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Development of Multifaceted Risk Taking and the Relations to Sex Steroid Hormones: A Longitudinal Study

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Risk taking is a multidimensional construct. It is currently unclear which aspects of risk-taking change most during adolescence and if/how sex hormones contribute to risk-taking tendencies. This study applied a longitudinal design with three time-points, separated by 2 years, in participants aged 8–29 years (670 observations). The Balloon Analogue Risk Task, a delay discounting task, and various self-report questionnaires were administered, to measure aspects of risk taking. Longitudinal analyses demonstrated mostly nonlinear age-related patterns in risk-taking behavior and approach-related personality characteristics (peaking in late adolescence). Increased testosterone and estradiol were found to increase risk-taking behavior and impulsive personality, but decrease avoidance-like personality. This study demonstrates that risk taking is most pronounced in mid-to-late adolescence and suggests that sex hormones accelerate this maturational process.

Adolescence is defined as the developmental phase between childhood and adulthood that ranges from ages 10 to 22 years. This period is often characterized by an increase in explorative and risk-taking behavior, possibly related to the need to develop autonomy and independence (Steinberg, 2008). For example, adolescents are often engaged in traffic accidents, sexual risk behaviors, and alcohol drinking, leading to a range of negative health consequences (Kim-Spoon et al., 2016; Victor & Hariri, 2016). These findings have previously been explained in terms of higher social-affective sensitivities in adolescents that may drive them toward rewards and novelty, and which leads them to take more risks in daily life (Steinberg et al., 2008). Despite these general observations, there is much controversy about whether there is indeed an adolescent-specific rise in risk-taking behaviors when administrating controlled laboratory assessments (Defoe, Dubas, Figner, & van Aken, 2015; Pfeifer & Allen, 2012). Moreover, risk taking is a multidimensional construct (Frey, Pedroni, Mata, Rieskamp, & Hertwig, 2017; Harden et al., 2016; Mamerow, Frey, & Mata, 2016) and there is currently much unknown about which aspects of risk taking change most during adolescence.

Risk taking is typically defined as behaviors that result in uncertain outcomes (Figner, Mackinlay, Wilkening, & Weber, 2009) and often occurs in a context where there is the potential for an immediate reward at the expense of future benefits. Prior studies that examined risk-taking behavior in adolescence used of a variety of measures and tasks, ranging from self-report measures to risk-taking tasks, which possibly tap into different processes that underlie risk taking. One line of research used experimental laboratory tasks that are suitable to test actual risk-taking behaviors. Experimental tasks that tap into (social) reward processing reported peaks in adolescent risk taking, for example, in the domain of reward-driven risk taking (Braams, van Duijvenvoorde, Peper, & Crone, 2015), risk taking

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in the presence of peers (Gardner & Steinberg, 2005) or uncertain rewards (Burnett, Bault, Coricelli, & Blakemore, 2010; Figner et al., 2009), although not all studies confirm this (Defoe et al., 2015). In contrast, tasks that tap into impulsive choice (e.g., delay discounting tasks) showed gradual age-related decreases from childhood into adulthood (Achterberg, Peper, Van Duijvenvoorde, Mandl, & Crone, 2016; van den Bos, Rodriguez, Schweitzer, & McClure, 2015). Another line of research used self-report measurements, which are thought to provide sensitive measures of general tendencies of individuals to show certain types of behavior. These self-report measures showed gradual age-related declines in impulsivity, whereas self-reported sensation seeking and reward drive peaked in mid-adolescence (Steinberg et al.,2008), although this was not confirmed by all studies (Alarcon, Cservenka, & Nagel, 2017; Braams et al., 2015). Taken together, it remains unclear for which risk-related processes—captured either by self-report or task-related measures—an adolescent rise in risk taking is observed (Defoe et al., 2015).

An important new direction that will prove valuable to resolve this question is the use of multiple risk-taking measures. Both experimental tasks and self-report measures are needed within the same participants to decompose the time courses of separable risk-taking processes (Frey et al., 2017; Harden et al., 2016; van Duijvenvoorde et al., 2015). A second important direction is testing risk-taking behaviors longitudinally. The advantage of this approach is that it allows for the test of stability and change in measurements within individuals. This will prove important for knowing which types of risk taking are trait like (i.e., high stability over time) and which types are sensitive to developmental changes (i.e., showing changes over time). In addition, longitudinal measures can cover the whole range of childhood to adulthood, reducing potential cohort effects, and resulting in more power. Finally, longitudinal measures allow for the estimation of linear, quadratic and cubic growth curves (Ordaz, Foran, Velanova, & Luna, 2013), which can answer some of the inconsistencies of prior studies that used different age ranges or different participant selections.

A more mechanistic issue is what drives the increase in risk taking in adolescence. One potential mechanism could be the increase in sex steroid hormones. Both hormones testosterone and estradiol are rapidly increasing in boys and girls, roughly between ages 11 and 15, and may enhance sensation seeking and responsiveness to rewards by affecting related brain regions (Peper & Dahl, 2013). Indirect evidence suggesting that sex hormones are related to risk taking, comes from studies showing that males exhibit higher levels of sensation seeking and lower levels of impulse control than females. Moreover, sex differences also emerge in the *developmental trajectories* of sensation seeking and impulse control (Shulman, Harden, Chein, & Steinberg, 2015). Additionally, a recent study reported that the development of secondary sexual characteristics was related to reward-related approach behavior on the Iowa gambling task, whereas cost-avoidance was best predicted by chronological age (Icenogle et al., 2017). Since these studies did not directly measure sex hormonal levels, the effect of *changes* in sex steroid levels over time on changes in risk-taking behavior remains unknown. Our previous *cross-sectional* studies showed that testosterone (but not estradiol) is related to increased risk-taking behavior on the Balloon Analogue Risk-Taking Task (BART; Peper, Koolschijn, & Crone, 2013) and to lower avoidance-related personality characteristics, such as neuroticism (Schutter, Meuwese, Bos, Crone, & Peper, 2017). Increased estradiol was related to higher impulsive aggression in boys (Peper, de Reus, van den Heuvel, & Schutter, 2015). Moreover, testosterone was positively associated with activation in brain regions that are important for reward processing in adolescents, as examined in a relatively small sample using a risky gambling paradigm (Op de Macks et al., 2011). Previous studies have selected specific age groups and showed that sex steroids may indeed drive some of the rises in risk-taking behavior, as measured by probabilistic decision-making tasks (Op de Macks et al., 2016; Spielberg et al., 2015). Taken together, it is currently not understood how sex steroid changes explain variation in different aspects of risk-taking tendencies and their changes *over time across the full range of adolescence*.

This study used the *novel approach* of utilizing (a) an accelerated longitudinal design combined with (b) multiple aspects of risk-taking, covering (c) a wide age range of 8–29 years with (d) three assessments for each individual, each separated by 2 years. We also tested participants in early adulthood because we previously reported that maturation of testosterone levels are observed even in the early-to-mid-20s (Buttler et al., 2016). The selection of tasks was motivated by prior studies that included self-report and laboratory assessments to test for their common relations as well as different developmental time courses. Self-report measures included the Barratt Impulsiveness Scale, Version

11 (BIS–11), a measure of impulsivity; the Behavioral Inhibition (BIS)/Behavioral Activation (BAS) scale to assess avoidance and approach behaviors; the Buss Perry Aggression (BPA) questionnaire to test for impulsiveness in the aggressive domain (Zuckerman & Kuhlman, 2000); and the Neuroticism-Extraversion-Openness-Personality Inventory (NEO-PI) neuroticism scale, as this measure is found to be inversely related to risk taking and testosterone levels (Schutter et al., 2017). Experimental laboratory tasks included a delay discounting task to measure impulsive decision making (Achterberg et al., 2016) and the Balloon Analogue Risk Taking (BART) task to assess risk taking (Lejuez et al., 2002; Peper, Koolschijn, et al., 2013). Based on prior studies of others (e.g., Dougherty et al., 2015; Steinberg et al., 2008) and our own work (Achterberg et al., 2016; Braams et al., 2015), we predicted that delay discounting and self-reported impulsivity should decrease gradually during adolescence, whereas risk taking (on the BART) as well as self-reported approach behaviors were expected to peak in adolescence.

The contribution of the sex steroids testosterone and estradiol was examined across the full age range as well as within the period that a sharp rise in sex steroids takes place (11–15 years; Biro et al., 2014; Buttler et al., 2016). We predicted that sex steroids are positively related to approach-related behaviors, but negatively related to avoidance-related behaviors (i.e., BIS/neuroticism), and that this relationship was most pronounced between the ages of 10–15 years in both boys and girls. For risk-taking measures that rise or peak during adolescence, sex steroids may be important driving factors and may therefore explain additional variance in the growth curve model, above and beyond age.

Method

Sample

Participants were part of the "BRAINTIME" study, a large longitudinal study on brain development based in Leiden, the Netherlands. Participants were recruited through local schools and advertisements, as described elsewhere (e.g., Achterberg et al., 2016; Braams et al., 2015; Peters & Crone, 2017; Schreuders et al., 2018).

Initially (at *T1*), a total number of 299 participants were enrolled in the study (51% females; M_{age} = 14.2 ± 3.8 years; age range = 8.1–25.9 years; Table 1) and included 97% Caucasian, 2% Asian and 1% Northern African participants. Two years later (at *T2*), 271 participants were assessed (52% females; M_{age} = 15.8 ± 3.6 years, range = 9.9–26.6 years); Δ in years between T1 and T2: M = 1.99, SD = 0.10. The final assessment (*T3*)—2 years after T2, involved 224 participants (49% females; M_{age} = 18.0 ± 3.7 years, range = 11.9–28.7 years); Δ in years T2–T3: M = 2.02, SD = 0.09. There were no significant differences in the measures of interest between the group with complete waves of data (N_{max} = 214) and the group with one or two missing waves of data collection (N_{max} = 92). Data collection across the three time-points took place between May 2011 and January 2016.

Participants were free from psychiatric and endocrine disorders—as screened through telephone interviews—and had normal intelligence (as estimated with the subscales Block Design and

Table 1
Analysed Data for Each Measure on Each Time-Point

	T1		T2		T3	
	N (males)	*M* (*SD*)	*N* (males)	*M* (*SD*)	*N* (males)	*M* (*SD*)
Discounting	269 (128)	0.45 (0.30)	237 (113)	0.48 (0.27)	224 (108)	0.55 (0.28)
BART money	267 (128)	8.25 (3.69)	238 (113)	8.91 (3.82)	222 (106)	9.14 (3.55)
BART explosions	267 (128)	10.89 (3.78)	238 (113)	11.80 (3.70)	222 (106)	12.71 (3.43)
BIS–11	248 (115)	61.36 (8.95)	241 (115)	62.52 (9.18)	249 (115)	62.32 (9.29)
BIS avoidance	248 (115)	19.61 (3.86)	241 (115)	19.67 (3.39)	246 (113)	20.21 (3.95)
BAS approach	248 (115)	39.64 (4.35)	241 (115)	39.84 (4.35)	246 (113)	39.90 (4.80)
BPA-Q	248 (115)	85.92 (19.18)	241 (115)	87.51 (18.51)	246 (113)	87.31 (20.57)
NEO-PI	168 (85)	63.00 (13.09)	208 (104)	65.57 (12.19)	246 (113)	68.14 (12.58)
Testosterone (log)	241 (115)	1.55 (0.65)	262 (123)	1.74 (0.62)	236 (118)	1.82 (0.66)
Estradiol (log)	228 (104)	0.32 (0.24)	230 (109)	0.27 (0.25)	237 (120)	0.38 (0.19)

Note. BART = Balloon Analogue Risk-Taking Task; BIS–11 = Barratt Impulsiveness Scale, Version 11; BPA-Q = Buss Perry Aggression Questionnaire; NEO-PI = Neuroticism-Extraversion-Openness-Personality Inventory.

Similarities from the Wechsler Intelligence Scale for Children at < 16 years, or Wechsler Adult Intelligence Scale at ≥ 16 years). IQ ranged between 80 and 143 (M = 109.72, SD = 10.52). No information on socioeconomic status was obtained. Adult participants (≥ 18 years) were paid 60€ for their participation in the entire study. Minor participants were "paid" in the form of gifts (e.g., brain-gadgets)—equaling 20–30€, in addition to the compensation of travel expenses for the parents or legal guardians. The Medical Ethics Committee of the Leiden University Medical Centre approved the study.

Behavioral and Personality Measures

BART Risk Taking

The BART is a validated task relating to real-life risk-taking behavior (Lejuez et al., 2002) and has been described earlier in this sample (Braams et al., 2015; Peper, Koolschijn, et al., 2013). In brief, on a computer screen, participants saw a small balloon, a balloon pump, a button with "Total Earned," a button with "Earned on last balloon" and a cash (€€€)-button. By mouse clicking on the pump, the balloon was inflated and 0.05€ was gained for each pump. The total amount of collected money on each trial was stored in a temporary bank (not displayed on the screen). Participants could decide to stop inflating the balloon at any time and collect their money by clicking the €€€-button. Then, their money was transferred to the permanent bank (accompanied by a slot-machine sound) and the amount was displayed on the screen. When the balloon exploded, the computer played a "pop" sound, and the temporarily saved money on that trial was lost. The BART consisted of 30 trials, including 10 orange, 10 yellow, and 10 blue balloons presented in a random order. Each color had a different probability of exploding, with an average explosion point of 4, 16, and 64, respectively (Lejuez et al., 2002). Participants were told that at some point each balloon would explode and that this explosion could occur as early as the first pump all the way up to the point at which the balloon had expanded to fill the entire computer screen. No information was provided on the diverse explosion probabilities of the balloons. Participants were instructed to gain as much money as possible, but were not directly paid for this task. The variables of interest were total money earned (i.e., the cumulative amount of money that was successfully transferred to the bank) and number of explosions (i.e., equaling the number of unsuccessful trials, ending in an explosion). Balloon colors were collapsed, as the score across all 30 balloons is typically more reliable than any single 10 balloon block (Wallsten et al., 2005).

In our previous cross-sectional study based on Time-point 1 (Peper, Koolschijn, et al., 2013), we found that the number of explosions on the BART (i.e., the number of unsuccessful trials, referred to as "disadvantageous" risk taking) was related to testosterone and was higher in boys. However, the amount of money earned (cumulating the trials where money was successfully transferred to the bank, referred to as "advantageous" risk taking) was best explained by chronological age. On the basis of these previous results, we again made the distinction between both variables.

Delay Discounting Task

A computerized version of a hypothetical delay discounting task described by Peper, Mandl, et al. (2013) was used, based on the paradigm introduced by Richards, Zhang, Mitchell, and de Wit (1999). Participants were asked to make a series of choices, between either a small, immediately available amount of money or €10 available after a delay. Discounting was assessed at four delays (2, 30, 180, and 365 days later). Trials with different delays were presented in a random order. Furthermore, the task incorporated an adjustment algorithm (Du, Green, & Myerson, 2002), which implied that the task was adaptive: after the choice for the immediately available money, this amount was decreased on a next trial, whereas if the delayed money was preferred, the amount of immediately available money on the next trial was increased.

The amount of immediately available money the participant considered to be equivalent to the €10 delayed reward was taken to indicate the subjective value of the delayed rewards. Based on these so called "indifference points," the area under the discounting curve (AUC) was obtained, an often-used measure of amount of discounting (Myerson, Green, & Warusawitharana, 2001). The normalized AUC ranges from 0 (complete discounting) to 1 (no discounting). The smaller the AUC, the faster people discount the delayed reward and the more impulsive (or delay aversive) they are.

Barratt Impulsiveness Scale, Version 11

We administered a validated Dutch translation of the BIS–11, measuring impulsive personality (Patton, Stanford, & Barratt, 1995). The BIS–11 questionnaire contains 30 items, and comprises of the subscales motor impulsivity (e.g., "I act without

thinking"), nonplanning impulsivity (e.g., "I am not interested in the future, but in today"), and attentional impulsivity (e.g., "I have difficulties sitting still during lectures/at school").

The cumulative score of the BIS–11 was used for analysis.

Behavioral Inhibition (BIS) and Behavioral Activation (BAS)

The BIS/BAS questionnaire (Carver & White, 1994) is thought to measure two motivational systems underlying behavior: the behavioral inhibition (or avoidance) system (BIS) and the BAS (or approach) system (BAS). The BAS-system has been involved in risk-taking tendencies during adolescence (Braams et al., 2015). The BIS-BAS questionnaire consists of 24 items and is comprised of four subscales: BIS (e.g., "I feel pretty worried or upset when I think or know somebody is angry at me"), BAS reward responsiveness (e.g., "It would excite me to win a contest"), BAS fun seeking (e.g., "I'm always willing to try something new if I think it will be fun"), and BAS drive (e.g., "I go out of my way to get things I want"). Participants rate themselves on a 4-points scale ranging from 1 (*very true for me*) to 4 (*very false for me*). Here, we analyzed BIS and a cumulative BAS-score as a measure of risk-taking personality.

BPA-Questionnaire

The Buss Perry Aggression Questionnaire (BPA-Q) was administered (Buss & Perry, 1992), consisting of 29 items across four subscales: physical aggression (e.g., "I get into fights very often"), verbal aggression (e.g., "most of the time I disagree with people"), anger (e.g., "I have difficulties controlling my temper"), and hostility (e.g., "I believe that people are making fun of me behind my back"). Participants rate themselves on a 7-point scale from 1 (*extremely uncharacteristic of me*) to 7 (*extremely characteristic of me*). The cumulative score on total aggression was used for analysis.

NEO-PI Neuroticism

Three 8-item subscales of the Neuroticism personality trait were measured using the revised NEO Personality Inventory (NEO-PI–R): impulsivity (e.g., "I have a hard time resisting temptations"), depression (e.g., "I have a low opinion of myself"), and anxiety (e.g., "I have less fears than others"; Hoekstra, Ormel, & De Fruyt, 1996). Responses were collected on a 5 point scale (1 = *strongly disagree*; 2 = *moderately disagree*; 3 = *neither disagree nor agree*; 4 = *moderately agree*; 5 = *strongly disagree*. The cumulative score on neuroticism was used for analysis. The NEO-PI was not administered in children under the age of 12.

Sex Steroids

Morning saliva samples were collected at home in tubes with cap of 10 ml, 79 × 16 mm (Sarstedt, Nümbrecht, Germany), directly after waking up. The samples were stored in a freezer at −18° Celsius before the lab visit, which was checked by the experimenters. No samples were destroyed due to inferior quality. Premenarcheal girls and boys collected saliva on the day of behavioral testing, whereas postmenarcheal girls collected saliva on the same day within the early follicular phase of their menstrual cycle (Day 7), as described previously (Peper, Koolschijn, et al., 2013; Peper et al., 2015). In this way, the influence of circadian rhythms, intraindividual daily fluctuations, and hormonal fluctuations across the menstrual cycle were limited (Dabbs, 1990). Participants were instructed not to eat or brush their teeth before collecting saliva. Girls using hormonal intrauterine devices were excluded from participating in this study. Saliva samples were assayed for endogenous testosterone levels at the Department of Clinical Chemistry of the VU Amsterdam Medical Centre, Amsterdam, and the Netherlands. Estradiol was determined at the Technical University of Dresden, Germany). Salivary testosterone level was determined by isotope dilution—online solid phase extraction liquid chromatography—tandem mass spectrometry (ID-XLC-MS/MS; Buttler et al., 2016; Peper et al., 2015). Estradiol levels were determined by luminescence immunoassay.

For testosterone, intraassay coefficient of variation (CV) was 11% and 4%, at 10 and 140 pmol/L. Interassay CV was 8% and 5%, at 31 and 195 pmol/L. For estradiol, the interassay CVs were 12% for low E2 levels (3 pg/ml), and 4% for high E2 levels (12 pg/ml). The intraassay CVs were 6% at low concentrations (3 pg/ml) and 5% at high E2 levels (12 pg/ml).

Both testosterone and estradiol values were not normally distributed, therefore a log transformation was carried out leading to a normal distribution.

Statistical Analyses

Intraclass Correlations

To test the homogeneity of the data across the three time-points, intraclass correlations (ICC)

were calculated between time-points 1, 2, and 3 of all the variables (Delay discounting, BART money/explosions, BIS–11 impulsivity, BPA aggression, BIS, BAS, NEO neuroticism; Table 2). All ICCs were > .50, which indicates sufficient nesting of observations within individuals, necessary for mixed-model fitting procedures (Ordaz et al., 2013). Pearson's correlations between the behavioral measures at T1 are depicted in Table 3.

Mixed-Model Analyses

A mixed-models approach was adopted using the statistical program R (R Core Team (2014) with the *nlme* package (Pinheiro et al., 2013). This approach is suitable for analysis of longitudinal data as it recognizes the dependent nature of the data due to nesting of time-points within participants.

The first aim was to examine normative development of risk-taking aspects in relation to age. To that end, mixed-models were used to determine age-related patterns in laboratory risk taking (BART), delay discounting behavior, and self-reported impulsivity (BIS–11), behavioral approach and avoidance tendencies (BIS/BAS), impulsive aggression (BPA-Q) and neuroticism (NEO-PI). The following model-fitting procedure was used: first, a null model including a random intercept to allow for individual differences in starting points was run. The null model was then compared to three polynomial terms (linear, quadratic, and cubic), where a linear effect of age implies a monotonic change over time, a quadratic effect indicates an adolescent-specific increase or decrease, whereas a cubic age-related pattern suggests an adolescent-emergent pattern as opposed to relative stability during childhood and adulthood. Akaike information criterion (AIC) values and Bayesian information criterion (BIC) values were compared between the null model and the polynomial age-terms and log-likelihood tests were carried out to determine the best-fitting model. In a second step, sex and the interaction between age and sex were added to the model. In case Sex × Age interaction effects were found, the age model-fitting procedure was rerun in each sex separately.

Table 2
ICC Values for All Variables Between Time-Points 1, 2, and 3 for Total Sample and 8–12 Years, 13–17 Years, and 18 Years and Older

Measure	ICC all	ICC 8–12	ICC 13–17	ICC 18+
Delay discounting (AUC)	.76	.78	.75	.77
BART money	.58	.40	.62	.67
BART explosions	.64	.61	.52	.85
BIS–11 impulsivity	.78	.70	.83	.86
BIS-avoidance	.69	.53	.75	.82
BPA aggression	.77	.65	.85	.86
BAS approach	.67	.59	.75	.59
NEO neuroticism	.82	.86	.79	.86
Testosterone	.90	.72	.91	.96
Estradiol	.59	.52	.44	.62

Note. ICC = intraclass correlations; AUC = area under the curve; BART = Balloon Analogue Risk-Taking Task; BIS–11 = Barratt Impulsiveness Scale, Version 11; BPA = Buss Perry Aggression; NEO = Neuroticism-Extraversion-Openness.

To address the second aim of the study—scrutinize the role of the sex hormones testosterone and estradiol in risk-taking aspects and their development—two different analyses were carried out for each of the sexes separately:

1a. The first analyses (1a) were run on the full 8- to 29-year-old sample in which we tested whether testosterone or estradiol explained additional variance above age. To do so, we first included the best-fitting polynomial for age based on the age analyses for each risk-taking measure separately. Then, in a second step, we ran a model with a linear term for testosterone or estradiol. Only a linear polynomial was tested based on a priori hypotheses about the relationship between sex hormones and other variables. Again, model fit was assessed by evaluation of AIC and BIC values, and log-likelihood ratio tests.

1b. The next question we aimed to answer was whether changes in sex hormones account for changes in the dependent measure. To answer this question, a relative change in hormone production from T1 to T3 was related to change in behavior. The change score was accounted for baseline levels of hormones, but not for age. The change score was calculated with the following formula:

$$\Delta\text{Hormone} = \frac{\text{Hormone T3} - \text{Hormone T1}}{\text{Hormone T1}}$$

The second set of analyses was performed in a subset of the sample with a restricted age-range, but with high interindividual variability in hormonal level (i.e., 11–15 years; $N = 211$ (105 boys and 106 girls). In case multiple measurements were available in a participant, the first time-point was

Table 3
Pearson's Correlations Between All Constructs at Time-Point 1 (N = *279)*

	Discounting	BART money	BART explosions	BIS–11	BIS-avoidance	BAS approach	Aggression	Neuroticism[a]
Discounting		—	—	—	—	—	—	—
BART money	—		.49***	—	—	—	—	—
BART explosions	—	.45***		.14*	—	—	—	—
BIS–11	—	—	.14*		—	.24***	.33***	.16*
BIS avoidance	—	—	−.15*				.13*	.58***
BAS approach	—	—	—	.24***	—		.28***	—
Aggression	—	—	—	.33***	.14*	.28***		.45***
Neuroticism	−.18**	−.14*	−.18**	.16*	.58***	—	.53***	

Note. Only significant values are reported. Values above the diagonal are uncorrected for age, values below the diagonal are corrected for age. Discounting is inversely scored: a smaller area under the curve means more impulsive. BIS–11 = Barratt Impulsiveness Scale, Version 11. The black shades only mark the diagonal. Values below the diagonal are correlations uncorrected for age, and values above the diagonal are corrected for age.
[a]Correlations with neuroticism are based on 195 participants > 12 years.
*$p < .05$. **$p < .01$. ***$p < .001$.

selected. In this sample we aimed to test the contribution of the puberty-specific rise in testosterone and estradiol to different aspects of risk taking (Quevedo, Benning, Gunnar, & Dahl, 2009). To that end, in analyses 2a, a regression analysis was carried out. To account for any age-related variance still remaining in this "puberty-specific" group, age was also included in the model (note that in this analysis, only one measurement per participant was analyzed).

2b. Finally, to examine whether higher pubertal production of sex hormones relates to more risk taking *compared to same-aged peers*, *z*-scores were calculated within each sex to approximate age-standardized hormone values for participants at 11, 12, 13, 14, and 15 years of age:

$$z = \frac{X - M}{SD},$$

where z refers to the standardized hormonal value for an 11-year old girl, an 11-year old boy, 12-year old girl, etc. This method can particularly be informative when establishing reference values, and a similar procedure has been adopted for other hormones such as growth hormone (Hua, Wu, Chemaitilly, Lukose, & Merchant, 2012), insulin growth factor (Alberti et al., 2011), and testosterone (Holmboe et al., 2015).

Table 4
AIC and BIC Values for Null, Linear, Quadratic, and Cubic Models to Describe the Relationship With Age and Each of the Measures

	Age model								Sex			
	Null		Linear		Quadratic		Cubic		Main		Age × Sex	
Measure	AIC	BIC	AIC	BIC	AIC	BIC	AIC	BIC	AIC	BIC	AIC	BIC
BART money	3,711	3,724	3,688	3,706	**3,686**	**3,709**	3,688	3,715	—	—	—	—
BART explosions	3,706	3,720	3,673	3,692	3,662	3,685	**3,656**	**3,683**	**3,654**	**3,686**[a]	—	—
Discounting	135	149	107	125	**105**	**128**	107	134	—	—	—	—
BIS–11 impulsivity	4,842	4,856	4,844	4,862	**4,841**	**4,864**	4,843	4,870	—	—	—	—
BIS avoidance	3,637	3,651	**3,631**	**3,649**	3,632	3,655	3,633	3,660	**3,576**	**3,598**	—	—
BAS approach	3,917	3,930	3,915	3,933	3,917	3,939	**3,912**	**3,939**	—	—	—	—
BPA aggression	**5,830**	**5,843**	5,831	5,849	5,833	5,855	5,834	5,861	—	—	—	—
NEO neuroticism	4,588	4,601	4,543	4,560	**4,539**	**4,560**	4,539	4,565	**4,514**	**4,551**	—	—

Note. Preferred models are indicated in bold. AIC = Akaike information criterion; BIC = Bayesian information criterion; BART = Balloon Analogue Risk-Taking Task; BIS–11 = Barratt Impulsiveness Scale, Version 11; BPA = Buss Perry Aggression; NEO = Neuroticism-Extraversion-Openness.
[a]The main effect of sex on BART explosions is at trend-level significant ($p = .07$).

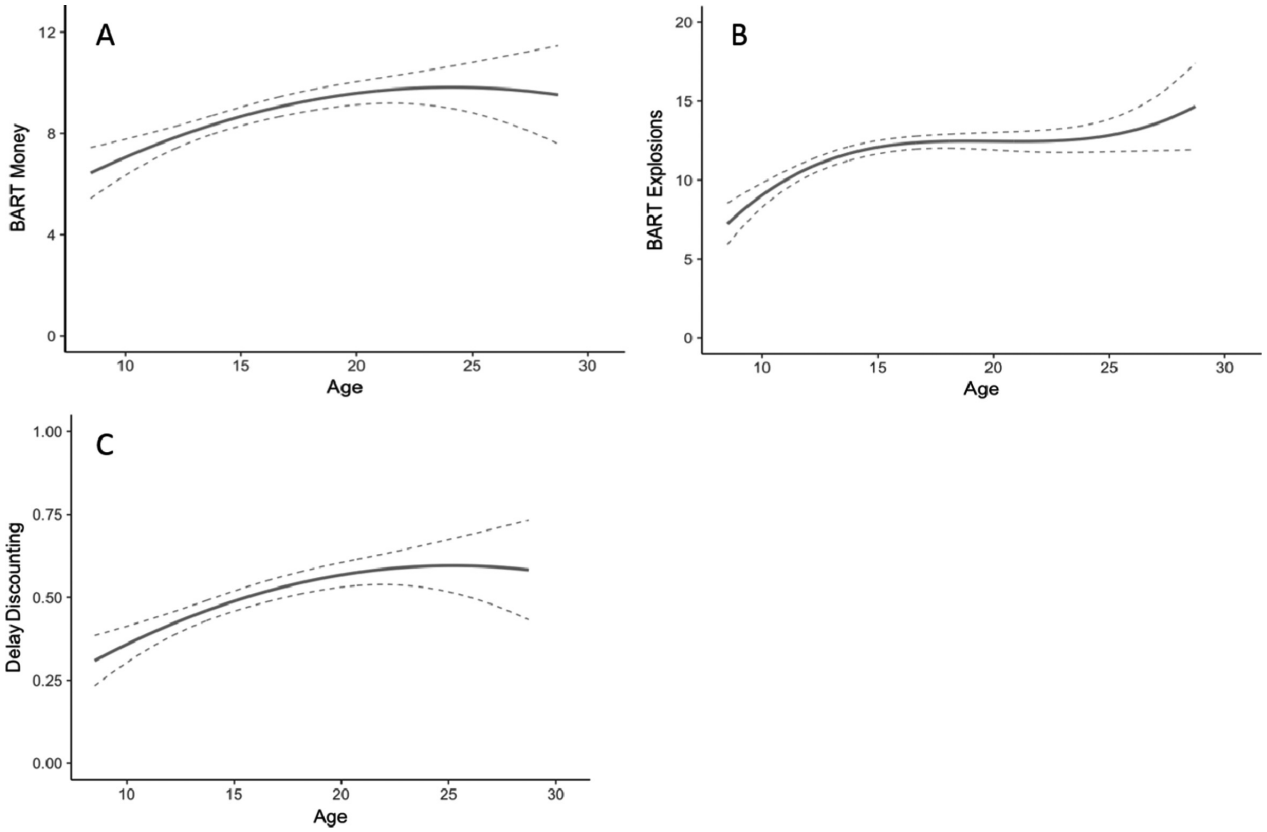

Figure 1. Age-related changes in experimental tasks. Money earned (in Euro's) on the Balloon Analogue Risk-Taking Task (BART; A), explosions on the BART (B) and delay discounting (area under the curve; C).

Results

Normative Age-Related Patterns

BART—Risk-Taking Behavior

A quadratic model best explained the association between money won on the BART and age (Table 4), showing a pre/mid adolescent increase in money earned with age and a slight decrease in early adulthood (Figure 1A). There were no significant effects of sex or Sex × Age interactions pertaining to money earned on the BART. The association between BART explosions and age was best explained by a cubic model, showing an adolescent-increase in explosions reaching a plateau during mid/late-adolescence (Figure 1B). There was a trend toward a sex difference in BART explosions ($p = .07$) where males tended to have more balloon explosion than females. There was no Sex × Age interaction for BART explosions.

Delay Discounting Behavior

The association between delay discounting (AUC) and age was best explained by a quadratic age-model (Table 4), indicating the largest AUC (least discounting/least impulsive decisions) during late adolescence followed by a slight decline in early adulthood (Figure 1C). There were no significant effects of sex or Sex × Age interactions.

Barratt Impulsiveness Scale, Version 11

A quadratic model best described age-related effects in impulsive personality measured with the BIS–11 (Table 4), indicating higher mid-adolescent impulsive personality values compared to children and adults. There was no main effect of sex and no Age × Sex interaction on the BIS–11 (Figure 2A).

BIS-Avoidance/BAS Approach

A linear model best explained age-related changes in BIS-avoidance personality of the BIS/BAS scales (Table 4; Figure 2C), indicating a monotonic increase across development. There was a main effect of sex ($p < .001$), demonstrating that females had higher BIS avoidance values than

males. No Sex × Age interaction was found for BIS avoidance.

A cubic age-model best explained development in BAS approach, indicating relative stability during childhood and adolescence, followed by a decline in adulthood (Figure 2B). There were no sex or Sex × Age interaction effects on the BAS approach scale.

Aggression (BPA-Q)

Aggression levels on the BPA-Q did not change with age, that is: the null-model best fitted the data. Moreover, no sex or Sex × Age interaction effects could be determined with respect to aggressive personality.

Neuroticism (NEO-PI)

A quadratic model best explained age-related changes in neuroticism, indicating highest levels during late adolescence compared to childhood and adulthood (Figure 2D). There was a main effect of sex ($p < .001$), with females having higher neuroticism values than males. No Age × Sex interaction effect was found.

In summary, longitudinal analyses demonstrated mostly nonlinear age-related patterns in risk-taking behavior and approach-related personality characteristics (peaking in late adolescence or increasing further in young adulthood) and steep increases in avoidance-related personality characteristics.

Associations With Sex Steroid Hormones

First, age-related change in testosterone and estradiol levels was examined. In males and females testosterone levels showed a cubic age-related pattern, demonstrating rapid increases during early/mid adolescence in both sexes, leveling off in young adulthood. In males, testosterone reaches a plateau in early adulthood, whereas in adult females

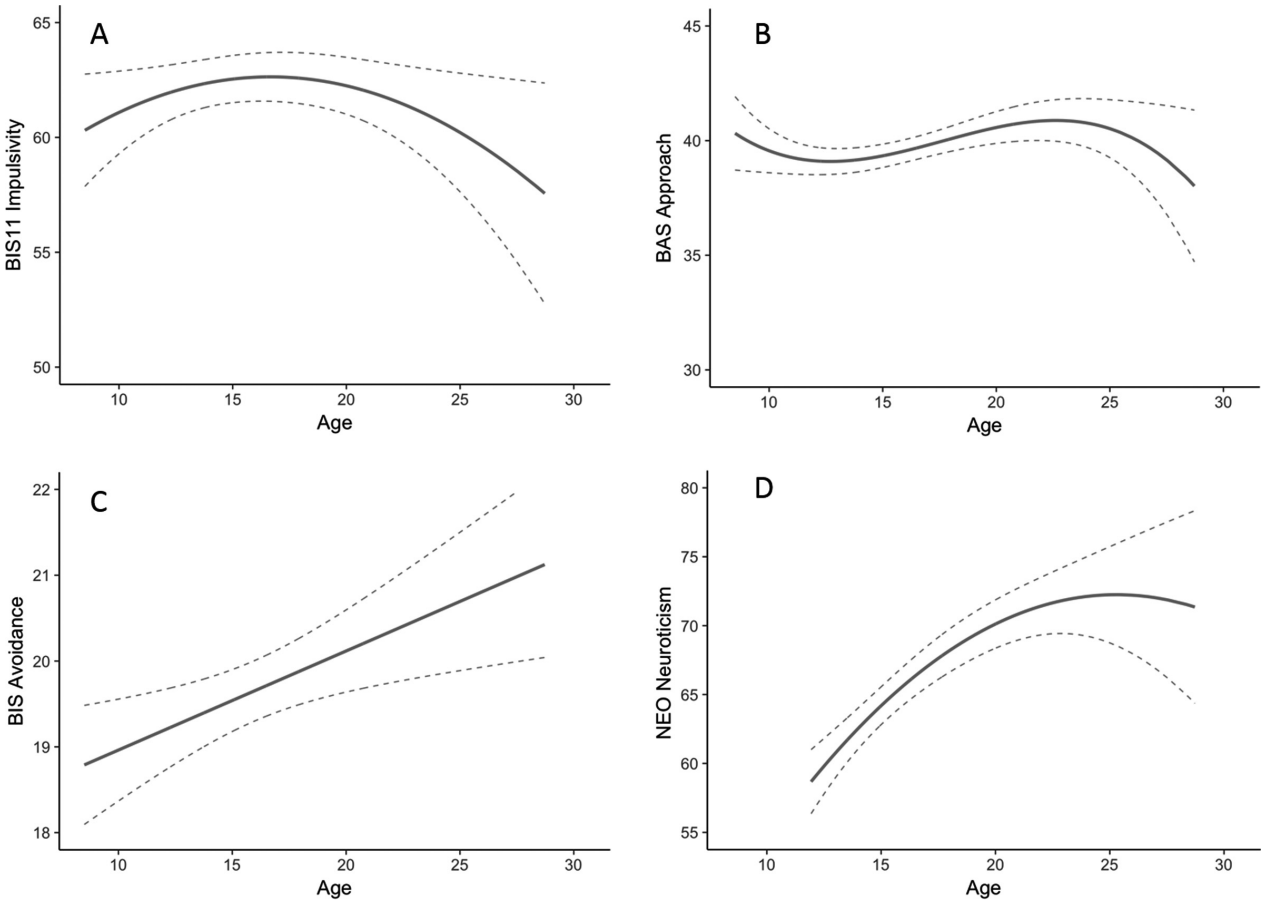

Figure 2. Age-related change in self-report measures: Barratt Impulsiveness Scale, Version 11 (BIS–11) impulsive personality (A), Behavioral Activation System (BAS) approach (B), BIS avoidance (C), Neuroticism-Extraversion-Openness (NEO) neuroticism (D). NEO was administered in children older than 12 years. BIS avoidance and NEO neuroticism showed a significant main effect of sex (f > m).

testosterone levels increased further (Figure 3A). Similar to testosterone, estradiol levels developed according to a cubic fashion in both sexes, showing a steep increase during early and midadolescence, leveling off in adulthood (Figure 3B).

Relations to Sex Steroids Across the Full Sample

In the first analysis (1a), the associations between testosterone, estradiol, and risk-taking measures were examined across the whole age-range (i.e., 8–29 years) of the sample.

In males, on top of age-related effects, testosterone did not explain any additional variance on the BART or delay discounting behavior (Table 5). With respect to the self-report personality measures in males, it was found that testosterone was related to higher impulsive personality of the BIS–11 (p = .028). Moreover, a higher level of testosterone was related to lower levels of neuroticism in males (p = .028) and to lower levels of BIS avoidance (p = .027). Behavioral approach (BAS), and aggressive personality were not related to testosterone levels in males (p's > .280). Estradiol levels were not associated with risk-taking tendencies in males (p's > .130).

In females, on top of age-related changes, neither testosterone nor estradiol explained additional variance in risk-taking tendencies across the full range of adolescence (Table 5; p's > .168).

In the second change-change analysis performed on the whole sample (1b), relative changes in sex steroid levels over time were associated with changes in various aspects of risk taking. In males, we observed that a relatively large increase in testosterone level was related to a larger decrease in discounting (i.e., less impulsive decision making) albeit at trend-level (p = .061; Table 6; Figure 4A) and to larger increases in self-reported BIS–11 impulsive personality (p = .043; Figure 4B). Changes in other aspects of risk taking were not related to changes in testosterone levels in males (p's > .262) and no relations to changes in estradiol levels were observed (p's > .136).

In females, a larger increase in testosterone levels over time was related to a larger increase in BART explosions (p = .021; Table 6; Figure 4C), which was at trend-level significant for the increase in estradiol level as well (p = .066) Changes in other aspects of risk taking were not related to changes in testosterone or estradiol levels in females (p's > .268).

Puberty-Specific Relations to Sex Steroids

Next, in the regression analysis within a restricted age-range of 11–15 years boys and girls (2a), the contribution of testosterone and estradiol production was studied during puberty to explain individual differences in risk-taking aspects.

In boys, on top of age-related change, higher pubertal testosterone as well as estradiol were related to higher scores on the BIS–11 impulsive personality questionnaire (p = .005 for testosterone and p = .015 for estradiol; Table 7). Pubertal testosterone and estradiol in boys were unrelated to BART performance, delay discounting behavior and to self-reported behavioral approach and avoidance, impulsive aggression and neuroticism (p's > .116).

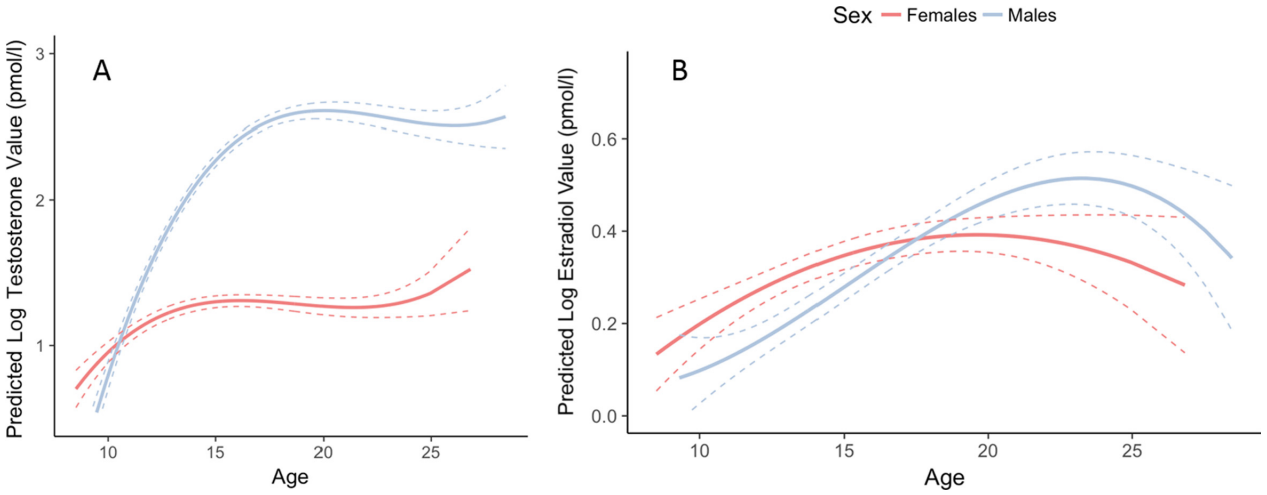

Figure 3. Age-related change in testosterone (A) and estradiol (B) in males and females. [Color figure can be viewed at wileyonlinelibrary.com]

Table 5
Mixed-Model Results of Testosterone, Estradiol, and Risk-Taking Measures Across 8–29 Years

		Females				Males			
Measure	Model	Var	β	*SE*	*p*	Var	β	*SE*	*p*
BART money	Random effect								
	Intercept	1.891 (1.884)				1.777 (1.746)			
	Fixed effect								
	Intercept		8.502	0.232	< .001		8.930	0.228	< .001
	(Age^2 &) Testosterone		2.456	4.041	.544		−5.025	6.272	.424
	Intercept		8.501	0.232	< .001		8.934	0.227	< .001
	(Age^2 &) Estradiol		0.134	3.802	.972		3.615	4.048	.373
BART explosions	Random effect								
	Intercept	2.141 (2.155)				2.290 (2.297)			
	Fixed effect								
	Intercept		11.134	0.927	< .001		10.721	1.446	< .001
	(Age^3 &) Testosterone		0.147	0.731	.841		0.692	0.648	.287
	Intercept		11.080	0.358	< .001		12.219	0.406	< .001
	(Age^3 &) Estradiol		0.697	0.806	.388		0.070	0.987	.944
Discounting	Random effect								
	Intercept	0.187 (0.184)				0.191 (0.190)			
	Fixed effect								
	Intercept		0.491	0.019	< .001		0.497	0.020	< .001
	(Age^2 &) Testosterone		−0.222	0.282	.432		0.309	0.473	.515
	Intercept		0.490	0.019	< .001		0.497	0.020	< .001
	(Age^2 &) Estradiol		0.362	0.265	.174		−0.281	0.303	.355
BIS–11 impulse	Random effect								
	Intercept	6.802 (6.838)				6.975 (7.055)			
	Fixed effect								
	Intercept		59.450	2.246	< .001		56.199	3.040	< .001
	(Age^2 &) Testosterone		2.426	1.752	.168		2.514	1.337	.062
	Intercept		61.871	0.938	< .001		60.781	0.944	< .001
	(Age^2 &) Estradiol		1.651	1.898	.407		3.126	2.055	.130
BIS avoidance	Random effect								
	Intercept	1.992 (1.986)				2.129 (2.225)			
	Fixed effect								
	Intercept		20.875	.218	< .001		18.381	0.241	< .001
	(Age^1 &) Testosterone		−2.830	3.449	.413		−10.084	4.516	**.027**
	Intercept		20.878	0.218	< .001		18.374	0.247	< .001
	Age^1 &) Estradiol		−2.706	3.299	.413		4.463	3.763	.237
BAS approach	Random effect								
	Intercept	2.559 (2.597)				3.138 (3.142)			
	Fixed effect								
	Intercept		40.063	0.279	< .001		39.310	0.332	< .001
	(Age^3 &) Testosterone		7.912	4.669	.092		0.116	7.890	.980
	Intercept		40.061	0.281	< .001		39.310	0.332	< .001
	(Age^3 &) Estradiol		−1.169	4.274	.785		1.886	4.891	.700
BPA aggression	Random effect								
	Intercept	12.871 (10.054)				14.179 (12.405)			
	Fixed effect								
	Intercept		86.828	1.295	< .001		86.414	1.413	< .001
	(Age^1 &) Testosterone		17.135	18.237	.349		−1.750	22.044	.937
	Intercept		88.303	1.139	< .001		88.108	1.288	< .001
	(Age^1 &) Estradiol		−0.819	17.387	.962		24.483	17.940	.174

Table 5
Continued

Measure	Model	Females				Males			
		Var	β	*SE*	*p*	Var	β	*SE*	*p*
NEO neuroticism	Random effect								
	Intercept	9.417 (9.408)				7.787 (7.770)			
	Fixed effect								
	Intercept		69.051	0.947	< .001		62.795	0.815	< .001
	(Age^2 &) Testosterone		−3.929	11.327	.729		−30.568	13.629	**.026**
	Intercept		69.059	0.947	< .001		62.774	0.816	< .001
	(Age^2 &) Estradiol		−0.252	11.207	.982		10.569	11.457	.358

Note. The best-fitting age polynomial for each sex (1 = linear, 2 = quadratic, 3 = cubic) was added to the hormonal model. Testosterone and estradiol were separately modeled. The variance in the table belongs to the model of age and testosterone, whereas the variance between brackets belongs to the model of age and estradiol. Var = variance; BART = Balloon Analogue Risk-Taking Task; BIS–11 = Barratt Impulsiveness Scale, Version 11; BPA = Buss Perry Aggression; NEO = Neuroticism-Extraversion-Openness.
Bold values are significant at a *p*-level <. 05.

Table 6
Associations Between Relative Change in Testosterone, Estradiol, and Change in Risk-Taking Aspects Between T1 and T3 (Accounting for Baseline Levels at T1)

Measure	Females				Males			
	β	*SE*	R^2	*p*	β	*SE*	R^2	*p*
BART money								
Testosterone	−0.225	1.459	.000	.878	0.652	0.825	.007	.432
Estradiol	1.128	1.914	.004	.557	0.070	2.168	.000	.974
BART explosions								
Testosterone	2.835	1.205	.060	**.021**	0.887	0.791	.014	.265
Estradiol	2.988	1.602	.038	.066[a]	−0.398	2.086	.000	.849
Discounting								
Testosterone	−0.095	0.089	.012	.290	0.101	0.053	.039	.061[b]
Estradiol	0.070	0.119	.004	.556	−0.062	0.141	.002	.659
BIS–11								
Testosterone	2.163	2.896	.006	.457	3.545	1.727	.049	**.043**
Estradiol	2.094	3.861	.003	.589	6.024	3.998	.027	.136
BIS avoidance								
Testosterone	1.420	1.274	.013	.268	−0.373	0.924	.002	.687
Estradiol	−0.173	1.707	.000	.920	2.033	2.119	.011	.340
BAS approach								
Testosterone	−1.275	1.794	.006	.479	−1.392	1.056	.021	.262
Estradiol	−1.437	2.390	.004	.549	2.344	2.446	.011	.341
BPA aggression								
Testosterone	5.080	7.340	.005	.490	−0.124	3.741	.000	.974
Estradiol	−5.125	9.782	.003	.602	2.601	8.617	.001	.764
NEO neuroticism								
Testosterone	1.112	6.420	.001	.863	−0.935	3.013	.002	.757
Estradiol	8.877	8.728	.018	.313	3.525	5.743	.006	.542

Note. BART = Balloon Analogue Risk-Taking Task; BIS–11 = Barratt Impulsiveness Scale, Version 11; BPA = Buss Perry Aggression; NEO = Neuroticism-Extraversion-Openness.
[a]A larger increase in estradiol in females is at trend-level related to a larger increase in BART explosions over time. [b]A larger increase in testosterone in males is at trend-level related to a larger increase in the area under the curve (less discounting) over time.
Bold values are significant at a *p*-level <. 05.

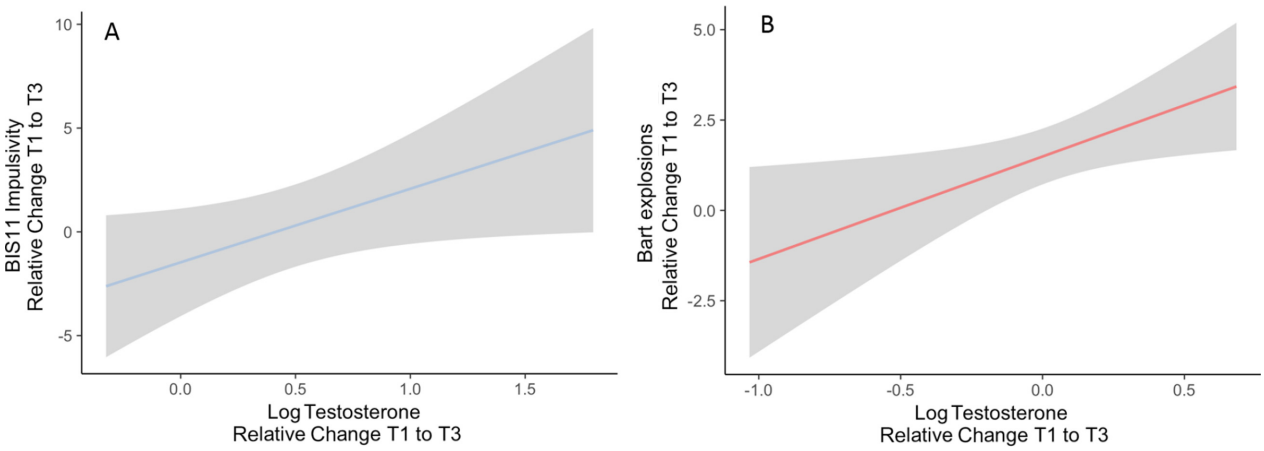

Figure 4. Relative change in testosterone level and change in risk-taking aspects from Time-point 1 to Time-point 3-across 8 to 29 years. Change in male testosterone and change in Barratt Impulsiveness Scale, Version 11 (BIS–11; A) and female testosterone and change in Balloon Analogue Risk-Taking Task (BART) explosions (B). [Color figure can be viewed at wileyonlinelibrary.com]

In girls, pubertal testosterone was also related to increased BIS–11 (p = .024) and increased aggression (p = .034; Table 7). Higher estradiol was at trend-level related to lower BIS avoidance (p = .065) Pubertal testosterone and estradiol in girls were unrelated to BART risk taking, delay discounting behavior and to self-reported behavioral approach and neuroticism (p's > .141).

Finally, in analysis 2b, age-standardized z-scores were calculated for hormonal levels within each sex and each age-bin (11 year-old girls, 11-year-old boys, 12 year-old girls, etc., up to 15 years) to examine whether compared to same-aged peers higher testosterone and/or estradiol levels relate to more risk-taking behavior. The results indicated that in boys, higher testosterone production compared to same-aged peers was related to more explosions on the BART (p = .027; Table 8) and—at trend-level to higher BIS–11 impulsive personality (p = .060) and lower BIS avoidance (.062). Higher estradiol in boys compared to same-aged peers was related to higher BIS–11 impulsive personality scores (p = .007) and higher aggression (p = .039). In girls, higher testosterone production compared to same-aged peers was at trend-level related to higher aggression (p = .053), and higher estradiol was related to lower BIS avoidance (p = .029).

In summary, across the whole sample, higher absolute testosterone levels—above and beyond age effects—were mainly associated with higher impulsive personality and to lower behavioral avoidance in males. A larger increase in testosterone with time was associated with a larger decrease in discounting behavior in males and to a larger increase in risk taking in females. During puberty, more testosterone was related to increased risk taking in boys and higher impulsivity and aggression in boys and girls. Higher pubertal estradiol was also associated with more aggression in boys and lower BIS avoidance in girls.

Discussion

In this study we aimed to decompose the time courses of, and hormonal contributions to, separable risk-taking processes, as assessed with the BART and delay discounting task, as well as self-report risk taking in personality measures, including impulsive personality, approach and avoidance-related personality, impulsive aggression, and neuroticism. We hypothesized that BART risk taking as well as self-reported approach behaviors would peak in adolescence, whereas delay discounting and self-reported impulsivity would decrease gradually during adolescence.

Prior studies showed that the BART is a valid index of reward-driven risk-taking behavior (Lejuez et al., 2002), but the developmental trajectory across adolescence was unknown. In this study, we calculated two variables based on the behavior during BART that potentially represent unsuccessful risk taking (number of explosions) and successful risk taking (money earned). We observed that these two variables showed distinct age-related patterns, partly confirming our hypothesis based on our prior cross-sectional study (Peper, Koolschijn, et al., 2013). Specifically, the number of explosions increased into midadolescence, then stabilized to

Table 7
Testosterone, Estradiol, and Risk-Taking Measures Between 11 and 15 Years of Age

	Girls			Boys		
Measure	β	*SE*	*P*	β	*SE*	*p*
BART money						
(Age[1] &) Testosterone	2.95	4.032	.465	0.803	4.727	.866
(Age[1] &) Estradiol	−1.965	4.035	.627	3.955	3.945	.319
BART explosions						
(Age[1] &) Testosterone	0.905	3.833	.814	7.830	4.936	.116
(Age[1] &) Estradiol	−0.492	3.831	.898	−0.183	4.195	.965
Discounting						
(Age[1] &) Testosterone	−0.213	0.326	.516	−0.205	0.429	.634
(Age[1] &) Estradiol	0.082	0.324	.800	−0.198	0.358	.582
BIS–11						
(Age[1] &) Testosterone	25.006	10.922	**.024**	38.267	13.301	**.005**
(Age[1] &) Estradiol	7.768	11.563	.503	27.588	11.160	**.015**
BIS avoidance						
(Age[1] &) Testosterone	−4.117	3.820	0.284	−7.727	5.189	.140
(Age[1] &) Estradiol	−7.281	3.897	0.065[a]	−2.671	4.349	.541
BAS approach						
(Age[1] &) Testosterone	0.465	4.819	.923	5.486	6.843	.425
(Age[1] &) Estradiol	0.166	4.977	.974	−4.180	5.681	.464
BPA aggression						
(Age[1] &) Testosterone	41.902	19.465	**.034**	37.241	27.564	.180
(Age[1] &) Estradiol	−8.072	20.854	.700	40.892	22.681	.075
NEO neuroticism						
(Age[1] &) Testosterone	4.639	14.758	.754	−6.933	16.381	.673
(Age[1] &) Estradiol	−17.480	15.685	.269	16.178	14.839	.279

Note. Age was added as a linear term to both a model with testosterone and to a model with estradiol (i.e., both hormones are modeled separately). BART = Balloon Analogue Risk-Taking Task; BIS–11 = Barratt Impulsiveness Scale, Version 11; BPA = Buss Perry Aggression; NEO = Neuroticism-Extraversion-Openness.
[a]BIS avoidance was at trend-level (p = .065) related to estradiol in pubertal girls.
Bold values are significant at a p-level <. 05.

increase again in early adulthood (although the latter should be interpreted with caution, due to the wide confidence interval in adults). Interestingly, the amount of money won on the task—possibly reflecting "advantageous" risk taking—increased into late adolescence and tended to slightly decline in adulthood. Thus, our data suggest that the developmental pattern of money earned on the task and of the number of explosions follow distinct trajectories. These data support the hypothesis that early adolescents show less efficient (or less strategic) risk taking (i.e., relatively more exploded balloons), which transforms into a more optimal form of risk taking in late adolescence, as evidenced by relatively larger payoffs (Crone, van Duijvenvoorde, & Peper, 2016). These findings are consistent with other studies that have suggested a rise in risk-taking behavior from childhood to midadolescence, especially for "hot" risk-taking tasks that include affective components of decision making (Burnett et al., 2010; Figner et al., 2009; Steinberg et al., 2018).

Delay discounting behavior, a type of impulsive decision making influenced by impatience and reward sensitivity (Steinberg & Chein, 2015), followed a quadratic pattern with age. That is, the ability to delay gratification increased into late adolescence and tended to decline again thereafter. These three-wave longitudinal data fit with cross-sectional work (Scheres, Tontsch, Thoeny, & Sumiya, 2014) and extend our previous study based on two longitudinal time-points (Achterberg et al., 2016). These data could be interpreted as late adolescents showing more tolerance to uncertain probabilities compared to children and adults (i.e., the current task was based on hypothetical rewards, not real rewards; Tymula et al., 2012; van den Bos & Hertwig, 2017).

With respect to personality measures, we found that on the one hand, impulsive personality and

Table 8
Age-Standardized Testosterone and Estradiol Associations With Risk-Taking Measures Between 11 and 15 years

	Girls				Boys			
Measure	β	*SE*	R^2	*p*	β	*SE*	R^2	*p*
BART money								
Testosterone	1.253	3.758	.001	.740	2.889	3.460	.007	.406
Estradiol	−3.063	3.804	.007	.423	3.468	3.749	.009	.357
BART explosions								
Testosterone	3.823	3.669	.010	.300	8.374	3.561	.053	**.027**
Estradiol	−0.358	3.697	.000	.923	0.687	3.989	.000	.864
Discounting								
Testosterone	0.003	0.296	.000	.990	0.045	0.318	.000	.885
Estradiol	−0.155	0.304	.003	.610	−0.071	0.344	.000	.836
BIS–11								
Testosterone	13.780	10.347	.019	.186	18.595	9.794	.039	.060[a]
Estradiol	11.493	10.708	.012	.286	28.916	10.476	.077	**.007**
BIS avoidance								
Testosterone	−4.403	3.529	.017	.215	−7.289	3.866	.038	.062[a]
Estradiol	−8.081	3.652	.050	**.029**	−5.359	4.091	.019	.194
BAS approach								
Testosterone	−2.308	4.500	.003	.609	6.610	4.885	.020	.179
Estradiol	0.850	4.721	.000	.857	−6.062	5.350	.014	.260
BPA aggression								
Testosterone	39.183	20.030	.037	**.053**	11.468	20.088	.004	.570
Estradiol	−11.268	20.388	.003	.582	44.714	21.318	.048	**.039**
NEO neuroticism								
Testosterone	12.979	14.096	.012	.360	−10.578	11.510	.011	.361
Estradiol	−11.007	14.017	.008	.435	18.927	13.432	.025	.163

Note. *Z*-transformations were calculated for testosterone level and 11-year-old boys, 11-year-old girls, 12-year-old boys, etc., up to 15 years of age. BART = Balloon Analogue Risk-Taking Task; BIS–11 = Barratt Impulsiveness Scale, Version 11; BPA = Buss Perry Aggression; NEO = Neuroticism-Extraversion-Openness.
[a]Higher levels of age-standardized testosterone in boys is at trend-level related to increased BIS–11 impulsivity and to lower BIS avoidance.
Bold values are significant at a *p*-level <. 05.

neuroticism increased into midadolescence (albeit most pronounced in boys), followed by a decline in young adulthood. On the other hand, behavioral avoidance-related personality (BIS) increased linearly from childhood to adulthood, which was most pronounced in females. Our findings of longitudinal change in (impulsivity-related) personality characteristics are comparable to earlier studies in adolescents (Pagliaccio et al., 2016) and adults (Ludtke, Trautwein, & Husemann, 2009; Milojev & Sibley, 2017). Behavioral approach (BAS) levels were similarly high in children and adolescents, and decreased into adulthood. The adult decline in BAS converges with reports in other samples (Urosevic, Collins, Muetzel, Lim, & Luciana, 2012) and our own sample based on two time-points (Braams et al., 2015). Although aggressive personality was correlated with impulsive personality and neuroticism, its levels were stable with age, suggesting that (self-reported) aggression is a measure of individual differences rather than developmental differences (Xie, Drabick, & Chen, 2011; but see Meeus, Van de Schoot, Hawk, Hale, & Branje, 2016).

Taken together, it might be argued that adolescents, more so than children, show exploratory behavior and reward sensitivity, but adaptively use self-control for the purpose of reward maximization as they progress through adolescence (Crone & Dahl, 2012). These findings could contribute to the debate about whether risk taking shows linear versus adolescent-specific changes. First of all, the current results show that adolescents show more risk taking than children not only in real-life settings (Defoe et al., 2015), but also in laboratory settings. Some of the measures show a peak in mid to late adolescence and others a cubic rise, but both patterns are consistent with the hypothesis of an adolescent-specific increase in risk taking. Self-reported

aspects of risk taking, such as the behavioral approach system and impulsive personality characteristics, showed a similar adolescent increase. However, on the other side of the spectrum—possibly reflecting aversion to loss or punishment—behavioral avoidance (in girls) and neuroticism also increased with age. These findings also underscore the increase in emotional vulnerability during adolescence (Guyer et al., 2016; Kendall et al., 2015).

Our second aim was to examine the contribution of the sex steroid hormones testosterone and estradiol to risk-taking tendencies during development. Through animal studies it has become clear that sex hormones exert powerful and long-lasting effects on neuronal properties, such as dendritic branching and myelination (for review, see Schultz et al., 2016). Also, the pubertal period has been marked as a sensitive period for steroid hormones to organize brain structure. It is therefore of great importance to examine the effects of adolescent steroid hormone production on typical adolescent behavioral changes (e.g., Herting & Sowell, 2017; Peper & Dahl, 2013; Piekarski et al., 2017). To our knowledge, this is the first longitudinal study that directly addresses the dynamic relations between testosterone, estradiol, and several aspects of risk taking and impulsivity in a large sample of boys and girls spanning the full adolescent period. We predicted that testosterone and estradiol were positively related to approach-related behaviors, but negatively related to avoidance-related behaviors (i.e., BIS/neuroticism), and that this relationship was expected to be most pronounced between the ages of 11–15 years in both boys and girls.

First, we investigated the general developmental pattern of both hormones, both of which were increasing steeply in males and females, albeit less pronounced in females compared to males. While no normative data are available for developmental patterns of sex steroids in this wide age range (including young adults), the general developmental pattern of midadolescent increases complements earlier work (Biro et al., 2014; Khairullah et al., 2014). Our data also indicate a slight female increase in adult estradiol levels. However, the confidence interval is wide and should therefore be interpreted with caution.

With respect to sex steroids and risk-taking tendencies, our hypothesis could partly be confirmed. That is, in both males and females, testosterone levels—and to some extent also estradiol levels—were related to certain aspects of risk taking and impulsivity after a stringent correction for age. Specifically, a larger increase in testosterone over time (and at trend-level also in estradiol) was related to an increase in the number of explosions on the BART in females and to larger increases of impulsive personality in both sexes. Also, in males only, higher testosterone levels related to less behavioral avoidance (neuroticism and BIS punishment sensitivity).

These data replicate the findings from our previous cross-sectional study in adolescents (Peper, Koolschijn, et al., 2013 Schutter et al., 2017) and correspond with findings in other cross-sectional samples (Op de Macks et al., 2016). A possible underlying mechanism could be that testosterone binds to androgen receptors in limbic brain areas, which are implicated in risky behavior (Peper & Dahl, 2013). This might in turn predispose adolescents to greater sensation seeking and/or exploratory tendencies (Crone & Dahl, 2012) as well as lower fear and anxiety (Spielberg et al., 2015). With respect to changes in delay discounting behavior, our data suggest—contrary to our expectations—that a larger increase in testosterone in males was related to less delay discounting over time. To our knowledge, no other developmental study has addressed the association between testosterone and discounting. It has been suggested that—depending on the context—testosterone can act as an "instrumental" hormone (van Honk et al., 2016). Therefore, testosterone might have influenced reward maximization, as measured by the delay discounting task. That is, obtaining a delayed reward comes with a level of uncertainty, and the tolerance to uncertainty might be related to levels of testosterone (Stanton et al., 2011; Zilioli et al., 2014). As the effect size of this finding was small after the stringent age-correction, the results should be replicated in a more restricted age-range, to better distinguish age and hormonal effects.

With respect to the self-report data, we observed that higher testosterone levels in males were associated with fewer behavioral avoidance-related characteristics, such as neuroticism and behavioral inhibition/punishment sensitivity (BIS-scale). The potentially "suppressing" effect of testosterone on behavioral avoidance or punishment sensitivity is similar to earlier reports, including lowered fear and anxiety-like traits during adolescence (Enter, Terburg, Harrewijn, Spinhoven, & Roelofs, 2016; Schutter et al., 2017). Interestingly, both neuroticism and behavioral inhibition/punishment sensitivity were negatively correlated with risk taking and delay discounting. These findings further illustrate how testosterone may influence multiple aspects of risk taking and personality in different ways.

An important question we aimed to address was whether testosterone showed specific effects in puberty, indicating a possible driving role of pubertal hormones. Therefore, next to the full age-range, we also analyzed the associations with testosterone in a puberty-specific age group, as previous work in normatively developing adolescents suggests that the production of pubertal testosterone rises steeply between ages 11 and 15 years (Goddings et al., 2014; Herting et al., 2015; Spielberg et al., 2015). In contrast to our hypothesis, the results within this restricted pubertal sample mostly showed overlapping results compared to the full developmental sample, with higher testosterone in boys and girls being associated with more (BIS–11) impulsivity. Moreover, a higher production of testosterone *compared to same-aged peers* was related to more explosions on the BART in boys, to higher levels of self-reported impulsivity in both boys and girls and to more aggression in girls. Finally, both higher testosterone in boys as well as higher estradiol levels in pubertal girls were related to lower behavioral avoidance (BIS), compared to same-aged peers. This negative association between estradiol and punishment sensitivity is supported by animal studies that reported a causal effect of estradiol administration, which reduced fear and increased behavioral exploration (Walf & Frye, 2007). Furthermore, this negative association fits with data showing that relatively high levels of estradiol during the luteal phase of the menstrual cycle are related to lower punishment learning (Diekhof & Ratnayake, 2016).

This study had several strengths including a longitudinal design, a wide age range and large sample size, as well as consistency across measures over time. However, the following limitations should be considered when interpreting the current findings. First, participants were paid a flat fee for participation and behavior was not incentivized per trial. For example, since participants were not actually paid the amount of money they won on the BART could have increased their level of risk taking, as their behavior on the task did not have real consequences. Therefore, performance on the BART in this study might not have reflected real-life risk-taking tendencies of the participants. A similar limitation must be taken into account for the (hypothetical) delay discounting task, although performance on hypothetical and actual discounting tasks (with real rewards/delays) is highly correlated (Scheres et al., 2014).

Second, adolescent risk taking is influenced by the social context, such as the presence of peers or parents (Chein, Albert, O'Brien, Uckert, & Steinberg, 2011; Smith, Chein, & Steinberg, 2013; Telzer et al., 2015). Our laboratory tasks and questionnaires were completed alone, which could have affected their performance and the comparability to real-life risk-taking behavior, which often occurs in a social context. Future studies should examine in more detail the effects of contextual factors on behavior.

In conclusion, in this three-wave longitudinal study, we demonstrated nonlinear age-related patterns in risk-taking behavior and approach-related personality characteristics, combined with an increased ability to delay gratification. Increases in testosterone levels (and to a lesser extent also estradiol levels) in boys and girls were found to increase risk-taking behavior and impulsive personality, both during puberty as well as across the entire period of adolescence. Moreover, higher testosterone levels in males were related to fewer avoidance-like personality characteristics (e.g., neuroticism and punishment sensitivity). It can therefore be argued that salivary testosterone can be used as a biological marker for developmental processes as well as for individual differences (whereas estradiol seems to be a marker of individual differences in risk taking [personality] only). Finally, this study confirms the nonlinear developmental pattern of risk-taking behavior and suggests that testosterone might accelerate this maturational process.

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