Westenberg, & Crone, 2008; van Leijenhorst et al., 2010), a cake is used to visually display the probability of obtaining a monetary reward associated with two choice options. The cake consists of six wedges that are either brown or pink, with a 4:2 ratio. Selection of the color that is most prevalent in the cake results in a high probability of obtaining a small monetary reward. Thus, the more prevalent colored wedge is considered to be the low-risk option. Choosing the least prevalent color is associated with a low probability of obtaining a larger reward, and is considered the high-risk option. In the CG task, the reward magnitudes associated with each option are depicted as a stack of coins. Using this task, van Leijenhorst et al. (2008) originally did not find a difference in the percentage of high-risk decisions between adolescents and adults. However, the expected value (EV; Probability \times Reward Magnitude) of the high-risk option was always higher than the EV of the low-risk option in this study.

In a later study, van Leijenhorst et al. (2010) did find that adolescents (12–14 years) made more high-risk decisions than young adults, but only in trials in which the EVs of the high-risk and low-risk options were equal. They interpreted this result as indicating that adolescents take more risks than adults when choices are relatively ambiguous. Thus, these findings point to the importance of matching the EV of the high-risk and low-risk options. In the van Leijenhorst et al. (2010) study, both the probabilities associated with each option and the magnitude of the low-risk reward (€1) were held constant, while the high-risk reward (€2–8) was varied in magnitude, such that only the lowest high-risk reward (€2) was matched on EV with the low-risk reward. To control for the potentially confounding effects of EV differences between options, all high- and low-risk options were matched on EV in this study by systematically varying the reward magnitudes associated with both options.

Relation Between TD and Risky Decision Making

In prior research, age-related differences in TD and risky decision making were mostly studied in isolation. Therefore, little is known about their relation across ages. One might assume that TD and risk taking are positively related, since impulsive actions (e.g., smoking) can frequently be

characterized as risky and vice versa. A negative correlation between TD and risk taking might also be expected, since choosing for a delayed reward entails the risk of not receiving that reward as something might prevent its reward delivery (Green & Myerson, 2004). Recent findings suggest that this is not necessarily the case, though. During childhood and adolescence, TD is not correlated with probability discounting (a measure of risky decision making; Scheres et al., 2006) and IGT performance (Prencipe et al., 2011). To our knowledge, only one study examined the relation between TD and risky decision making during adolescence and adulthood (Olson et al., 2007). In this study, TD was not correlated with probability discounting, but more delayed reward choices were associated with less risky decisions in the IGT. Whether TD is related to risky decisions in a gambling task in which reward magnitudes are systematically varied, and whether this relation differs as a function of the reward magnitude of the risky options, remains an open question.

Reward Valuation

In studies on age-related differences in TD and risky decision making, it is of crucial importance to take age differences in (monetary) reward valuation into account (e.g., Demurie et al., 2012b), since participants of all ages make decisions involving the same monetary rewards. However, a 12-year-old might value a reward of €5 more than a 25-year-old would. Both the delayed reward in TD tasks and the risky option in gambling tasks are usually larger than the immediate reward and less risky option, respectively. Therefore, age differences in decision making might actually reflect differences in reward valuation. To the best of our knowledge, no study to date has systematically evaluated whether reward valuation is associated with age and decision making in TD tasks and gambling tasks, and whether age differences in these tasks remain after controlling for differences in reward valuation.

Pubertal Development

In addition to age-related differences in TD and risk taking, other interindividual differences are important to consider as well. Individual differences in adolescents might be related to their degree of pubertal development. Puberty, and particularly the associated surge of pubertal hormones, is proposed to be associated with enhanced

activation in brain regions involved in reward processing (Op de Macks et al., 2011), thereby promoting impulsive and sensation-seeking behaviors (Crone & Dahl, 2012; Peper & Dahl, 2013). Indeed, adolescents who report more advanced pubertal maturation relative to their peers also report higher levels of daily-life impulsive behaviors, such as alcohol use (de Water, Braams, Crone, & Peper, 2013). A couple of studies have suggested that pubertal development also contributes to decision making in experimental tasks. Steinberg et al. (2008) found that adolescents who reported more advanced pubertal development showed more sensation-seeking behavior in a computerized driving task. Similarly, Peper, Koolschijn, and Crone (2013) demonstrated that adolescents who reported greater pubertal maturation, particularly girls, engaged in higher levels of sensation-seeking behavior in the Balloon Analogue Risk Task (BART). Whether pubertal development is also associated with TD remains unclear, since this has not yet been explored.

The Present Study

To summarize, the aims of this study were: (a) to examine age-related differences in (i) TD and (ii) risky decision making during adolescence and young adulthood, (b) to investigate whether TD and risky decision making are correlated across ages, (c) to study whether age differences in TD and risky decision making remain after controlling for individual differences in reward valuation, and (d) to test whether pubertal development is associated with TD and risky decision making. To this end, a TD task and the CG task were administered to 337 participants aged 12–27 years. In addition, all participants were asked to rate four monetary rewards that were used in these tasks, and adolescent participants completed a pubertal development scale.

In relation to the four aims of this study, the following hypotheses were specified:

Hypothesis 1a: Regarding age-related differences in TD, several opposing hypotheses could be proposed due to inconsistent findings of prior research. Discounting might be hypothesized to decrease linearly with age during adolescence and young adulthood (Olson et al., 2007; Scheres et al., 2006; Steinberg et al., 2009). In contrast, nonlinear age-related differences in TD, with *decreased* discounting (Scheres, Tontsch, et al., 2013) in mid adolescence could also be predicted. Alternatively, discounting could be expected to remain stable during late adolescence and young

adulthood (Audrain-McGovern et al., 2009). To address these competing hypotheses, we tested both linear and nonlinear (i.e., quadratic and cubic) age effects in this study.

Hypothesis 1b: On the basis of previous research (van Leijenhorst et al., 2010), we anticipated that adolescents would make more high-risk decisions than would young adults in our version of the CG task in which the EV of the high- and low-risk options was matched.

Hypothesis 2 Due to conflicting findings of prior studies, two competing hypotheses could be formulated regarding the correlation between TD and risky decision making. It might be predicted that TD and risky decision making are uncorrelated (Prencipe et al., 2011; Scheres et al., 2006), but a positive correlation (Olson et al., 2007) or a negative correlation (Green & Myerson, 2004) between discounting behavior and high-risk decisions in the CG task could also be expected.

Hypothesis 3: Given the lack of prior research on the influence of reward valuation on age-related differences in TD and risky decision making, we explored whether age differences in TD and risky decision making remained after controlling for reward valuation without specifying an a priori hypothesis.

Hypothesis 4: We hypothesized that advanced degree of pubertal development would be related to increased discounting and greater high-risk decisions in the CG task (de Water et al., 2013; Peper, Koolschijn, et al., 2013).

Method

Participants

A total of 337 individuals participated in this study (see Table 1 for descriptive statistics). The sample consisted of 195 adolescents (96 girls) aged 12–17 years ($M = 15.15$ years, $SD = 1.37$ years) and 142 young adults (107 women) aged 18–27 years ($M = 20.71$ years, $SD = 1.94$). Adolescent participants were recruited by contacting local high schools, while adult participants were recruited from the Radboud University population using flyers and an online participant database (Sona Systems, Tallinn, Estonia). The gender distribution differed significantly between the adolescent and adult groups, $\chi^2(2) = 30.65$, $p < .001$. Specifically, females were overrepresented in the adult group, reflecting the uneven gender distribution of the student body of the Faculty of Social and Behavioral Sciences from which the adult group was mainly

Table 1
Descriptive Statistics of the Sample

	Adolescents (<i>n</i> = 195)		Adults (<i>n</i> = 142)	
	<i>M</i> (<i>SD</i>)	Range	<i>M</i> (<i>SD</i>)	Range
Age in years	15.15 (1.37)	12.49–17.97	20.71 (1.94)	18.02–27.50
Raven score ^a	33.06 (5.36)	10–46	36.60 (4.86)	8–47
Reward valuation slope ^b	0.25 (0.20)	–0.48 to 0.80	0.31 (0.21)	–0.20 to 0.80
% High-risk decisions in €2 trials of CG task	42.63 (24.33)	0–100	35.80 (27.35)	0–100
% High-risk decisions in €4 trials of CG task	42.55 (25.52)	0–100	35.90 (24.52)	0–100
% High-risk decisions in €6 trials of CG task	43.95 (26.57)	0–100	37.25 (25.76)	0–100
% High-risk decisions in €8 trials of CG task	49.64 (27.54)	0–100	42.03 (27.94)	0–100
Area under the curve in TD task	0.34 (0.28)	0.01–0.99	0.49 (0.29)	0.01–0.99

Note. CG = Cake Gambling; TD = temporal discounting.

^aThe number of correct answers on Sets B–E (48 items) of Raven's Standard Progressive Matrices. ^bThe unstandardized coefficient of the regression analysis with reward magnitude (€2.50, €5, €7.50, €10) as predictor and reward rating (7-point scale) as dependent variable.

recruited. To address this potential issue, two sets of results are reported. First, we report findings based on the total sample of 337 participants, including all 142 adults. In addition, we repeated our analyses with the full sample of adolescents, and a subsample of 70 adults. The adult subsample consisted of all 35 male participants, and a random sample of 35 female adult participants (drawn from the total sample of female adults to match the even gender distribution of the adolescent group).

Informed consent was obtained from all adult participants, and adolescent participants gave informed assent. Parents of the adolescents gave passive consent. All procedures were approved by the Institutional Review Board at the Faculty of Social Sciences, Radboud University Nijmegen, the Netherlands.

Measures

TD Task

To assess preferences for immediate rewards, a TD task was administered. In each trial of this task (see Figure 1A), participants chose between a relatively small immediate monetary reward (IR) they could receive today, or a reward of €10 they would receive after a delay (DR). By varying the amount of the IR and the delay preceding the larger reward (€10), participants' SV of €10 could be estimated for each delay. Five delays were used: 2, 14, 30, 180, and 365 days. For each delay, participants were presented with a series of six choices. If they completed these choices, they began a new series of six choices at the next delay. The delays were pre-

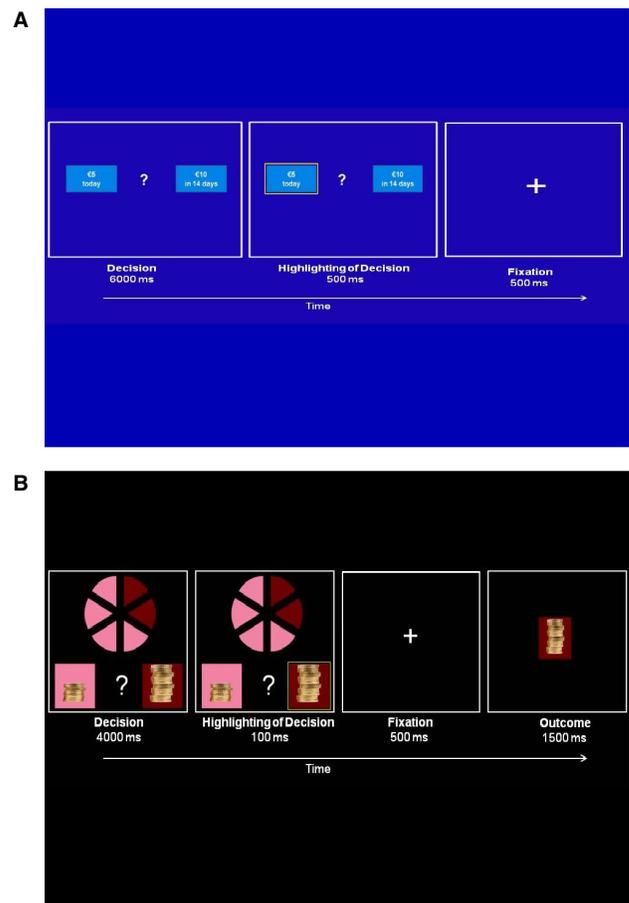


Figure 1. (A) Trial procedure of the temporal discounting task. (B) Trial procedure of the Cake Gambling task. The time indicated underneath the decision phase of both tasks is the maximum amount of time allowed to make a decision. When participants indicated their preference within this time period, the trial continued immediately after they pressed the button corresponding to their preference.

sented in a random order for each participant. The IR was always €5 on the first choice at each delay. The amount of the IR on later choices was adjusted based on participants' preferences (Du, Green, & Myerson, 2002). If participants chose the IR, the amount of the IR was *decreased* by half on the next choice, whereas this amount was *increased* by half if they chose the DR. For example, a first choice would be between €5 today or €10 in 2 days. If a participant preferred the €5 today, the next choice would be between €2.50 today or €10 in 2 days.

The amount of the IR that would have been presented on the seventh trial of the series at each delay was used as the estimate of the participants' SV of the DR. These SVs were used to calculate the dependent variable: area under the curve (AUC). AUC was calculated using the procedure described by Myerson, Green, and Warusawitharana (2001). AUC ranges between 0 and 1, where smaller values indicate an increased preference for immediate rewards.

One of the rewards was presented on the right side of the screen and the other reward was presented on the left side of the screen. The position of the rewards was counterbalanced across trials. Participants had to indicate their preference by pressing the corresponding computer key. The preference of the participant was highlighted by a yellow line surrounding the option, followed by the presentation of a fixation cross. The TD task consisted of six practice choices at a delay that was not used in the actual task (1 day), and 30 experimental trials, with a duration of 5 min.

TD tasks demonstrate high validity, in that individuals with psychiatric disorders characterized by impaired impulse control (e.g., ADHD, substance abuse) show a strong preference for immediate rewards in these tasks (Demurie et al., 2012a; Scheres, Tontsch, et al., 2010). In addition, TD has been reported to show trait-like stability in young adults, with a test-retest reliability of up to .91 (Odum, 2011).

CG Task

Risk-taking behavior was assessed using a modified version of the CG task (van Leijenhorst et al., 2008; van Leijenhorst et al., 2010). In this task, participants made repeated choices between a high-risk option with a 33.3% probability of obtaining a large monetary reward, and a low-risk option with a 66.7% probability of obtaining a smaller monetary reward. The probabilities associated with the two options were kept constant but the reward associated with both options was varied. The reward associated

with the high-risk option (four magnitudes: €2, €4, €6, or €8) was always twice as large as the low-risk reward, such that the EV (Probability \times Reward Magnitude) of both options was always equal. The high-risk option is considered more risky because the probability of obtaining a reward is smaller, while the variance in potential outcomes is larger.

The trial procedure of the CG task is illustrated in Figure 1B. First, participants viewed a cake composed of six wedges. These wedges were either pink ("strawberry flavored") or brown ("chocolate flavored") in a 4:2 ratio (the majority color was counterbalanced across trials). Underneath the cake, a pink square and a brown square were presented on the left and right sides of the screen (counterbalanced across trials), each containing a stack of 50 cent coins to indicate the reward associated with each flavor. During the time period in which the cake was presented on the screen, participants had to choose which of the two flavors they wanted to gamble with, by pressing the corresponding computer key. After participants indicated their choice, it was highlighted by a yellow line surrounding the square. Participants subsequently viewed a fixation cross, during which the computer randomly selected one of the six wedges of the cake. If the flavor of the selected wedge matched the flavor chosen by participants, they gained the amount of coins associated with that flavor. If not, they did not gain any coins. Gain feedback was presented by showing the stack of coins participants had gambled with, while no-gain feedback was depicted by this stack of coins with a cross through them. The CG task consisted of 8 practice trials and 72 experimental trials (18 repetitions of each of the four reward magnitudes), with a duration of approximately 8 min.

High-risk decisions on the CG task have been shown to be positively associated with self-reported sensation-seeking behavior in daily life (van Leijenhorst et al., 2008).

Reward Valuation

All participants were asked to rate on a 7-point scale how much they enjoyed receiving each of four rewards that were within the range of rewards used in the CG and TD tasks (€2.50, €5, €7.50, €10). A regression analysis with reward magnitude (€2.50, €5, €7.50, €10) as predictor and reward rating (the 7-point scale rating of each reward) as dependent variable was performed for each participant separately. The slope (unstandardized regression coefficient) of this regression analysis was used as a measure of reward valuation in

subsequent analyses. A positive and larger slope indicates that larger rewards are rated more positively than lower rewards. The mean of the four different reward ratings ($\alpha = .83$ for the total sample) was highly correlated with the reward valuation slope ($\rho = -.70, p < .001$), and findings were similar when analyses were conducted with this measure of reward valuation. Therefore, only the results in which the reward valuation slope was included as measure of reward valuation are reported.

Raven's Standard Progressive Matrices

Sets B–E (48 items) of Raven's Standard Progressive Matrices (SPM; Raven, Raven, & Court, 1998) were administered, with a 10-min time limit, to screen for general intelligence. Set A was not administered, since prior research has shown that contrary to the items in Sets B–E, the items in Set A primarily measure visuospatial abilities instead of analogical reasoning abilities (van der Ven & Ellis, 2000). Performance on a speeded (e.g., including a time limit) Raven is highly correlated with performance on the same test when no time limit is imposed (Hamel & Schmittmann, 2006). The total number of correct responses on Raven's SPM was used in the analyses, and will be referred to as Raven score from now on.

Pubertal Development

The Pubertal Development Scale (PDS) was administered to the adolescents to quantify pubertal development (Petersen, Crockett, Richards, & Boxer, 1988). Adolescents indicated their physical development on a 4-point scale (ranging from 1 = *no development or change* to 4 = *complete development*). Boys were asked to indicate their body growth, body hair (pubic and axillary hair), facial hair, skin changes, and voice changes, whereas girls indicated their body growth, body hair, breast development, skin changes, and whether they had reached menarche. The mean PDS score (mean of all items) was used in subsequent analyses. Consistent with a recent study on pubertal development and sensation seeking in an experimental task (Peper, Koolschijn, et al., 2013), we also computed Puberty Category Scores (Crockett, 1988; see <http://www.sleepforscience.org/contentmgr/showdetails.php/id/91>). Mean PDS scores were highly correlated with Puberty Category Scores ($\rho = .66$ for girls; $\rho = .87$ for boys) and the findings were similar with either measure of pubertal development. Thus,

only the findings with mean PDS score as measure of pubertal development are reported.

Procedure

Adolescents were tested in their school classroom, with a teacher present. One class (18–29 students) was tested at a time, using notebooks. Partitions were placed on both sides of each notebook to ensure adolescents' privacy. Furthermore, a team of research assistants was present during testing to explain the tasks and to answer participants' questions. To mimic the test setting of the adolescents as closely as possible, adults were tested in groups (8–16 participants) in a room at their university, using the same type of notebooks and partitions that were used to administer the tasks to the adolescents.

The computer tasks and questionnaires were administered in a fixed order across all participants. First, Sets B–E of Raven's SPM were administered with a 10-min time limit. Subsequently, adolescent participants completed a demographic questionnaire and the PDS on their notebooks, while adults filled out paper-and-pencil versions of a demographic questionnaire. Finally, participants performed the CG task on their notebook, followed by the TD task and the reward valuation questions. To increase participant motivation and ecological validity, participants were told that at the end of the experimental session, one of their outcomes of the CG task and one choice of the TD task would be randomly selected by the computer, and that they would receive both outcomes. However, to keep differences between participants small and our expenses manageable, payment was actually determined at random from a narrow range of values (€6–€9).

Statistical Analyses

Data were analyzed using SPSS Version 19 (Armonk, NY). Extreme outliers ($> 3 SD \pm$ the mean of one's age group on at least one of the dependent variables) were excluded from analyses (3 adolescents and 2 adults). Analyses were first performed across all participants. Since the gender distribution was strongly skewed in the adult group, we subsequently repeated the analyses with all adolescent participants and a subsample of 70 adult participants (all 35 males, and a random sample of 35 females).

Checks of Experimental Tasks

To investigate whether the SV of the delayed reward decreased with increasing delay in the TD

task, a repeated measures (RM) analysis of variance (ANOVA) was conducted, with delay as a within-subject variable, and SV of the delayed reward as dependent variable. An RM ANOVA with high-risk reward magnitude as within-subject variable and percent high-risk decisions in the CG task as dependent variable was performed, to test whether risk taking increased with increasing magnitude of the high-risk reward. Similarly, we tested whether reward valuation increased with increasing reward magnitude by performing an RM ANOVA with reward magnitude as within-subject variable, and reward valuation as dependent variable. In case of a significant multivariate test of these RM ANOVAs, follow-up pairwise comparisons were conducted, with a Bonferroni correction to adjust for multiple comparisons. The checks of the experimental tasks were performed for adolescent and adult participants separately.

Age-Related Analyses

To examine age-related differences in risk taking and TD during adolescence and adulthood, a series of hierarchical multiple regression analyses were conducted across all participants with the percentage of high-risk decisions in the CG task and AUC on the TD task as dependent variables. To control for potential confounders, Raven score (which was positively related to age; $\rho = .38$, $p < .001$) and reward valuation were first entered as predictors, and age was added to the model in the second step of the analysis. Both linear and nonlinear (i.e., quadratic and cubic) age trends were tested. In case of a significant age effect, follow-up analyses were conducted to determine which specific ages differed from each other. Specifically, to test whether successive ages differed from each other (e.g., 12-year-olds from 13-year-olds, 13-year-olds from 14-year-olds, etc.), an analysis of covariance (ANCOVA) was performed with age as independent variable and age as contrast factor (contrast type = repeated), Raven score and reward valuation as covariates, and AUC on the TD task or the percentage of high-risk decisions in the CG task as dependent variables.

To test whether risk taking and TD are related across ages, multiple linear regression analyses were performed. The dependent variable in these analyses was AUC, with the percentage of high-risk decisions in the CG task as main predictor. Age, Raven score, and reward valuation were added as additional predictors to control for the potentially confounding effects of these variables. Furthermore,

to test whether the association between AUC and risk taking was different for participants of different ages, the High Risk Decisions \times Age interaction was added to these multiple regression analyses as predictor. The correlation between age and reward valuation slope was computed using Spearman's rho.

To explore whether pubertal development was associated with risk taking and TD in the group of adolescents, the mean PDS score was entered as a predictor in multiple regression analyses with the percentage of high-risk decision and AUC as dependent variables. To control for confounding effects of age in these analyses, age was entered as a predictor as well. These analyses were conducted separately for boys and girls.

Reward Valuation and Decision Making

The correlation between reward valuation and risk taking and TD was examined by performing a multiple regression analysis with reward valuation as dependent variable, and AUC and the percentage of high-risk decisions as predictors. Age and Raven score were entered as additional predictors to this regression to control for their potentially confounding effects.

Gender Differences

Gender differences in the percentage of high-risk decisions and AUC were explored using independent samples *t* tests, for adolescents and adults separately.

Correction for Multiple Testing

Given the large number of statistical tests that were performed, a false discovery rate (FDR) correction was applied to control for multiple testing. An FDR correction is a Bonferroni-type correction, which has greater power to detect an effect than the traditional Bonferroni correction (Benjamini & Hochberg, 1995). Based on an uncorrected *p* value of .05 and the number of statistical tests performed in this study, all $ps \leq .013$ were considered significant after FDR correction for multiple testing (see Benjamini & Hochberg, 1995, for the procedure of determining the FDR-corrected *p* value). Therefore, only $ps \leq .013$ are reported as significant. Note, however, that this only applies to the regression analyses. The checks of the experimental tasks were done by performing RM ANOVAs, which included Bonferroni-corrected pairwise comparisons. For these analyses, $ps < .05$ are reported as significant.

Results

Age-Related Differences in TD

The SV of the delayed reward differed significantly as a function of delay duration in adolescents, $F(4, 191) = 91.40$, $p < .001$, $\eta_p^2 = .66$, and adults, $F(4, 137) = 87.81$, $p < .001$, $\eta_p^2 = .72$. Specifically, the SV of the delayed reward decreased significantly with each successive delay (i.e., 2, 14, 30, 180, and 365 days) in adolescents (all $ps \leq .026$) and adults (all $ps \leq .013$). In other words, both adolescents and adults showed TD (see Figure 2).

In line with our hypotheses, age was positively related to AUC after controlling for reward valuation and Raven score ($\beta = 0.36$, $t = 3.49$, $p = .001$). This indicates that the ability to wait for a delayed reward increases with age. Only the linear age trend was significant, and not the quadratic ($p = .52$) or cubic age trends ($p = .78$). Figure 3A illustrates this positive linear relation between age and AUC, and further shows that there seem to be increases in AUC at specific ages: from 12 to 13 years, from 15 to 16 years, and from 20 to 22 years. A follow-up ANCOVA (controlling for Raven score and reward valuation) in which all successive ages were tested against each other indicated that only the 16-year-olds indeed have a significantly larger AUC than 15-year-olds ($p = .009$).

Adolescent boys and girls did not differ in AUC ($p = .32$). In contrast, male adult participants showed a significantly larger AUC than female adult participants, $t(139) = 2.64$, $p = .009$.

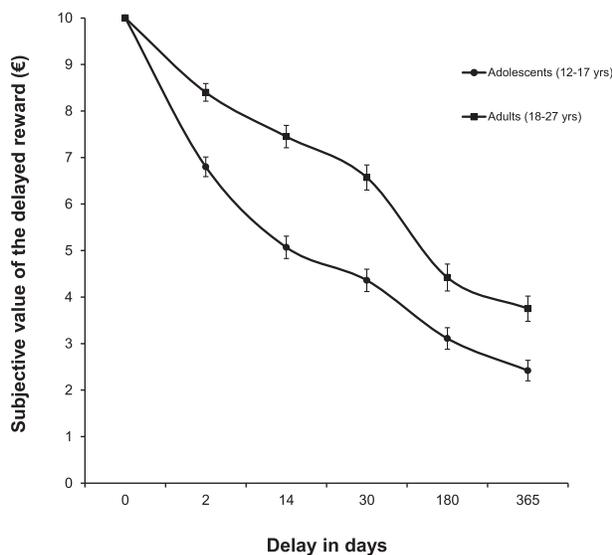


Figure 2. Temporal discounting curves of adolescents and young adults.

Age-Related Differences in Risk-Taking Behavior

High-risk decisions increased as a function of reward magnitude in adolescents, $F(3, 192) = 13.78$, $p < .001$, $\eta_p^2 = .18$, and adults, $F(3, 139) = 5.21$, $p = .002$, $\eta_p^2 = .10$. Specifically, the percentage of high-risk decisions was greater when the reward associated with the high-risk option was €8 compared to when this reward was €2, €4, or €6 (all $ps < .05$ in adults; all $ps < .001$ in adolescents). Risk taking in the three lowest reward conditions (high-risk rewards of €2, €4, and €6) did not differ significantly in adolescents and adults (all $ps = 1$; see Figure 4). Therefore, we used two measures of risk taking in subsequent analyses: the mean percentage of high-risk decisions in the three lowest reward conditions combined (Cronbach's $\alpha = .90$ for the total sample), and the percentage of high-risk decisions in the €8 condition.

Inconsistent with our predictions, age was not significantly correlated with high-risk decisions in the lower reward (€2–€6) condition and the €8 condition ($ps > .013$; see Figure 3B). There were no significant gender differences in risk taking in the group of adolescents (all $ps > .07$) and adults (all $ps > .12$).

Relation Between TD and Risk-Taking Behavior

Risky decisions in the three lowest reward conditions and in the €8 condition were not significantly associated with AUC when controlling for Raven score, reward valuation, age, and risky decisions in the other reward condition (which were controlled for to be able to examine the unique relation between TD and risk taking when potential rewards are low vs. high; all $ps > .013$). The Age \times High-Risk Decisions interactions did not significantly predict AUC (all $ps > .33$), indicating that risk taking and TD were not correlated across ages.

Reward Valuation

Ratings of the rewards significantly differed as a function of reward magnitude in adolescents, $F(3, 191) = 100.45$, $p < .001$, $\eta_p^2 = .61$, and adults, $F(3, 136) = 97.01$, $p < .001$, $\eta_p^2 = .68$. Reward ratings increased significantly (all $ps < .001$ in adolescents and adults) with each successive reward magnitude (€2.50, €5, €7.50, €10).

The enhanced reward valuation with increasing reward magnitude interacted with age (see Figure 5), as indicated by a significant positive correlation between reward valuation slope and age ($\rho = .15$, $p = .007$). This finding indicates that

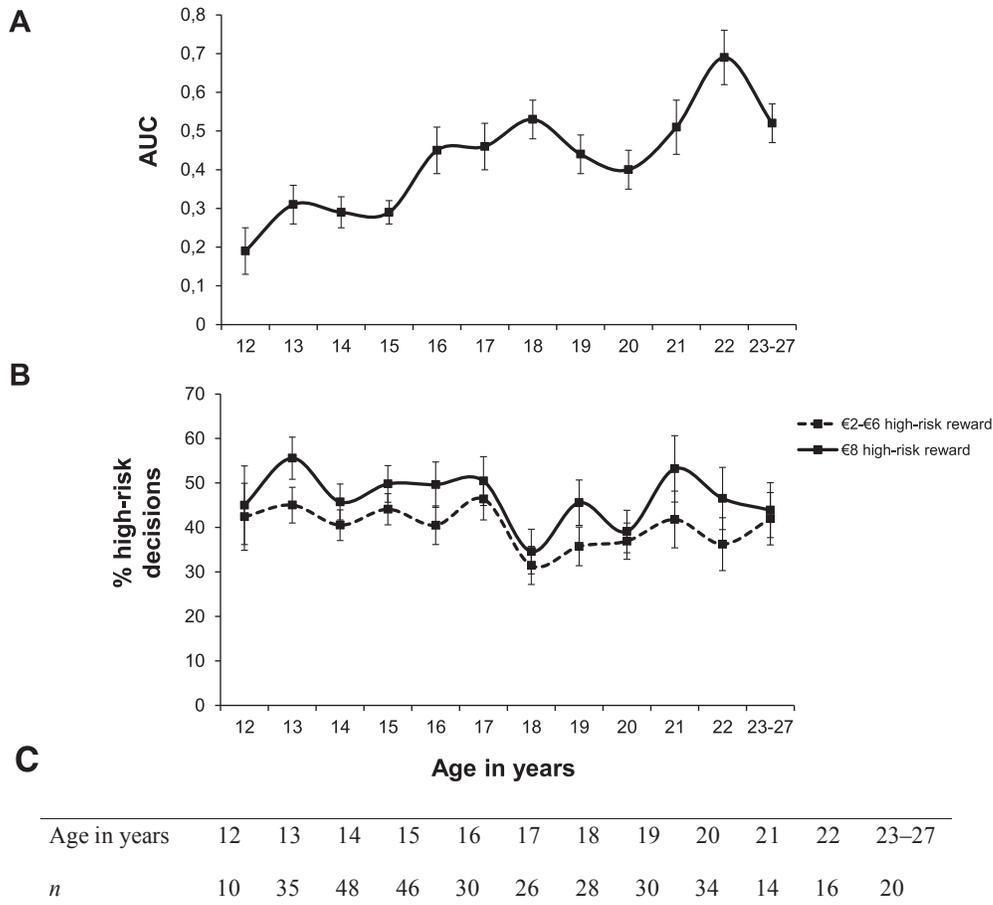


Figure 3. (A) Development of delayed reward preferences in the temporal discounting task. (B) Percentage of high-risk decisions in the Cake Gambling task as a function of age. (C) Number of participants per age group. AUC = area under the curve. Larger AUC values indicate a stronger preference for delayed rewards; 23–27-year-olds are shown as one age group due to the relatively small number of participants in the separate age groups (e.g., 23-year-olds, 24-year-olds, etc.).

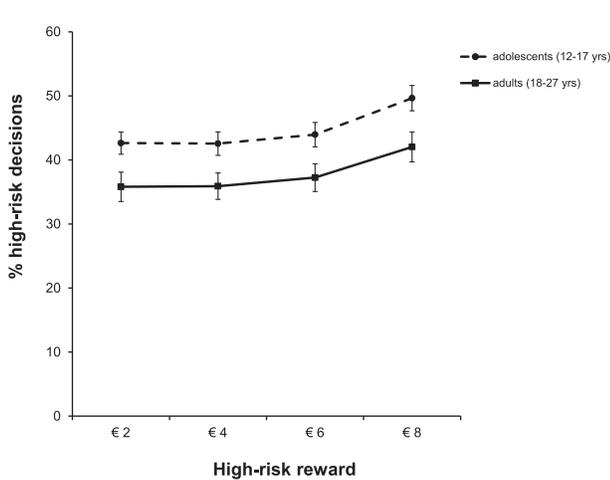


Figure 4. Mean percentage of high-risk decisions in the Cake Gambling task as a function of reward magnitude of the high-risk option.

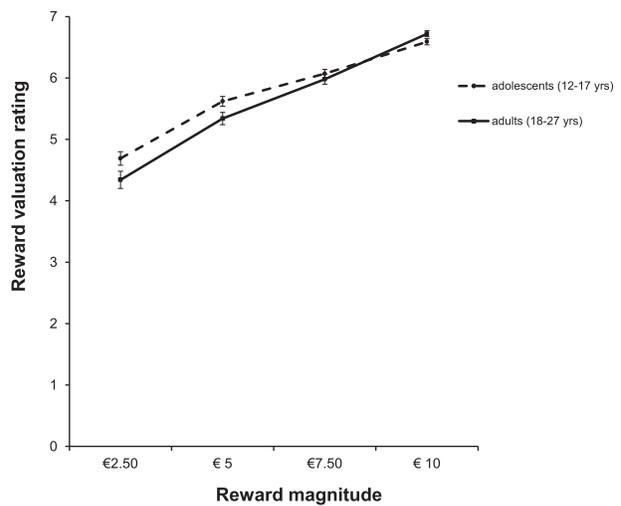


Figure 5. Mean reward valuation ratings (range = 1–7) for each of the four reward magnitudes.

younger participants value smaller monetary rewards more than older participants.

When controlling for age and Raven score, reward valuation was not significantly associated with AUC and high-risk decisions in the CG task in all participants (all $ps > .03$). Furthermore, as mentioned above, all significant age effects remained after controlling for individual differences in reward valuation. Together, these findings suggest that even though adolescents show subtle differences in monetary reward valuation relative to young adults, these differences cannot explain age differences in decision-making tasks in which monetary rewards are used.

Pubertal Development

Contrary to our expectations, when controlling for age, pubertal development was not significantly associated with risk taking or TD in boys (all $ps > .09$) and girls (all $ps > .41$).

Controlling for Unequal Gender Distribution: Random Sample of Female Adults

As mentioned above, the gender distribution was strongly skewed across the age groups in this study, in that the adult group contained significantly more females than males compared to the group of adolescents. To address this potential issue, we randomly selected 35 female adult participants to match the number of male adult participants in our sample, and repeated our age-related differences analyses with this random sample of females ($n = 35$), all male adult participants ($n = 35$), and all adolescent participants ($n = 195$). The random sample of women did not differ from the women who were not included in the random sample in terms of age, Raven score, risk taking, AUC, and reward valuation (all $ps > .16$). Consistent with the analyses in the total sample, age was significantly positively related to AUC (when controlling for Raven score and reward valuation; $\beta = 0.36$, $t = 2.98$, $p = .003$). Mirroring the findings in the total sample, only the linear age trend, and not the cubic or quadratic trends, was significant (all $ps > .58$). In keeping with the findings in the total sample, age was not significantly related to risk taking in the lower reward conditions and the €8 reward condition ($ps = .193$ and $.906$, respectively).

In sum, these findings suggest that the observed increase in AUC with age cannot be attributed to a greater proportion of females in the adult group.

Discussion

The goals of this study were to examine: (a) age-related differences in TD and risk taking in adolescents and young adults, (b) the association between TD and risk taking across ages, (c) whether individual differences in monetary reward valuation could explain individual and age differences in TD and risky decision making, and (d) the relation between pubertal development and TD and risk taking in adolescents. Unlike many prior studies, we were able to directly compare linear and nonlinear (i.e., quadratic and cubic) age-related differences in TD and risk taking, due to our large sample of participants with a wide age range.

Age-Related Differences in TD

As predicted, we found that age was positively related to the ability to wait for a delayed reward (i.e., decreased TD). These age-related differences were described best by a linear, and not by a nonlinear, trend. These findings are consistent with several other studies in which a linear decrease in TD with age has been reported in adolescents and young adults (Olson et al., 2007; Scheres et al., 2006; Steinberg et al., 2009). Interestingly, TD decreased particularly strongly from 15 to 16 years (even when controlling for Raven score and reward valuation) in this study, which is similar to the findings of a prior study (Steinberg et al., 2009). Decreased discounting with increasing age might be accounted for by the maturation of several cognitive functions, and the brain regions subserving these functions. Cognitive control processes, including working memory and response inhibition, improve during adolescence (Huizinga et al., 2006; Luciana et al., 2005), and might be associated with a greater ability to wait for a delayed reward.

On the neural level, choices between immediate and delayed rewards are associated with activation in both reward-related brain regions, such as the ventral striatum (VS) and ventromedial prefrontal cortex (vmPFC), and brain regions involved in self-control, including the dorsolateral prefrontal cortex (DLPFC) and parietal cortex (see Scheres, de Water, & Mies, 2013, for a review). Activation of self-control regions is thought to promote delayed reward choices, while activity in reward-related regions contributes to immediate reward choices. Indeed, *disruption* of the DLPFC results in increased discounting of delayed rewards (Figner et al., 2010). In addition, increased discounting is correlated with

poor integrity of white matter tracts that connect the prefrontal cortex with the VS (Peper, Koolschijn, et al., 2013). Similarly, the handful of studies that have been conducted on the neurocognitive development of TD have suggested that reductions in TD with increasing age are accompanied by increased activation of the DLPFC and parietal cortex, decreased activation of the VS, and enhanced functional connectivity between the vmPFC and VS in adolescents and young adults (Christakou, Brammer, & Rubia, 2011; Ripke et al., 2012). Whether the specific decrease in TD from 15 to 16 years that was observed in this study is driven by maturation of the DLPFC and parietal cortex remains an intriguing question for future study.

In contrast to the linear age-related differences in TD that were noted in this study, other studies (Scheres, Tontsch, et al., 2013) have documented nonlinear age-related differences in discounting, with decreased discounting in adolescence (13–17 years). These discrepant findings might be explained by the different delays and reward magnitudes that were used in the TD tasks across studies. Linear age effects are generally found in studies, including this study, in which relatively large monetary rewards (e.g., \$10–100) and long delays (e.g., up to 1 year) are used (Olson et al., 2007; Steinberg et al., 2009; but see Scheres et al., 2006, for an exception). Nonlinear age effects have been observed when shorter delays and smaller reward magnitudes are used. For instance, Scheres, Tontsch, et al. (2013) used a real (or experimental) TD task, in which all rewards and delays were actually experienced. Therefore, delays were in the range of seconds and the delayed reward was 10 cents in this study.

Both TD tasks with small rewards and short delays and TD tasks with larger rewards and longer delays are sensitive to individual differences in daily-life impulsivity. In other words, the validity of both types of tasks is equally high. For instance, adolescents with ADHD and adolescents who report high levels of smoking show relatively steep discounting in both types of TD tasks (Demurie et al., 2012a; Reynolds & Fields, 2012; Scheres, Tontsch, et al., 2010). Nonetheless, discounting of delayed rewards in real TD tasks (which include small rewards and short delays), and in hypothetical TD tasks (in which delays and rewards are not experienced, and large rewards and delays are typically used), is not highly correlated (Scheres, Sumiya, & Thoeny, 2010). These differences in discounting behavior when using different types of tasks might be due to the fact that distinct cognitive

and affective processes are involved in each type of task. It might be hypothesized that behavior in real TD tasks is strongly influenced by affective processes (e.g., reward sensitivity and delay aversion), while behavior in TD tasks with long delays and large rewards (which are typically used in hypothetical tasks) also depends on more cognitive processes (e.g., subjective time perception and working memory), which follow a protracted developmental trajectory (Casey et al., 2008; Crone & Dahl, 2012). Differential involvement of these processes might account for the distinct age-related differences that are observed when using different TD tasks. Moreover, adolescents might display different behavior in real and hypothetical tasks, even when reward and delay magnitudes are matched. These hypotheses need to be tested in future research, by administering a real TD task, a hypothetical TD task with long delays and large rewards, and a hypothetical TD task with small rewards and short delays to individuals of a large age range.

Gender Differences in TD

Young adult males discounted delayed rewards less steeply than females, while there were no gender differences in TD in adolescents. A similar gender difference in young adults has also been observed in one recent study (Ramos, Victor, Seidl-de-Moura, & Daly, 2013), but it has been reported that women discount delayed rewards less steeply than men as well (Peper, Mandl, et al., 2013). The increased preference for larger delayed rewards in young adult males in the present investigation might suggest that men were more motivated than women to maximize their own rewards. It must be noted, though, that due to the relatively small sample of males, one should be careful in interpreting this finding. Future research should explore gender differences in TD and their underlying mechanisms in more detail.

Age-Related Differences in Risk Taking

In line with previous research using the CG task (van Leijenhorst et al., 2008), risky decision making was not correlated with age in this study. Studies in which other risky decision-making tasks were employed also did not find differences in risk taking between adolescents and young adults (Cauuffman et al., 2010; Overman et al., 2004). In contrast, van Leijenhorst et al. (2010) reported that 12- to 14-year-olds made fewer high-risk decisions than 19- to 26-year-olds on trials of the CG task in which

the high- and low-risk options were matched on EV. Although we matched all low- and high-risk options on EV in this study, the 12- to 14-year-olds in our sample did not differ from the 19- to 26-year-olds regarding the percentage of high-risk decisions. When closely comparing the findings across these studies, it becomes apparent that the 12- to 14-year-olds showed similar levels of risk taking in both studies, while the 19- to 26-year-olds engaged in higher levels of risk taking in this study relative to the van Leijenhorst et al. (2010) study. Differences in sample sizes ($n = 93$ – 113 per age group in this study vs. $n = 15$ per age group in the van Leijenhorst et al., 2010, study) and settings and procedures (our behavioral study conducted in classrooms/groups vs. a functional MRI study) between studies might have contributed to these different results.

Contrary to the findings of this study, many studies did demonstrate either decreased risk taking with age (Crone & van der Molen, 2004, 2007; Hooper et al., 2004; Mitchell et al., 2008; Steinberg et al., 2008; van Duijvenvoorde et al., 2012) or a peak in risky decisions in (mid) adolescence (Burnett et al., 2010; Smith et al., 2012). The majority of these prior studies used (modified versions of) the IGT, which draws heavily upon working memory (van Duijvenvoorde et al., 2012) and other complex executive functions that are still developing during adolescence. A decline in risky decisions with age in this task might therefore partially reflect the increased maturation of executive functions during adolescent development. In this study, demands on executive functioning were reduced by using a gambling task in which all information on the rewards and probabilities associated with each choice was presented visually during each trial. This explicit presentation of the probabilities might have also contributed to the lack of age effects in this study. It has been reported that adolescents do not take more risks than adults when the probabilities of potential outcomes are known, but they do take more risks compared to adults when the probabilities are ambiguous (Tymula et al., 2012).

The nonlinear age-related differences in risk taking that were observed in other studies (Burnett et al., 2010; Smith et al., 2012) could indicate the effect of the emotional salience of the task on decision making. Brain areas involved in the processing of (positive) emotions and rewards have been found to show an inverted U-shaped development, with a peak in activation in (mid) adolescence (Casey et al., 2008; Crone & Dahl, 2012). This enhanced reward sensitivity could promote increased risk taking in tasks with a strong affective component, such as

dynamic tasks in which the level of risk increases after each risky decision (Figner et al., 2009), or tasks that are performed in the presence of peers (Gardner & Steinberg, 2005). In this light, it would be interesting to administer the CG task to adolescents in both neutral and emotionally salient contexts, and to compare the age-related differences in both versions.

Relation Between Risk Taking and TD

In this study, TD and risk taking were not correlated, and their age-related differences during adolescence and young adulthood were distinct. These findings are congruent with prior research (Olson et al., 2007; Prencipe et al., 2011; Scheres et al., 2006) and suggest that impulsivity and risk taking are not necessarily similar constructs in adolescence and young adulthood. While the neural correlates of risky and impulsive decision making partly overlap, there are also distinct neural systems involved in both types of decision making. Specifically, the lateral PFC and parietal cortex are more active during risky choices relative to choices between immediate and delayed rewards (Weber & Huettel, 2008). The posterior cingulate cortex (Weber & Huettel, 2008) and middle occipital areas (Peters & Buechel, 2009) are more active during choices between immediate and delayed rewards, compared to risky choices. These distinct neural systems involved in both types of decision making could partly contribute to the lack of a correlation between TD and risk taking.

It might be hypothesized that the different age-related differences in TD and risk taking could be attributed to some extent to the different demands of the tasks that were used to assess these constructs in this study. For instance, being able to wait for a reward that is delayed up to 1 year in time requires not only self-control but also the ability to accurately estimate extended time intervals and to project oneself into the future, which in turn depends on working memory. These higher order cognitive functions are thought to depend on brain regions that show a relatively protracted development during adolescence, such as the DLPFC (Casey et al., 2008; Crone & Dahl, 2012). However, in the CG task, all information that is needed to make a decision was presented visually, thereby reducing demands on working memory and cognitive control.

Reward Valuation

Interestingly, we found that valuation of the monetary rewards that were used in the TD task

and gambling task was not related to the decisions in these tasks. As a consequence, the linear decrease in TD with age remained significant after controlling for individual differences in reward valuation. These findings argue against the hypothesis that age effects in decision-making tasks in which monetary rewards are used could be attributed to age differences in reward valuation. To our knowledge, this is the first study to systematically compare age differences in monetary reward valuation and its relation with discounting and risk-taking behavior.

Pubertal Development

Contrary to our hypotheses, pubertal development was not related to risk taking and TD in adolescent boys and girls. Two previous studies did find a relation between advanced pubertal development and sensation seeking in experimental tasks (Peper, Koolschijn, et al., 2013; Steinberg et al., 2008). Differences between the experimental tasks used in these prior studies and the task employed in this study could explain these discrepant findings. Peper, Koolschijn, et al. (2013) administered the BART, in which participants could gain money by pumping a balloon, but would lose the money if the balloon exploded. Steinberg et al. (2008) administered a driving task, in which participants would crash with other cars if they took too many risks. In our CG task, risky decisions could lead to not gaining a monetary reward. These differences in the intensity of the potential negative consequence of a risky choice across studies might have contributed to different findings. It could be hypothesized that advanced pubertal development is particularly associated with a greater enjoyment of thrills, and the potentially large negative consequences following a risky choice in tasks used by Steinberg et al. (2008) and Peper, Koolschijn, et al. (2013) provide an arguably larger thrill than the task used in this study.

The lack of an association between pubertal development and TD could suggest that TD is not related to puberty. Nonetheless, it could also be argued that we might have found significant associations if we would have used more objective measures of pubertal status, such as levels of pubertal hormones (e.g., testosterone). Future studies should, therefore, include both self-report and hormonal assessments of pubertal development.

Limitations

It should be noted that this study also has some limitations. Even though we controlled for the

potentially confounding effects of reward valuation and Raven score, there are still other factors that might have contributed to the observed positive relation between age and the ability to wait for a delayed reward. These include possible age differences in subjective time perception, working memory, and delay aversion. Future studies should investigate the role of each of these factors in TD and its development.

Moreover, while this study included a large number of participants from a wide age range, the design was cross-sectional and therefore perhaps less sensitive to subtle developmental changes than a longitudinal design (e.g., Audrain-McGovern et al., 2009). Nevertheless, our findings of stable discounting behavior between the ages of 16 and 20 were strikingly similar to the findings of the longitudinal Audrain-McGovern et al. (2009) study.

In line with prior research (van Leijenhorst et al., 2008; van Leijenhorst et al., 2010), the exact reward magnitude associated with the options in the CG task was not made explicit to participants, but instead presented visually as a stack of coins. While this minimized the information that needed to be processed by participants, it might have been difficult for them to confirm that both options were equal in EV. Future studies could make the reward magnitude associated with the options more explicit by presenting the actual number of the reward that can be obtained.

The reward valuation questions were administered after completion of the TD and risk-taking tasks in all participants. Counterbalancing the order of the reward valuation questions is recommended to ascertain whether valuation of rewards *before* performing TD and risk-taking tasks impacts the results differently as compared to valuation of rewards *after* completing these tasks.

Finally, the TD task and the risk-taking task differed in the dynamic nature of the choices, in that the immediate rewards were adjusted based on participants' choices in the TD task, while the rewards and risk levels were fixed (or static) in the risk-taking task. To circumvent this issue, dynamic risk-taking tasks, such as the Columbia Card Sorting Task (Figner et al., 2009) could be administered in addition to the TD task in future investigations.

Conclusions

In conclusion, we found that TD declined linearly with age in adolescents, even when controlling for individual differences in reward valuation. A particularly sharp decline in discounting was

observed from 15 to 16 years. Risk-taking behavior was stable across ages, and discounting and risk taking were not correlated. These findings suggest that TD and risk taking are two separate constructs in adolescence and young adulthood, and that age-related differences in both constructs might be accounted for by different underlying (neural) mechanisms.

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