Why teens take risks ... : a neurocognitive analysis of developmental changes and individual differences in decision-making under risk

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A heart rate analysis of risky decision-making, reward sensitivity, and outcome monitoring in adolescence

The ability to evaluate risks, and monitor choices and their outcomes are important components of mature decision-making. Immature decision-making and heightened sensitivity to rewards are thought to underlie adolescent risky behavior. We tested for the development of decision-making abilities in adolescence, and measured heart rate (HR) changes to gain insight in the temporal dynamics of decision-making. Participants from three age groups (11-12-year-olds, 14-15-year-olds, and 17-18-year-olds) chose between high-risk and low-risk probabilistic gambles with varying magnitudes of reward. Risk-taking decreased with age, and HR data showed that 11-12-year-olds showed a heightened sensitivity to rewards. Age related changes in HR responses were related to the anticipation of the outcome of risky decisions, not to the evaluation of outcomes. These findings support the hypothesis that a heightened sensitivity to rewards contributes to adolescent risk-taking, and suggest that developmental changes are related to the perception of risks, not their consequences.

5.1 Introduction

The slow development of decision-making has been well documented. One of the key aspects of mature decision-making is the ability to identify and avoid immediate and long-term undesirable consequences of actions, or in other words, avoid excessive risk (Beyth-Marom, 1993; Garon & Moore, 2004). Many studies have shown that children's decisions are more likely to be risky and oriented towards short-term rewards compared to adults' decisions (Blakemore & Choudhury, 2006; Boyer, 2006; Crone, Bullens, Van der Plas, Kijkuit & Zelazo, 2008; Lejuez, Aklin, Zvolensky & Pedulla, 2003; Reyna & Ellis, 1994), and that the ability to take the long term consequences of choices into account improves until late adolescence (Hooper, Luciana, Conklin & Yarger, 2004; Overman et al., 2004). Adolescence is a developmental phase in which many problems are related to risky behavior, for example involvement in accidents, experimentation with illicit drugs or alcohol, and problems in school. Immature decision-making abilities are thought to underlie these problems (Arnett, 1992; Rivers, Reyna & Mills, 2008; Steinberg, 2004).

The study of decision-making development and its contribution to risk-taking is complicated because age differences in risk-taking have been difficult to measure using laboratory tasks (see Boyer 2006 for a review). The results of previous studies using laboratory tasks of risk-taking seem inconsistent with the idea that decision-making abilities are immature in adolescence. For example, when the demands on learning and working memory are minimized by making outcome values and associated probabilities explicit, no age differences in decision-making behavior are found from age 8 to 30 (van Leijenhorst, Westenberg & Crone, 2008). Other developmental studies have shown that 5-6 year old children show an understanding of probabilities (Acredolo, O'Connor, Banks & Horobin, 1989; Schlottmann, 2001). However, in real life situations, decisions and their outcomes have to be monitored and this information has to be used to optimize behavior. The Iowa Gambling Task (IGT) was designed to mimic these real life requirements (Bechara, Damasio, Damasio & Anderson, 1994), in this task participants have to learn form the outcomes of their decisions which choice options are risky. Developmental studies using this paradigm have shown an increased ability to learn to avoid the risky options throughout adolescence (Crone & Van der Molen, 2004; Hooper et al., 2004). Importantly, these behavioral studies have limited ability to inform us whether developmental changes in performance monitoring occur around the moment decisions are made, when the outcomes of decisions are processed, or during both these moments. Therefore, it remains unclear what aspects of child and adolescent decision-making contribute to risky behavior.

Psychophysiological measures can give further insight into the development of performance monitoring. Event-related potentials (ERPs) have been used to examine the temporal dynamics of central nervous system processes related to evaluating the outcomes of risky decisions. Gehring & Willoughby (2002) showed that negative outcomes of 2-choice gambles result in a frontally located negative brain potential, which peaks approximately 265 ms after the presentation of the negative outcome. They concluded that this ERP response, referred to as the Medial Frontal Negativity (MFN), was specific for negative outcomes, because it was not affected by information which signaled that participants had chosen the wrong gamble (i.e., when the alternative choice would have resulted in even a greater loss). This MFN potential has the same temporal dynamics as the feedback-related negativity (FRN), a brain potential which is elicited by feedback indicating an incorrect responses (Holroyd & Coles, 2002). The FRN is also associated with response uncertainty or response conflict and with the detection of errors. Localization studies examining the underlying neuroanatomical source of these negative brain potentials have reported that the resolution of negative or erroneous outcomes is located in or near the anterior cingulate cortex (ACC) (Miltner et al., 2003; Ridderinkhof, Ullsperger, Crone & Nieuwenhuis, 2004). Studies on the development of error-related ERP responses related to performance monitoring, suggest that error-related ERP responses continue to develop well into adolescence (Davies, Segalowitz & Gavin, 2004a, 2004b; Ladouceur, Dahl & Carter, 2004). Even though these developmental studies focused on response-related error monitoring (internal evaluation) and not on feedback-related error monitoring (external evaluation), the results lead to the hypothesis that performance monitoring is still immature in adolescents.

Performance monitoring is also reflected in autonomic nervous system changes. It is well documented that beat-to-beat heart rate changes are related to information processing demands. Heart rate decelerates when attention has to be directed to detect information relevant to the task that is performed, and accelerates when that information is processed or used actively in working memory (Lacey & Lacey, 1974; Van der Molen, Somsen & Orlebeke, 1985). These cardiac changes are thought to result from a parasympathetic system which affects the heart very quickly resulting in a change in heart rate within tens of milliseconds (Somsen, Jennings & Van der Molen, 2004), and which is related to self regulatory cognitive functions (Posner & Rothbart, 1998). Heart rate typically slows in anticipation of a stimulus or a behavioral response, followed by an acceleratory recovery to baseline (Jennings & Van der Molen, 2002). Processing of negative performance feedback typically results in a delay of this return to baseline, as reflected in a lengthening of the inter beat interval, or heart rate deceleration (Somsen, Van der Molen, Jennings & Van Beek, 2000; Van der Veen, Van der Molen, Crone & Jennings, 2004). This lengthening suggests that heart rate is sensitive to the valence (negative/positive) of performance feedback (Somsen et al., 2000; Van der Veen et al., 2004). Similarly, the anticipation of performance feedback results in cardiac slowing, and this slowing is prolonged when outcomes are different (better or worse) than expected (Crone, Bunge, de Klerk & Van der Molen, 2005a; Crone, Bunge, Latenstein & Van der Molen, 2005b; Crone, Somsen, Van Beek & Van Der Molen, 2004b). This study suggests that heart rate changes not only respond to the valence of the feedback, but reflects a performance monitoring system that responds differentially to feedback that is informative for optimizing task performance (Crone et al., 2003; Somsen et al., 2000).

In a gambling context, we have shown that the amount of rewards associated with decisions affects the pattern of cardiac changes (Crone et al., 2005a). In this study, young adult participants gambled for low or high amounts of money and we studied the cardiac changes during the anticipation and evaluation of the outcomes of these gambles. As expected, we observed heart rate slowing during periods when participants were anticipating the outcomes of gambles, and this slowing was larger when more money was at stake. Further, heart rate slowed more following feedback for high reward gambles relative to low reward gambles, independent of whether the feedback indicated a loss or a gain. These results show that beat to beat heart rate changes are a sensitive index of both the anticipation of the outcomes of uncertain decisions and of the monitoring of these outcomes (Crone & Van der Molen, 2007), and the high temporal resolution enables the differentiation of these response related and feedback related cognitive processes.

In prior work, we have shown that heart rate changes can be used in children and adolescents (Crone & Van der Molen, 2007; Van Leijenhorst, Crone & Van der Molen, 2007). In a study using the IGT paradigm, heart rate responses in children of three age groups (8-10, 12-14, 16-18 years old) were assessed when they were anticipating and evaluating the outcomes of choices (Crone & Van der Molen, 2007). Participants were instructed to make choices from four locations on a computer screen, and each location was associated with a high or a low reward. Over the course of the task, participants had to learn that those locations which resulted in high reward also resulted in high punishments, leading to long-term loss. In contrast, those locations which resulted in low reward also resulted in low punishment, leading to long-term gain. The feedback results were the same as previously reported in adults (Bechara, Tranel, Damasio & Damasio, 1996; Crone et al., 2004b). That is, losses resulted in larger cardiac slowing than gain, and the slowing was larger when the loss was greater or when the loss was unexpected (Somsen et al., 2000). These results show an age related difference in the ability to anticipate negative outcomes. Whereas 16-18-year-olds, comparable to adults showed differentiated autonomic responses prior to risky outcomes, the younger age groups showed autonomic responses prior to all outcomes. These results suggest that while the processing of outcomes is similar for all age groups, the anticipation of these outcomes is immature in adolescence. It should be noted that the learning requirements of the IGT put demands on working memory capacity (Bechara, Damasio, Tranel & Anderson, 1998), and it is therefore unclear whether the observed differences were related to anticipating the outcomes of risky decisions and the way in which risks are perceived, or to differences in working memory capacity and the ability to learn from the outcomes of choices.

The goal of the present study was to gain insight into adolescent risk-taking by examining the development of decision-making. Specifically, we used measures of heart rate changes to differentiate the relative contributions of the development of processes related to the anticipation and evaluation of gamble outcomes. Three age groups participated in the present study (11-12, 14-15, 17-18-years old), reflecting different stages of adolescent development (Steinberg, 2005; Westenberg, Hauser & Cohn, 2004). All participants performed a modified version of the Cake Gambling Task (van Leijenhorst et al., 2008) optimized for use in combination with autonomic measures. Participants were asked to repeatedly choose between a low-risk and a high-risk gamble, and were instructed to try and win as many credits as possible over the course of the experiment. Stimuli were cakes composed of six wedges in two colors, pink (strawberry flavor) and brown (chocolate flavor) according to a 1:5, 2:4 or 3:3 probability distribution. As a consequence, choosing the high-risk gamble was associated with a 17%, 33%, or 50% chance of winning. We manipulated the number of credits that was associated with the different decisions; in such a way that 3 or 7 credits were associated with the high-risk gamble, and 1 credit was always associated with the alternative low-risk gamble. We expected the behavioral results to resemble those found in our previous study using this paradigm (van Leijenhorst et al., 2008), in that the percentage of choices for the high-risk gamble would increase with the probability that this choice results in a win, and with the number of credits that were associated with it.

We focused our analyses of the psychophysiological changes on the comparison of low-risk versus high-risk gambles, associated with a low or high number of credits, based on research described above that suggests that the ability to estimate probabilities matures well before adolescence. First, we examined whether cardiac changes related to outcome anticipation following high-risk gambles would differ from low-risk gambles, and whether high-risk gambles for high reward would differ from high-risk gambles for low reward. Based on prior work, we expected that cardiac slowing associated with outcome anticipation would be larger for high-risk compared to low-risk gambles, and larger for high reward than low reward gambles (Crone et al., 2005a). Prior studies have demonstrated that the psychophysiological response in anticipation of uncertain outcomes becomes more differentiated with age during adolescence (Crone & Van der Molen, 2007), in the present study we therefore examine differences in anticipatory autonomic responses in distinct phases of adolescence, using a task with minimal working memory and learning demands.

Second, we examined cardiac changes in response to the resolution of high-risk and low-risk gambles. We expected cardiac slowing in response to the outcomes of trials (Crone et al., 2003; Hajcak, McDonald & Simons, 2003; Van der Veen et al., 2004), and we expected this slowing to be larger when the outcome was unexpected (Crone et al., 2003). The current study allowed us to test whether heart rate responsiveness in adolescence is sensitive to the valence of the feedback (van der Veen et al., 2004) or to the informative value provided by the feedback, for example when the feedback violates expectations (Somsen et al., 2000). Under the hypothesis that heart rate changes reflect the informative value of feedback, cardiac slowing was expected to be larger when high-risk gambles resulted in gain, and when low-risk gambles resulted in loss. Previous work showed that cardiac changes in response to the outcome of gambles did not show age related change (Crone & Van der Molen, 2007). Based on these findings, we did not expect age related differences in autonomic nervous system responses to loss and gain outcomes in the present study.

5.2 Method

5.2.1 Participants

Fifty adolescents distributed among three age groups participated in the experiment. Data from 7 participants had to be excluded from the analyses as a consequence of technical difficulties. Data from sixteen 11-12-year-olds (Mean = 12.22, *SD* = .55, 8 girls), sixteen 14-15-year-olds (Mean = 15.09, *SD* = .45, 7 girls), and eleven 17-18-year-olds (Mean = 18.07, *SD* = .53, 4 girls) were included in the final sample. All participants were recruited by contacting local schools in the Leiden area (the Netherlands), and selected with the help of their teachers. Written informed consent was obtained from all participants aged 18 and older. For participants younger than 18, written informed consent was obtained from a primary caregiver. In addition all participants gave verbal assent prior to inclusion in the study. Participants with learning or behavioral disorders or a history of neurological impairments, as indicated by their parents or teacher were not selected to take part in the study. No detailed information regarding parental income, parental education level, or family size of the participants was obtained. However, participants were mostly Caucasian, and came from families with average or above average SES. All procedures were approved by the Leiden University Department of Psychology Internal Review Board.

All participants completed the Raven Standard Progressive Matrices task (Raven SPM) in order to provide an estimate of participants' general intellectual ability (Raven, Raven & Court, 1998). A one-way analysis of variance (ANOVA) performed on the estimated IQ scores revealed a significant difference between the three age groups ($F(2, 41) = 5.03$, $p = .01$). Post hoc Tukey tests showed that 11-12-year-olds' scores (Mean IQ = 119.19, *SD* = 6.57) were significantly higher than 14-15-year-olds' scores (Mean = 108.73, *SD* = 11.87). Both age groups did not differ statistically from 17-18-year-olds' average scores (Mean IQ = 112.00, *SD* = 8.94). Importantly, estimated IQ scores for all age groups fell within the average to high average range. To test whether IQ differences influenced gambling behavior we correlated estimated IQ scores and the average percentage of risky decisions, and did not find a significant correlation ($r = .007$, $p = .97$), in addition after we excluded 5 participants (4 middle adolescents, and 1 older adolescent) with estimated IQ scores below 100, IQ scores no longer differed between age groups (Mean IQ scores were 119.19 (*SD* = 6.57), 114.00 (*SD* = 7.29), and 113.40 (*SD* = 8.06) for 11-12, 14-15, and 17-18-year-olds respectively) ($p > .05$). None of the results were affected by exclusion of these participants. Together these findings convince us that IQ as measured with the Raven SPM is not a factor in the reported effects.

5.2.2 Cake Gambling Task

In the Cake Gambling Task participants repeatedly choose between two gambles which are presented visually in order to make the choice options understandable to children. On every trial a stimulus depicting a cake composed of six wedges was presented at the center of the screen. The wedges could be brown or pink, and participants were told that these colors represented chocolate (brown) or strawberry (pink) flavored pieces of cake. The proportion of pink:brown wedges was varied systematically across trials to be 1:5, 2:4, or 3:3. In addition to varying this proportion, both colors were associated with a number of credits that formed the stake in the gambles. For each cake, one of the colors was associated with 1 credit, and the other color was associated with 3 or 7 credits. For the 1:5 and 2:4 cakes, 3 or 7 credits were always associated with the minority color, for the 3:3 cakes the 3 or 7 credits could be associated with both colors. A brown and pink square containing a number of coins, indicating the number of credits that was associated with each flavor, and a question mark were presented below each cake. On each trial the computer randomly selected one of the wedges, which resulted in a 17% (for 1:5 cakes), 33% (for 2:4 cakes) and 50% (for 3:3 cakes) chance of the color associated with the higher number of credits to be chosen by the computer. To ensure that the youngest participants would understand this instruction, all participants were told to think of the computer as someone who picks a piece of cake with their eyes closed.

Each trial started with a 500 ms fixation cross, followed by the presentation of a cake stimulus (see Figure 5.1). At this point, participants were instructed to decide and indicate with a button press which of the two possible gambles they wanted to accept. A low-risk gamble was a gamble in which one credit was at stake (which could be won or lost dependent on the outcome) whereas a high-risk gamble was

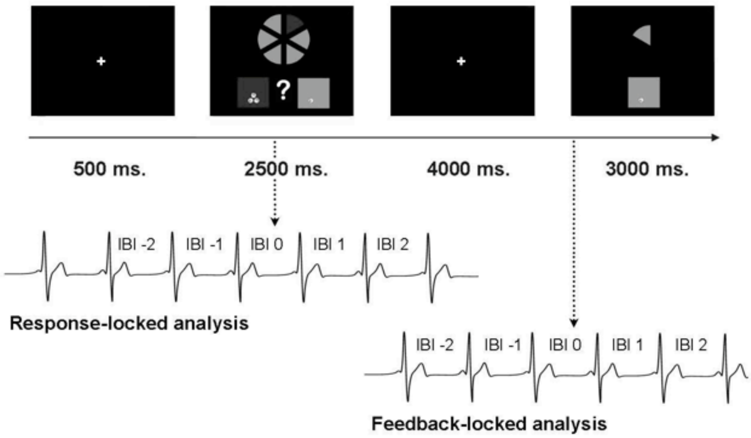

Figure 5.1 *Example of a trial in the Cake Gambling Task showing the 1:5 probability condition. Choosing the high-risk gamble (the least probable option - darker color) results in a 3 credit stake, whereas choosing the low-risk gamble (the most probable option – lighter color) results in a 1 credit stake. In this example the most likely option was chosen and 1 credit was won. Participants were given 2 Euro to play with at the beginning of the experiment. Trial timing and associated Inter beat intervals are shown. See text for further details. For the response locked analysis the average IBI length of IBI -2 was 772.01 ms (SE = 16.13); for the feedback locked analysis this was 763.94 ms (SE = 15.53).*

a gamble in which 3 or 7 credits were at stake (which could be won or lost). In the 1:5 and 2:4 conditions, low-risk gambles had a higher chance of resulting in a win, whereas high-risk gambles had a lower chance of resulting in a win. In the 3:3 conditions, the probabilities for high-risk and low-risk gambles were the same, and only the amount of credits at stake differed. The stimulus remained on the screen for 2500 ms and participants had to make their response within this time period with the index and middle finger of their dominant hand. The stimulus and response were followed by a 4000 ms period during which a fixation cross was presented and participants anticipated the outcome of the gamble that they had chosen. This time allowed for analysis of heart rate and skin conductance changes related to the decision and outcome anticipation phase of the trial. Following this fixation period a feedback stimulus was presented for 3000 ms. The valence of the feedback participants received was the result of the combination of the computer's random choice for either pink or brown and the participant's decision for the gamble associated with either pink or brown. If these two matched, participants received feedback indicating that they won the credits associated with the gamble they had chosen, and these credits were added to the total points score. If they did not match, participants received feedback indicating that they lost the credits associated with the gamble they had chosen and these credits were subtracted from the total points score. Participants were instructed to try to win as many credits as possible on every trial.

5.2.3 Psychophysiological Measures.

During performance of the Cake Gambling Task, participants' electrocardiogram (ECG), skin conductance levels (SCL) and respiration were continuously recorded using a Biopac MP150 system. The ECG was recorded from three electrodes, attached via the modified lead-2 placement. SCL was recorded using a constant voltage (0.5 V) with two electrodes attached to the middle and index fingers of participants' non dominant hand. Respiration was recorded using a temperature sensor placed under the nose. ECG signals, SCL and respiration signals were sampled and recorded at a rate of 400 Hz. Inter Beat Intervals (IBIs) were computed based on the ECG signals and were visually screened for physiologically impossible readings and artifacts, IBI scores which were more than 2 SD removed from the mean were taken out of the analysis using an algorithm developed in our laboratory. It should be noted that a lengthening of the IBI, or a larger IBI value indicates a slowing of heart rate. The results of the skin conductance and respiration measures are not presented in this report.

5.2.4 Procedure

All participants were tested individually in a quiet room. Stimuli were presented in color against a black background on a 17-inch laptop computer screen placed at a distance of approximately 70 centimeters from the participant. Preceding the task participants were given verbal instructions and were shown examples of trials and feedback displays. Following this instruction, all participants performed 21 practice trials on the laptop computer. Care was taken that all participants understood the instructions after practice.

At the start of the task all participants were given 2 Euro to gamble with; they were told that dependent on the number of credits they would win over the course of the task, they could lose, win or double the 2 Euro. The Cake Gambling Task consisted of 168 trials presented in four blocks of 42 trials and took approximately 40 minutes to complete, including instructions and 3 short breaks. The total points score was shown during the three breaks and at the end of the task. The colors pink and brown corresponded to the index and middle fingers of participants' dominant hand. This mapping was counterbalanced between participants to control for possible key preference, and color-credit associations were counterbalanced within subjects to control for a possible color preference. The Raven SPM (approx. 25 minutes to complete) was administered in the classroom within two weeks following the experimental task. After completion of the experiment participants were thanked for participation, and all were paid 4 Euro.

5.3 Results

The results are described in 2 sections; the first section describes the behavioral results, the second section describes the heart rate results. To correct for non-equal variances in the analyses with heart rate as within-subject factors, degrees of freedom were adjusted using the Huynh–Feldt correction.

5.3.1 Cake Gambling Task performance: Risk-taking

Participants' performance was examined by computing the percentage of choices for high-risk gambles for every combination of the probability of winning and the amount of credits. In addition, mean reaction times were recorded. Choices for high-risk gambles were defined as those trials for which participants chose the 3 or 7 credits gamble over the 1 credit alternative, even though this choice was associated with a smaller (1:5, 2:4) or equal (3:3) probability of resulting in a win. Choice data were submitted to repeated measures ANOVAs with Age Group (11-12-year-olds vs. 14-15-year-olds vs. 17-18-year-olds) as between-subjects factors and Probability (1:5 vs. 2:4 vs. 3:3) and Credits (3 or 7) as within-subjects factors. This analysis resulted in main effects of Credits (F(1, 40) = 26.11, p < .001), Probability (F(2, 80) = 20.65, p < .001), and a Probability x Credits interaction (F(2, 80) = 9.47, p < .001); participants were willing to choose the high-risk gamble more often when 7 credits could be won (Mean = 52.75 %, SE = 2.71) compared to when 3 credits could be won (Mean = 33.67 %, SE = 3.46), and more often when the probability of winning was 2:4 (Mean = 46.67 %, SE = 2.29) or 3:3 (Mean = 48.31%, *SE* = 2.60) relative to when it was 1:5 (Mean = 34.66 %, SE = 3.45). The latter effect was amplified in the 7 credits condition relative to the 3 credits condition. No main effect of Age Group (p = .08) or interaction of Age Group with any of the effects reported above was found (all p's > .1), this suggested that risk-taking behavior did not differ between early, middle and late adolescents (see Figure 5.2). However, when age as a continuous variable was correlated with average risk-taking, a negative correlation was found, suggesting less risk-taking in older adolescents. (r = -.36, p = .02). Correlation analyses for each credit condition separately showed that this correlation was only significant in the 3-credit condition (r = -.33, p < .05), not in the 7-credit condition. Together, these results show that younger participants were more willing to choose the high-risk gamble when 3 credits could be gained compared to older participants.

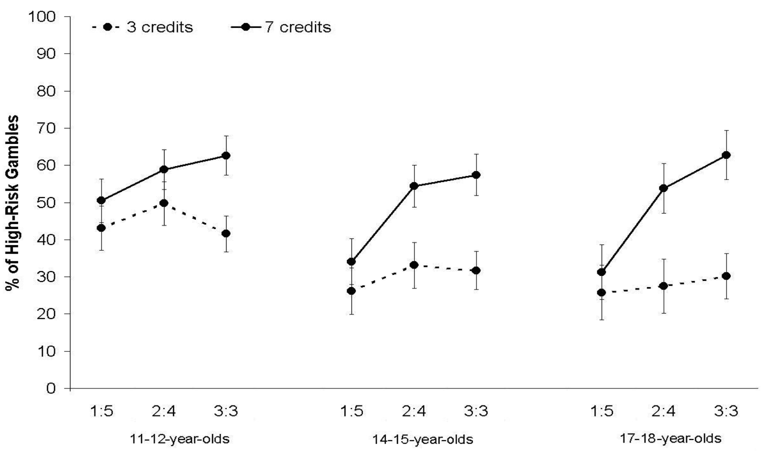

Figure 5.2 *Average percentage of choices for high-risk gambles plotted for 11-12, 14-15 and 17-18-year-olds as a function of the number of credits at stake (3 or 7) for the different probabilities of winning (1:5, 2:4 or 3:3). Error bars represent standard errors*

5.3.2 Reaction Times

Reaction time (RT) data for high-risk and low-risk gambles were submitted to repeated measures ANOVAs with Age Group (3) as between-subjects factors and Probability (1:5, 2:4 or 3:3), Credits (3 or 7), and Choice type (high-risk or low-risk) as within-subjects factors. This analysis resulted in a main effect of Choice type $F(1, 40) = 5.80$, $p < .05$. Choices for high-risk gambles were made faster (Mean RT = 1241.50, SE = 33.15) compared to choices for low-risk gambles (Mean RT = 1302.57, SE = 33.31). There were no other main or interaction effects. Mean RTs for 11-12 year olds (Mean = 1245.03, *SE* = 49.58), 14-15 year olds (Mean = 1306.07, *SE* = 49.58) and 17-18 year olds (Mean = 1265.02, *SE* = 59.79) did not differ ($p = .68$), and the effect of type of choice on RTs did not differ between the age groups ($p = .53$) (RTs per reward condition are reported in Table 5.1).

Table 5.1 *Mean reaction times for 11-12, 14-15, and 17-18 year olds for high-risk (3 or 7 credits) and associated low-risk (1 credit) choices.*

		High-Risk gamble		**Low-Risk gamble**	
		Mean RT	*SE*	*Mean RT*	*SE*
11-12 yrs.	*3 credits*	1241.45	64.06	1279.03	52.96
	7 credits	1188.67	62.61	1270.96	58.43
14-15 yrs.	*3 credits*	1247.77	64.06	1317.32	52.96
	7 credits	1339.04	62.61	1320.13	58.43
17-18 yrs.	*3 credits*	1226.24	77.26	1317.13	63.88
	7 credits	1310.84	75.52	1310.84	70.47

Taken together, consistent with previous reports, participants chose high-risk gambles more often when the probability of winning and the number of credits at stake were higher. Choices for high-risk gambles were made faster than choices for low-risk gambles, suggesting that either the latter required more deliberation time or that the high-risk gambles were selected more impulsively. Consistent with previous studies, differences in performance between the adolescent age groups were small. There were no age differences in performance when a large reward could be won, but when a small reward was associated with the high-risk decision, younger participants were more willing to take the risk and gamble for this reward. In the next section we examine in what way beat to beat changes in heart rate are related to risk-taking behavior and whether there are developmental differences in the sensitivity of this measures to specific phases of the task.

5.3.3 Risk-taking as reflected in Heart rate changes

The results from the analysis of changes in inter-beat-intervals (IBI) are organized in two sections, associated with two distinct phases of decision-making trials. The first phase involves the response and the anticipation of the outcome of gambles. The second phase involves the processing of these outcomes and their evaluation. In the analysis of both phases, we focused on whether the participant chose a low-risk or high-risk gamble, and whether the high-risk gamble option was associated with 3 or 7 credits. The current design and number of observations did not allow us to also distinguish between probability conditions and with reward amounts in one analysis. In addition, analyses on heart rate changes for the different probability conditions informed us that including probability in the analyses did not add to the interpretation of the mechanism underlying developmental changes in decision-making[1]. Therefore all analyses presented below are conducted on values collapsed across probability conditions.

5.3.4 Heart rate changes associated with decision-making and outcome anticipation.

To examine cardiac responses related to participants' choices, seven inter beat intervals (IBIs) were selected around the response, IBIs were computed for high-risk and low-risk gambles separately for the conditions in which 7 or 3 credits were at stake. The IBI concurrent to the response is referred to as IBI 0, and all IBIs were referenced to IBI -2 (which functioned as a baseline) (see Figure 5.1 for a schematic example of cardiac timing relative to trial timing). A larger IBI value

[1] IBIs were computed for high-risk and low-risk gambles for the 1:5, 2:4 and 3:3 Probability conditions separately. A Probability (1:5 vs. 2:4 vs. 3:3) x Choice type (high-risk vs. low-risk) x IBI (1, 2, 3) x Age group (11-12-year-olds, 14-15-year-olds, 17-18-year-olds) repeated measures ANOVA resulted in a main effect of IBI $F\ (2, 80) = 28.03\ p < .001$; heart rate slowed in anticipation of the response (from IBI -2 to IBI 0), followed by an acceleratory recovery to baseline (IBI 1, 2, 3 and 4). The Probability x IBI and the Probability x Choice type x IBI interactions did not reach significance (p's > .5). No differences between the age groups were found for any of these effects (all p's > .2), suggesting that the cardiac changes related to decision-making associated with the different probabilities did not differ between age groups.

indicates a slowing of heart rate relative to this baseline. To show the temporal characteristics of the cardiac changes associated with the response and anticipation of the outcome of gambles, the values of IBI -1, 0, 1, 2, 3, and 4 relative to the value of IBI -2 are plotted in Figure 5.3 for each of the Choice and Credit condition for the different age groups. These plots show the cardiac changes that are typically observed when participants prepare for a significant event; heart rate slows (an increase in IBI length) preceding the response, and subsequently returns to baseline (acceleratory recovery). A preliminary analysis of IBI -2 (Mean length = 772.01 ms, *SE* = 16.13 ms) revealed no significant differences in IBI length between the Age groups (*p* = .28), confirming that this IBI can be validly used as a baseline when comparing task related heart rate changes between the different age groups. Given that there was a 500 ms inter trial interval and the average response times were around 1200 ms, the IBI -2 value for the response locked analysis does not overlap with heart rate changes following feedback on the previous trial (see Figure 5.1).

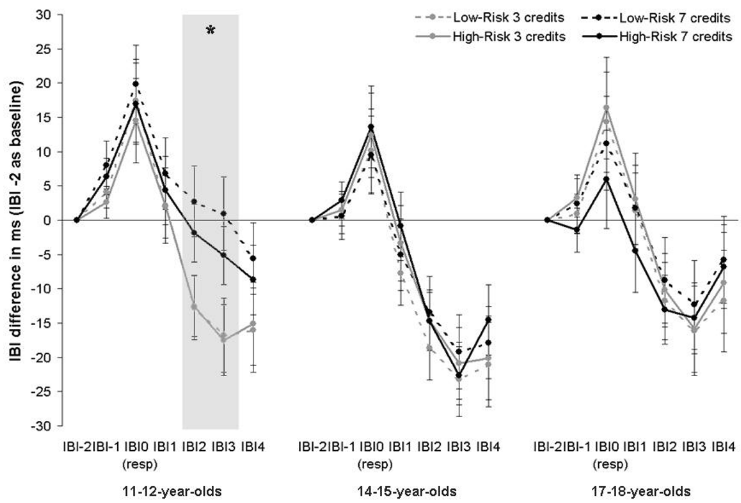

Figure 5.3 Heart rate changes related to high-risk (3 or 7 credits) gambles and associated outcome anticipation plotted for 11-12-year-olds, 14-15-year-olds and 17-18-year-olds. (denotes significant effect at p <.05). Error bars represent standard errors.*

To examine cardiac changes related to participants' choices and the anticipation of outcomes related to those choices, we focus the analysis on the first three IBIs following the response (IBI 1, 2 and 3). IBIs immediately following responses (Somsen, Van der Molen, Jennings & Orlebeke, 1985; Somsen et al., 2000) and feedback presentation (Crone, Somsen, Zanolie & Van der Molen, 2006; Crone et al., 2003) have been found to be most sensitive to HR changes. In addition, the feedback is not presented until after IBI 4, therefore cardiac changes in these IBIs cannot reflect outcome processing. This data selection resulted in a Credits (3 vs. 7) x Choice type (high-risk vs. low-risk) x IBI (1, 2, 3) x Age group (11-12-year-olds, 14-15-year-olds, 17-18-year-olds) repeated measures ANOVA. This ANOVA resulted in a main effect of IBI F (2, 80) = 29.53 $p < .001$, and a Credits x IBI interaction F (2, 80) = 4.25, $p < .05$, which showed that the heart rate responses differed for 3 credit and 7 credit gambles. An interaction with Age group (Age group x Credits x IBI, F (4, 80) = 4.19, $p < .005$), demonstrated that this heart rate pattern was influenced by the Credit condition to a different extent in the different age groups. ANOVAs for the age groups separately showed that for the 14-15-year-olds, and 17-18 year olds heart rate changes related to the response and associated outcome anticipation phase were not significantly influenced by the amount of credits at stake (*p's* > .05). In contrast, for the 11-12 year olds, the acceleratory recovery to baseline following the response was delayed for 7 credit gambles compared to 3 credit gambles (Credits x IBI, F (2, 30) = 6.55, p = .01). Follow up ANOVAs showed that the difference between gambles or 3 and 7 credits for 11-12 year olds was not significant at IBI 1 (p = .52), but was significant at IBI 2 F (1, 15) = 4.93, $p < .05$, and IBI 3 F (1, 15) = 5.90, $p < .05$. Interestingly, this effect was not modulated by whether 11-12-year-olds chose a low-risk or a high-risk gamble (Credits x Choice, p = .16; Credits x Choice x IBI, p = .79); the IBI response during outcome anticipation for the 7 credits relative to 3 credits condition was similarly elevated for both low-risk *and* high-risk gambles.

In sum, even though in all age groups heart rate changes did not differ for high-risk and low-risk choices, there were age related differences in heart rate responses during the outcome anticipation phase. In particular, 11-12 year-olds' heart rate decelerated in anticipation of the outcome of 7 credit gambles compared to 3 credit gambles, independent of whether they had chosen a high-risk or low-risk gamble. In contrast, no differences between conditions were found for the 14-15 and 17-18 year olds. These results suggest increased performance monitoring associated with the anticipation of the outcomes of high reward gambles in early adolescence.

5.3.5 Cardiac changes associated with outcome processing

To examine cardiac responses related to the processing of the outcomes of gambles, seven IBIs were selected around the presentation of the feedback, IBIs were computed for loss and gain trials, following 7 credits high-risk gambles, 3 credits high-risk gambles, and 1 credit low-risk gambles separately. For this analysis the IBI concurrent to the presentation of the feedback is referred to as IBI 0, and all IBIs were referenced to IBI -2 (the second IBI preceding the presentation of the feedback) (see Figure 5.1). Again, to show the temporal characteristics of cardiac changes , the values of IBI -1, 0, 1, 2, 3, and 4 relative to IBI -2, are plotted in Figure 5.4 following gain and loss feedback associated with 1 credit low-risk gambles and 3 or 7 credit high-risk gambles separately. Figure 5.4 shows the expected pattern; heart rate slows in anticipation of the presentation of the feedback, and subsequently returns to baseline. A preliminary analysis of IBI -2 (Mean length = 763.94 ms, *SE* = 15.53 ms) revealed no significant differences in IBI length between the Age groups (*p* = .32), confirming that this IBI could be validly used as a baseline when comparing task related heart rate changes between the different age groups. Similar to the response locked analysis, the IBI -2 value for the response feedback locked analysis does not overlap with heart rate changes following the preceding response (see Figure 5.1).

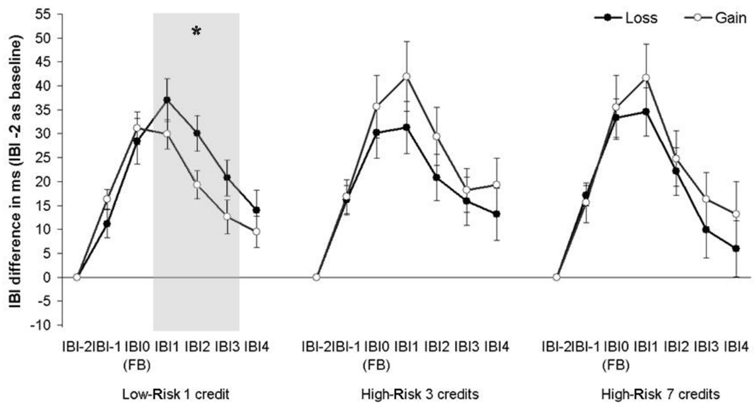

Figure 5.4 *Heart rate responses related to loss and gain feedback for high-risk (3 or 7 credits) and low-risk (1 credit) gambles. (* denotes significant effect at p < .05). Error bars represent standard errors.*

To examine cardiac changes related to the processing of gain and loss outcomes, we focused the analysis on the first three IBIs following the presentation of the feedback (IBI 1, 2 and 3). The feedback remains visible for 3000 ms, therefore cardiac changes in these IBIs are unlikely to reflect anticipation of the next trial. This data selection resulted in a Credits (1, 3, 7) x Feedback (gain vs. loss) x IBI (1, 2, 3) x Age group (11-12-year-olds, 14-15-year-olds, 17-18-year-olds) repeated-measures ANOVA.

The ANOVA resulted in a main effect of IBI, F (2, 80) = 27.30, $p < .001$, and a Credits x Feedback interaction F (2, 80) = 3.17, $p < .05$. No differences between the Age groups were found (all p's > .16), showing that in contrast to the decision phase, cardiac changes related to the outcome of gambles were similar in early, middle, and late adolescence. As can be seen in Figure 5.4, heart rate slowing following the presentation of the feedback was larger for gain relative to loss outcomes of high-risk gambles (3 and 7 credits), whereas heart rate slowing was larger for loss relative to gain outcomes for low-risk gambles (1 credit). These observations were statistically verified with ANOVAs for the credit conditions separately, which showed that the difference in the cardiac response following gain and loss feedback was not significant for 3 credit (p = .21) and 7 credit (p = .28) outcomes, but for low-risk 1 credit outcomes heart rate slowed more following feedback indicating loss (M = 29.29, *SE* = 3.48) relative to feedback indicating gain (M = 20.62, *SE* = 2.87) (main effect feedback; $F(1, 40) = 6.22$, $p = .017$)

In summary, the analysis of autonomic nervous system responses to the outcome of gambles indicate that heart rate slowed following the presentation of the feedback, and that this slowing was larger for loss than for gain feedback following low-risk gambles, whereas following high-risk gambles heart rate changes did not differ significantly for gain and loss. These results show that heart rate is not simply sensitive to the magnitude of gain or loss, but is responsive to the informative value of the feedback. That is, the heart rate response is more pronounced when the outcome is associated with the least predictable outcome (loss following a low-risk gamble). Consistent with prior studies, there were no age differences in the effects of feedback on autonomic nervous system changes (see also Crone & Van der Molen, 2007).

5.4 Discussion

The goal of this study was to gain insight into adolescent risk-taking. We examined adolescents' decision-making in a gambling task, and measured associated beat to beat changes in heart rate. This technique enabled us to differentiate the developmental trajectories of cognitive processes related to the anticipation and evaluation of the outcomes of gambles separately. The paradigm also allowed us to gain insight into age related changes in performance monitoring and the sensitivity to rewards in adolescence.

In a previous behavioral experiment in which we used a paradigm similar to the paradigm used here, we showed that participants ranging in age from 8 to 30 years take both the probability of winning and the number of credits associated with a gamble into account when they make risky decisions (van Leijenhorst et al., 2008). Our behavioral results are consistent with this finding; the percentage of choices for high-risk gambles increased with the associated probability of winning, and was higher for high reward gambles than low reward gambles. Gambling behavior did not differ between the age groups for high reward gambles, however, when a small reward was at stake younger adolescents were more likely to choose a high-risk gamble than older adolescents. This finding could suggest that in early adolescence the potential gain associated with low reward gambles is experienced as more rewarding, or that the potential loss associated with the low reward gamble is experienced as less negative. Heart rate changes can help us gain insight into this hypothesis.

Measures of cardiac changes associated with the decision and anticipation of the outcomes of gambles revealed that, consistent with prior studies (Crone, Jennings & Van der Molen, 2004a; Crone & Van der Molen, 2007; Somsen et al., 2000), decisions were associated with anticipatory heart rate slowing, followed by an acceleratory recovery to baseline in all age groups. These cardiac responses have been shown to reflect anticipatory cognitive processes related to a performance monitoring system (Somsen et al., 1985; Van der Molen et al., 1985). When monitoring increases and allocation of attentional resources is required, heart rate typically shows a phasic slowing (Jennings & Van der Molen, 2002). Contrary to our expectations, no difference in the cardiac response to high-risk or low-risk choices was found in any of the age groups.

If it is the case that the youngest participants chose the high-risk gamble for 3 credits more often than the older adolescents because of the way they experience the potential reward, performance monitoring should be increased, since a focus on the potential reward would make the outcome of their decisions more salient. In contrast, when they chose the high-risk gamble associated with low reward more often because of the way they experience the potential loss, performance monitoring should decrease, because the outcome is less salient. Even though high-risk gambles for low reward were not associated with age related differences in cardiac responses, the recovery to baseline was delayed for the 11-12-year-olds for high reward gambles. Heart rate slowed more for these participants, regardless of whether they had chosen a high-risk or low-risk gamble. This finding suggests that, even though participants in all age groups monitor their decisions and anticipate the outcome of their choices, in early adolescence participants are most likely more sensitive to rewards. In addition, this finding supports the hypothesis that younger participants are more willing to gamble because they experience potential rewards differently.

This interpretation is consistent with recent theories on adolescent risk-taking which suggest that early adolescents show more arousal related to potential rewards (Ernst et al., 2005; Galvan et al., 2006; Van Leijenhorst et al., 2009; Nelson, Leibenluft, McClure & Pine, 2005). In addition, self-regulatory, or executive skills develop slowly (Huizinga, Dolan & Van der Molen, 2006; Posner & Rothbart, 1998), the larger response to high reward gambles could reflect 11-12-year-olds' immature ability to regulate the arousal they experience in response to the potential reward. An alternative explanation is that because of the slow maturation of executive skills, 11-12-year-olds experience the task differently. They could, for example, find it more difficult to understand that the outcomes of gambles are randomly chosen and that they can not influence the trial sequence. This could result in increased performance monitoring.

Heart rate has also been found to be sensitive to performance feedback, showing more slowing when outcomes are more relevant (Crone et al., 2005a; Crone et al., 2005b). The outcome of gambles were associated with heart rate slowing as well; this slowing was most pronounced for unexpected feedback (losing following a low-risk gamble). Consistent with the findings from our prior studies, heart rate was sensitive to the *informative* value of the feedback and not to the valence of the outcome in itself (Crone et al., 2003; Van Leijenhorst et al., 2007). This data pattern again supports our hypothesis that heart rate responses reflect cognitive processes related to an executive control system (Jennings & Van der Molen, 2002; Somsen et al., 2000). No age related differences were observed during the feedback evaluation phase of the task. In this gambling task in which working memory requirements were minimal, and participants did not have to learn from the outcomes of their decisions, heart rate changes showed developmental change until mid adolescence during the anticipation phase of trials, but did not differ between age groups during the outcome processing phase. This finding is consistent with previous studies (Crone & Van der Molen, 2007; Somsen et al., 2000), showing that developmental change in performance monitoring is related to the anticipation of outcomes, not to the processing of outcomes. Moreover, this finding suggests that it is unlikely that adolescents engage in risky behavior because they experience the outcome of their choices differently from adults, but because they weigh the potential reward differently when they make a decision. In early adolescence, participants seem more sensitive to potential rewards. This interpretation fits well with recent theories on adolescent risk-taking based on new insights from studies on functional brain development. These studies show that reward related brain regions (e.g. the ventral striatum) show an enhanced response in adolescence (Ernst et al, 2005; Galvan et al., 2006; Van Leijenhorst et al., 2009), whereas brain regions which are important for cognitive control (e.g. the lateral prefrontal cortices) do not mature until well into young adulthood (Casey, Giedd, & Thomas, 2000; Giedd, 2004; Gogtay et al., 2004). These immature cognitive control abilities paired with the increased sensitivity to reward, are thought to bias adolescents towards risk-taking (Casey, Getz & Galvan, 2008; Ernst, Pine & Hardin, 2006; Steinberg, 2004).

5.4.1 Limitations and future directions

The laboratory context of this study also resulted in several limitations which should be addressed in future studies. First, optimization of the task for autonomic recordings resulted in relatively slow presentation of the stimuli, which made the task less comparable to real-life risk situations. Future studies could further examine the relation between decision-making in a task context and real life risky behavior by looking for correlations with self report measures of risky behavior. In addition future work could look at the role of performance monitoring as reflected in autonomic nervous system changes by examining the relation between cardiac changes on early trials and decision-making on later trials. Nevertheless, we found a decrease in risk-taking with age, and different reward related anticipatory cardiac responses in the youngest age group. Second, even though participants played for real money, the amount was relatively small (maximum of 4 Euro gain), and gambles were associated with a high or low number of abstract credits. This may have influenced the way in which the different age groups approached the task. While the pattern of heart rate changes suggests that all participants were attentive and were motivated throughout the experiment, 4 Euro could be a more salient reward for participants in the youngest age group. The question how comparable rewards are to participants of different ages cannot be answered with this study, but will have to be addressed in the future. Future studies could explore the subjective emotional reactions of participants to gain insight into their experience of the task. Finally, the brain-based explanations are not based on real brain assessments but are inferred based on the psychophysiological manifestation during separate phases of risk-taking. This approach reveals developmental changes in autonomic nervous system responses to reward in a gambling task, and informs neuroimaging studies on the neural mechanisms of adolescent risk-taking that are currently being conducted in our and other laboratories.

5.4.2 Conclusion

This study contributes to the literature on adolescent decision-making by describing its psychophysiological manifestation in terms of heart rate changes, and providing insight into the temporal resolution of decisions and associated age related differences. The results from this study suggest that developmental differences in reward sensitivity underlie increased risk-taking in adolescence. In particular, the response to rewards during the anticipation of the outcome of risky decisions changes with development, not the response to actual outcomes. These changes could be interpreted as slow maturation of self-regulatory functions which inhibit reward related arousal (Posner & Rothbart, 1998), and are supported by neuroimaging studies which have reported an adolescent specific enlarged response in reward related brain regions in anticipation of outcomes (Ernst et al., 2005; Galvan et al., 2006). Future studies should examine how the development of these systems relates to adolescent risky behavior as it is observed in real-life.