

Development of Decision Making in School-Aged Children and Adolescents: Evidence From Heart Rate and Skin Conductance Analysis

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Age differences in decision making indicate that children fail to anticipate outcomes of their decisions. Using heart rate and skin conductance analyses, we tested whether developmental changes in decision making are associated with (a) a failure to process outcomes of decisions, or (b) a failure to anticipate future outcomes of decisions. Children aged 8-10, 12-14, and 16-18 years performed the Hungry Donkey task, a child version of the Iowa Gambling Task, while heart rate and skin conductance activity were continuously recorded. Children aged 16-18 learned to make advantageous choices over task blocks faster than the two younger age groups. Age differences were present for anticipation-related autonomic activity but not outcome-related autonomic activity. The results are interpreted vis-à-vis models of prefrontal cortex maturation.

Many decisions in daily life are made under uncertain circumstances and therefore require deliberation about possible future consequences. Future outcomes cannot always be easily predicted, therefore, successful decision making requires deliberation about experienced, as well as expected, outcomes and feelings. Across school-aged development and adolescence, there are large changes in decision-making patterns, or the ability to anticipate future outcomes of choices. These are mainly reflected in a reward-oriented or risky response pattern in young children followed by more conservative decision making in older children and adults (Blakemore & Choudhury, 2006; Boyer, 2006). For example, children and adolescents between the ages of 8 and 18, relative to adults, engage in risk-taking behavior in “real-life” circumstances (Arnett, 1999; Laird, Pettitt, Bates, & Dodge, 2003), as well as in their performance on laboratory tasks, such as the Balloon Gambling Task (Lejuez, Aklin, Zvolensky, & Pedulla, 2003), probability risk-taking tasks (Reyna & Ellis, 1994), and neuropsychological gambling tasks (Hooper, Luciana, Conklin, & Yarger, 2004; Overman et al., 2004).

Decision-making research has benefited from recent developments in neuropsychological and neuroimaging studies. These studies have demonstrated that the ventromedial (VM) prefrontal cortex (PFC) is an important brain region for the ability to make long-term advantageous decisions. VMPFC is part of the frontal cortex, a region generally thought to be involved in the regulation of goal-directed behavior

(Fuster, 2001; Miller & Cohen, 2001; Norman & Shallice, 1986). VMPFC is located in the middle parts of the orbital gyri and the inferior part of medial frontal cortex, and includes Brodmann areas 11, 12, 13, 25, 32, and 10 (Bechara, Damasio, & Damasio, 2000a; Fuster, 2001). Damage to the VMPFC in adults results in impulsive, socially inappropriate behavior, while leaving intellectual and memory abilities intact (Damasio, 1994, 1996; Rolls, 2000).

A well-known task to examine decision-making deficits in VMPFC patients is the Iowa Gambling Task (IGT), in which reward and punishment probabilities are manipulated in a systematic way (Bechara, Damasio, Damasio, & Anderson, 1994; Bechara, Tranel, & Damasio, 2000b). Participants are confronted with four decks of cards and are instructed to pick cards in order to win as much money as possible. Two of the cards (A&B) yield high rewards on each trial, but on some trials, these decks also give large punishments, and therefore these decks are disadvantageous in the long run. Two other decks (C&D) yield small rewards on each trial, but also smaller punishments, and therefore these decks are advantageous in the long run. To increase complexity, one of the disadvantageous decks (A) and one of the advantageous decks (C) results in frequent, smaller magnitude punishment, whereas the other disadvantageous (B) and advantageous (D) decks result in infrequent, higher magnitude punishment. In a series of experiments, Bechara and colleagues (Bechara et al., 1994; Bechara et al., 2000a; Bechara, Damasio, Tranel, & Damasio, 1997; Bechara, Tranel, Damasio, &

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Damasio, 1996) demonstrated that healthy individuals learn across task blocks to select more cards from the advantageous decks, whereas patients with damage to the VMPFC mainly make choices from the disadvantageous decks, independent of the frequency with which punishments are delivered. These results were interpreted as showing that VMPFC patients have a myopia for the future, i.e., they fail to anticipate the future outcomes of their decisions. Indeed, neuroimaging research confirmed that VMPFC is important for processing abstract reward and punishment in healthy adults (O'Doherty, Kringelbach, Rolls, Hornak, & Andrews, 2001; Ursu & Carter, 2005). In subsequent studies, it was demonstrated that impaired performance was most evident for VMPFC patients with right hemisphere damage (Clark, Manes, Antoun, Sahakian, & Robbins, 2003; Tranel, Bechara, A, & Denburg, 2002). But, also patients with damage to dorsolateral (DL) and dorsomedial (DM) PFC (Fellows & Farah, 2005; Manes et al., 2002) perform disadvantageous on the IGT task. Thus, the IGT most likely recruits several regions within prefrontal cortex that contribute to different aspects of the task (Dunn, Dalgleish, & Lawrence, 2006).

Several behavioral studies have examined developmental differences in performance on the IGT, and these studies demonstrated that between ages 8 and 18, there is an increase in the rate with which individuals learn to select from the advantageous decks (Blair, Colledge, & Mitchell, 2001; Crone, Jennings, & Van der Molen, 2004a; Hooper et al., 2004; Overman et al., 2004). We previously showed that 6-to-9-year-old children and 10-12-year-old children have a strong bias towards disadvantageous choices, even though they switch decks immediately after receiving punishment, just like adults. Adolescents aged 13-15 years made more advantageous choices than younger children but still made more disadvantageous choices than adults, suggesting that advantageous decision making does not reach adult levels until late adolescence (Crone & van der Molen, 2004). Hooper et al. (2004) and Overman et al. (2004) demonstrated that developmental changes in IGT performance still continue during late adolescence. A comparison of performance of 11-13-year-old children and 14-17-year-old children revealed that both age groups learned to make advantageous choices over the course of the task, but the learning curve was faster for older adolescents (although not yet at the adult level, in comparison to other published studies). In addition to the IGT, Hooper et al. (2004) asked all participants to complete a go/nogo task indexing response inhibition and a digit span task indexing working memory. Developmental differences were

observed for all tasks, but hierarchical regressions did not support a specific relationship between the development of inhibition, working memory, and IGT performance. Thus, these tasks may tap into specific cognitive processes with separate underlying neural structures.

Together, these studies suggest that young children share with VMPFC patients a "myopia for the future" and that the ability to make advantageous future choices continues to develop in adolescence. This notion is reinforced by structural brain imaging studies (Giedd, 2004; Gogtay et al., 2004; Sowell et al., 2004), which demonstrated that the grey-white matter ratio shows changes in prefrontal cortex until late adolescence, and functional neuroimaging studies, which have shown that task-specific changes take place in DLPFC (Crone, Wendelken, Donohue, van Leijenhorst, & Bunge, 2006b) and lateral orbitofrontal cortex (Galvan et al., 2006) across adolescence. However, the Iowa Gambling Task is a complex task, and different factors may contribute to disadvantageous performance of young children. For example, Crone et al. (2004a) and Overman et al. (2004) showed that children have a preference for decks that result in infrequent punishment, relative to frequent punishment, irrespective of whether these decks are advantageous or disadvantageous. This sensitivity is not seen in VMPFC patients (Bechara et al., 1994), suggesting that children may solve the task in a different way.

One way to examine more specifically which processes lead to disadvantageous performance is by the inclusion of autonomic measures. Successful performance on the Iowa Gambling Task requires participants to pay attention to the outcomes of their decisions, and then incorporate that information in their future decisions. Thus, deficiencies in performance may result from (a) an insensitivity to loss, or (b) an inability to use outcome information in anticipation of future risk. In a prior study, Bechara et al. (1996) showed that healthy individuals develop anticipatory skin conductance responses before the selection of a disadvantageous choice, whereas this anticipatory response was absent in VMPFC patients. In contrast, healthy individuals and VMPFC patients both displayed skin conductance responses following loss, showing that the differences in performance cannot be due to an insensitivity of VMPFC patients to loss per se. Consistent with this interpretation, in a prior study we reported that healthy adults show skin conductance responses, as well as heart rate slowing, before the selection of a disadvantageous decision, and this response is *larger* for those individuals who performed more advantageous on the task.

In contrast, the autonomic reactions to the outcome of the choices (skin conductance rise and heart rate slowing following loss relative to reward) did not differ between participants who performed mainly advantageous or mainly disadvantageous (Crone, Somsen, Van Beek, & Van Der Molen, 2004b). It should be noted that when the probabilities of winning and losing are reversed in such a way that the high-paying decks are advantageous in the long run, healthy individuals develop anticipatory skin conductance responses preceding advantageous decks (Tomb, Hauser, Deldin, & Caramazza, 2002). Thus, the direction of the anticipation effect is not necessarily related to the future outcomes, but is more likely related to the learning of probabilities (Dunn et al., 2006). We previously interpreted the anticipation effects in terms of a learned autonomic anticipation response for disadvantageous choices (or secondary inducers), whereas the outcome response may indicate a general, learning-independent autonomic response to aversive outcomes of choices (primary inducers) (Bechara et al., 2000a; Crone et al., 2004b; Suzuki, Hirota, Takasawa, & Shigemasu, 2003).

In this study, we examined the specificity of the performance difference in IGT performance across three age groups using autonomic indices. The participants included in this study ranged in age from 8-10-years, 12-14-years, and 16-18-years, in order to make the results comparable to previous studies that have examined decision making across adolescence (Hooper et al., 2004; Overman et al., 2004). All participants completed the standard version of the Hungry Donkey Task, a child friendly analogue of the IGT (Crone, Bunge, Latenstein, & van der Molen, 2005; Crone & van der Molen, 2004). The basic format of the card gambling task was retained, but card gambling was changed into a pro-social game inviting the player to assist a hungry donkey to win as many apples as possible. The change of card gambling into a pro-social game served the purpose of making the Iowa Task more meaningful for children and of stirring their involvement—"you cannot let a hungry donkey down" (Falk & Wilkening, 1998).

During the task, heart rate and skin conductance changes were continuously recorded in order to test two hypotheses. The first hypothesis predicts that, if children perform poorly on the IGT because they are insensitive to loss, then developmental differences should be largest in the analysis that focuses on heart rate and skin conductance changes following outcomes. We predict that heart rate will slow and skin conductance will rise following feedback indicating loss (Crone et al., 2003a; Somsen, Van der Molen, Jennings, & van Beek, 2000). Differences between

autonomic responses to reward and loss should be largest for 16-18-year-olds and smallest for 8-10-year-olds, with 12-14-year-olds responding at an intermediate level. Support for this hypothesis comes from studies that have shown that 7-12-year-old children fail to monitor their own errors in a simple speeded two-choice task, as indicated by smaller event-related scalp potentials following an error (Davies, Segalowitz, & Gavin, 2004) and studies that have shown that 8-year-old children do not process feedback information as efficiently as adults in a categorization task, as indicated by undifferentiated heart rate responses (Crone et al., 2004a).

The alternative hypothesis predicts that, if children perform poorly on the IGT because they fail to *anticipate* the outcomes of their decisions, then developmental differences should be largest in the analysis that focuses on heart rate and skin conductance responses preceding the decision. This hypothesis predicts that heart rate will slow and skin conductance will rise before making a disadvantageous choice (Bechara et al., 1996), but these responses are expected to be present only for good performers (Crone et al., 2004b). Therefore, the anticipation hypothesis predicts that only 16-18-year-olds will show heart rate slowing and skin conductance rise preceding disadvantageous choices, and this difference will be absent in 8-10-year-olds. Twelve-fourteen-year-olds are expected to show an intermediate pattern.

One further precaution was taken into account. Across adolescence, there are large hormonal and physical changes that take place (Blakemore & Choudhury, 2006), which happen at different rates for boys and girls (Overman, 2004). Indeed, there are consistent gender differences reported on the IGT, where, in general, boys outperform girls (Crone et al., 2005; Garon & Moore, 2004; Overman, 2004). Therefore, in this study we also examined gender differences in performance, anticipatory, and outcome-related autonomic responses.

Method

Participants

Three age groups participated in the study, 22 children aged 8-10 years ($M = 9.5$; 10 boys, 12 girls), 29 children aged 12-14 years ($M = 13.3$; 14 boys, 15 girls), and 30 adolescents aged 16-18 years ($M = 17.3$; 7 boys, 23 girls). Chi-square analyses indicated that gender did not differ significantly between age groups ($\chi^2(2) = 4.5, p = .11$). Children and adolescents were

recruited by contacting schools. These participants were selected with the help of their teachers, and their primary caregivers signed a consent letter for participation. Participants received points during the task, but these were not translated in actual money. All participants reported to be healthy and took a computerized version of the Raven Standard Progressive Matrices task (Raven SPM) in order to obtain an estimate of their intelligence quotient (IQ). Estimated IQ scores were 113, 109, and 109 for the 8-10-year-olds, the 12-14-year-olds, and the 16-18-year-olds, respectively. A one-way analysis of variance (ANOVA) performed on the estimated IQ scores revealed no significant difference between age groups $F(2, 70) = .97, p = .39$.

Hungry Donkey Task

Format. The experimental task was derived from our previous studies (Crone et al., 2004b; Crone & van der Molen, 2004). Subjects were seated in front of a 15-inch computer monitor at a viewing distance of approximately 75 cm. The trial sequence started with the presentation of a stimulus display, followed by a 6,000 ms delay in which the subject could ponder which decision to make, followed by a cue indicating that the subject could respond. Following the response, a 1,000 ms blank screen, followed by a 2,500 ms outcome display, replaced the stimulus display. Responses were made approximately 500-1,000 ms following the cue, resulting in an intertrial interval of approximately 10 s.

The stimulus display consisted of four doors presented on a horizontal row, A, B, C, and D, followed by a donkey (the cue) in front of the doors (Figure 1; for a detailed description, see Crone et al., 2004b). Subjects were told to assist the hungry donkey to collect as many apples as possible by pressing one of four keys corresponding to the doors. The fingers

from the dominant hand were assigned to the “C, V, B and N,” keys of the computer keyboard. The “C, V, B and N,” keys were mapped onto the doors from left to right. Upon pressing one of the keys, the stimulus display was replaced by a blank screen, followed by the outcome display showing the number of (intact) apples gained or the number of (crossed) apples lost. A large horizontal bar was presented just below the donkey. At the beginning of the task, the left half was colored green, and the right half was colored red. During the course of the task, the color change of the bar corresponded to the amounts of apples won or lost, averaged across doors.

Task description. All subjects performed a standard task that contained 100 trials. The ultimate future yield of each door varied, because the wins were higher at the high-paying doors (A and B), and lower at the low-paying doors (C and D). The punishment frequency of each door varied, because punishment frequency was higher for doors A and C (50% of the trials) and lower for doors B and D (10% of the trials). Selecting door A or B resulted in a gain of four apples, whereas door C or D resulted in a gain of two apples. After selecting 10 A-doors, the subject received 40 apples but also encountered five unpredicted losses of either 8, 10, 10, 10, or 12 apples, bringing the total cost to 50 apples, thus incurring a net loss of 10 apples. After selecting 10 B-doors, the subject received 40 apples but encountered one unpredicted loss of 50 apples, also incurring a net loss of 10 apples. After selecting 10 C-doors, the subject received 20 apples, but encountered five unpredicted losses of 1, 2, 2, 2, or 3 apples, bringing the cost to 10 apples, incurring a net gain of 10 apples. The same happened at door D, except that instead of encountering five losses, there was one larger unpredicted loss of 10 apples. Thus, door D also resulted in a net gain of 10 apples. In sum, doors A and B were equivalent in terms of overall net

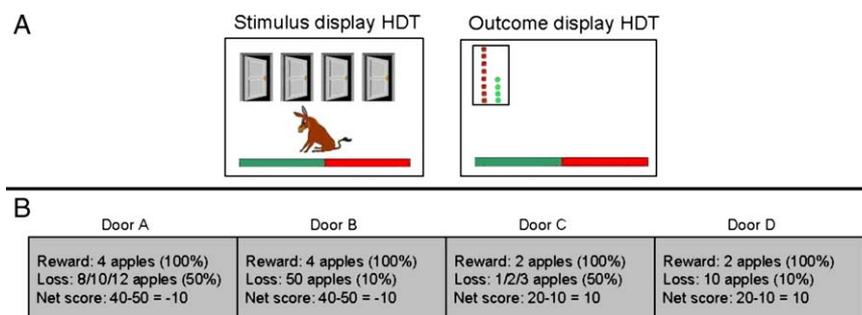


Figure 1. (A) Simplified presentation of stimulus and outcomes displays of the Hungry Donkey Task (child version, Crone & Van der Molen, 2004). (B) Schematic presentation of win and loss schedules. Net scores are presented per 10 trials. Each choice results in a reward and occasional punishment. Doors A&B are disadvantageous in the long run, and doors C&D are advantageous in the long run. Doors A and C result in frequent loss (50% of the trials) and doors B and D result in infrequent loss (10% of the trials).

loss over the trials. The difference was that at door A, the probability of loss was frequent, but of smaller magnitude, whereas at door B, the probability of loss was infrequent but larger. Doors C and D were also equivalent in terms of overall net loss. At door C, the probability of loss was frequent and of smaller magnitude, while at door D the probability loss was infrequent and of higher magnitude.

Procedure

All participants were tested individually in a quiet laboratory. The task took approximately 20-25 minutes to complete. The Raven SPM was administered following the completion of the task and took approximately 20-30 minutes to complete. Including instructions and breaks, participants spent approximately 50 minutes in the laboratory.

Data Recording and Reduction

The electrocardiogram (ECG), skin conductance level (SCL) and respiration were continuously recorded. The ECG was recorded from three AgAg/CL electrodes, attached via the modified lead-2 placement. Skin conductance activity was recorded using a constant voltage (.5V) using 1-cm³ AgAg/Cl electrodes attached to the medial phalanx surfaces of the middle and index finger of the nondominant hand. Respiration was recorded through a temperature sensor placed under the nose. The signals were amplified by a Nihon Kohden polygraph and sampled by a Keithley AD-converter at a rate of 400 Hz. The recorded Inter Beat Intervals (IBIs) were screened for physiologically impossible readings and artifacts. These were corrected by adjusting specific parameters in the program that extracted the IBIs from the digitized ECGs. Skin conductance values were transformed to microsiemens values using Pyslab software. The respiration signal was used to eliminate heart rate and skin conductance changes associated with gross respiratory changes. Each time the subject pressed a response key, this action was recorded as a pulse on the sampling computer to the nearest millisecond.

Results

Performance

Age differences. To examine whether age groups differed in the number of advantageous choices, a 3 (Age Group) \times 5 (Task Block) ANOVA was performed for difference scores (disadvantageous choices – advantageous choices), where “task block” represents a division of the task in segments of 20 trials. The

ANOVA resulted in the expected Age Group \times Task Block interaction, $F(8, 312) = 2.74, p < .01$. As can be seen in Figure 2, 16-18-year-old adolescents learned to make advantageous choices during the course of the task, statistically verified by an effect of Task Block, $F(4, 116) = 5.54, p < .001$. Separate task block comparisons within this age group showed that learning differences were most pronounced for the third relative to the second task block, $F(1, 29) = 7.52, p < .01$, and the fifth relative to the fourth task block, $F(1, 29) = 7.18, p < .01$. This Task Block effect was absent for 12-14-year-olds ($p = .10$) and 8-10-year-olds ($p = .84$). Separate comparisons for each task block revealed that the difference between age groups was significant only in the last task block, $F(2, 78) = 14.02, p < .001$.

To examine whether there were differences associated with the frequency with which punishment was given, we also analyzed the actual choices in a 3 (Age Group) \times 2 (Gain) \times 2 (Frequency) \times 5 (Task Block) ANOVA. Indeed, there was a main effect of Frequency, $F(1, 78) = 48.71, p < .001$, qualified by an interaction between Frequency and Gain, $F(1, 78) = 27.15, p < .001$. This interaction shows that when making disadvantageous choices, subjects preferred options with low punishment frequency ($M = 7.02, S.E. = .28$), compared to options with high punishment frequency ($M = 4.20, S.E. = .14$), $F(1, 78) = 64.40, p < .001$, whereas this preference was much smaller for advantageous choices, $F(1, 78) = 4.25, p < .05$, ($M = 4.70, S.E. = .19$ versus $M = 4.09, S.E. = .20$, respectively). Effects of Frequency did not interact with Age Group. However, when we analyzed each choice separately, an age-related decrease in disadvantageous choices was observed for door A, $F(2, 78) = 5.24, p < .01$ (8-10-yrs, $M = 4.6$; 12-14-yrs, $M = 4.5$; 16-18-yrs, $M = 3.6$), and an

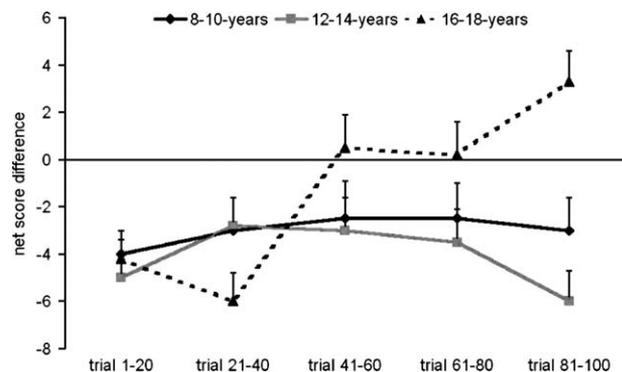


Figure 2. Net score difference ((C+D) – (A+B)) for each trial block of 20 trials and for each age group. Sixteen-eighteen-year-olds show a significant improvement in the number of advantageous choices over task blocks.

age-related increase in advantageous choices was observed for door C, $F(2, 78) = 3.23, p < .05$ (8-10-yrs, $M = 4.6$; 12-14-yrs, $M = 4.5$; 16-18-yrs, $M = 3.6$). These age differences were not observed for doors B and D (p 's $> .10$). These results show that age differences were most pronounced for doors with frequent punishment (A&C).

Gender differences. An additional analysis was performed to examine whether male participants outperformed female participants on the task (Overman, 2004). For this analysis, we performed a Gender (2) \times Age Group (3) \times Task Block (5) ANOVA for the differences scores (disadvantageous choices – advantageous choices). The number of choices from each deck is summarized in Table 1, averaged across task blocks for simplicity. The ANOVA resulted in the expected Gender \times Task Block interaction, $F(4, 300) = 3.28, p < .05$. This interaction reveals that in the first four task blocks, boys and girls did not differ in the number of advantageous choices (all p 's $< .10$), whereas boys made more advantageous choices than girls in the fifth task block, $F(1, 79) = 4.66, p < .05$.

Analysis of actual choices in which Frequency was added resulted in a four-way interaction between Block, Frequency, Gender, and Age Group, $F(8, 300) = 2.12, p < .05$. The interaction effects were followed up by comparisons for each age group separately (Gender \times Gain \times Frequency \times Task Block ANOVAs). The 8-10-year-olds demonstrated that, in general, boys made more advantageous choices (65 out of 100) than girls (52 out of 100) (Gain \times Gender, $F(1, 20) = 5.61, p < .05$), and this effect was not different across task blocks or frequencies (p 's $> .20$). This effect was not consistently found in the 12-14-year-olds (all p 's $> .20$). In 16-18-year-olds, boys made more advantageous choices (58 out of 100) than girls (47 out of 100) (Gain \times Gender, $F(1, 28) = 6.11, p < .05$). In addition, girls showed a preference for infrequent punishment trials (62 out of 100), relative to boys (47 out of 100) (Gender

\times Frequency, $F(1, 28) = 10.71, p < .01$), and this effect became stronger as the task progressed (Gender \times Frequency \times Task Block, $F(4, 112) = 4.25, p < .05$).

Given that girls, in general, performed less advantageous than boys, it is possible that the age differences reported above are only seen for boys and not for girls. Therefore, we performed an additional Age Group (3) \times Gain (2) \times Frequency (2) \times Task Block (4) ANOVA for girls only. Again, this analysis resulted in a significant Age Group \times Gain \times Task Block interaction, $F(8, 188) = 1.94, p < .05$, showing that age differences are present independent of gender differences.

To summarize, across task blocks and across age groups, boys outperformed girls in the number of advantageous choices, although this effect was not consistently found in 12-14-year-olds. In contrast, only in late adolescence (16-18-years) girls developed a preference for infrequent punishment trials relative to boys (see also Overman et al., 2004). Despite the influence of gender, these effects do not explain the age differences in performance.

Anticipation Effects as Reflected in Skin Conductance and Heart Rate Responses

The anticipation analyses were performed to examine whether the age groups differed in anticipation heart rate and skin conductance responses to possible outcomes. For this purpose, two separate analyses were performed; the first analysis focused on skin conductance responses and the second on heart rate responses. Data from four 8-10-year-olds (2 girls, 2 boys), one 12-14-year-old (1 girl) and two 16-18-year-olds (2 girls) were not analyzed due to equipment failure.

Age effects. Figure 3 shows skin conductance responses that were measured in a time interval 5,000 ms before the response for each choice and age group

Table 1

Gender and Age Differences in Number of Choices from Each of the Four Decks Numbers are Displayed as Averages Across Blocks of 20 trials, and the Standard Errors are Displayed Between Parentheses

Age		Door A: Disadvantageous/ Frequent loss	Door B: Disadvantageous/ Infrequent loss	Door C: Advantageous/ Frequent loss	Door D: Advantageous / Infrequent loss
8–10	Boys	5.9 (.4)	7.9 (.8)	2.8 (.5)	4.3 (.5)
	Girls	4.2 (.4)	6.2 (.7)	4.7 (.4)	4.9 (.5)
12–14	Boys	4.8 (.3)	7.3 (.6)	3.9 (.4)	3.9 (.5)
	Girls	4.1 (.3)	7.8 (.6)	3.4 (.4)	4.6 (.4)
16–18	Boys	3.3 (.5)	5.0 (.9)	7.3 (.6)	4.4 (.6)
	Girls	3.6 (.3)	7.0 (.5)	4.0 (.3)	5.4 (.4)

(Bechara et al., 1996; Crone et al., 2004b). The first 10 trials were not included in the analysis. The mean score preceding each choice was referred to the lowest SCL value during the task for each subject separately (Crone et al., 2004b). The difference scores were submitted to a 3 (Age Group) \times 2 (Gain) \times 2 (Frequency) ANOVA. The analysis resulted in a main effect of Frequency, $F(1, 74) = 8.31, p < .005$, and this effect was modulated by an interaction between Frequency and Age Group, $F(2, 74) = 3.25, p < .05$. The Age Group \times Frequency interaction showed that SCL preceding choices did not differentiate for 8-10-year-old children, $F(1, 23) = .02, p = .89$, or for 12-14-year-old children, $F(1, 25) = 1.32, p = .26$. Sixteen-eighteen-year-old adolescents, in contrast, showed larger SCL values preceding choices that could result in frequent punishment, compared to infrequent punishment, $F(1, 26) = 10.90, p < .005$. The main effect of Gain was not significant, $F(1, 74) = .07, p = .81$; neither

was the Age Group \times Gain interaction, $F(2, 74) = .37, p = .69$.

A similar analysis was performed for the interbeat interval preceding the interbeat interval in which the response occurred (Crone et al., 2004b). This analysis did not result in any significant effects. Similar analyses for the two additional interbeat intervals that preceded the response also did not result in significant differences. Analyses performed for each group separately also failed to reach statistical significance.

Gender differences. To examine whether there were gender differences in anticipatory arousal preceding choices from the four decks, the skin conductance difference scores were also submitted to a Gender \times Age Group \times Gain \times Frequency ANOVA. There was no main effect for Gender, but the analysis resulted in a significant Gender \times Frequency interaction ($F(1, 63) = 7.87, p < .01$) showing that girls had higher skin conductance arousal scores preceding choices that could result in frequent punishment ($F(1, 39) = 10.94, p < .01$), whereas this effect was not observed for boys ($F(1, 24) = .68, p = .42$); see Figure 5. The gender effects did not differ between Age Groups (all p 's $> .40$).

A similar analysis for interbeat intervals did not result in any significant effects for gender differences.

Effects of Performance Feedback on Heart Rate and Skin Conductance Responses

The feedback analyses focused on effects of performance feedback on heart rate and skin conductance responses. For this purpose, two separate analyses were performed; the first analysis focused on skin conductance responses and the second on heart rate responses. Data from four 8-10-year-olds (2 girls, 2 boys), one 12-14-year-old (1 girl) and two 16-18-year-olds (2 girls) were not analyzed due to equipment failure. Each choice could result in positive (reward) and negative (loss) feedback.

Age differences. For the skin conductance analysis, the microsiemens scores 5,000 ms following the presentation of the feedback were averaged, and these values were referred to the mean skin conductance level 1,000 ms preceding the presentation of feedback to provide a baseline (Bechara et al., 1996; Crone et al., 2004b). The difference scores were submitted to an Age Group (3) \times Gain (2) \times Frequency (2) \times Feedback (reward, loss) ANOVA. This analysis showed that skin conductance was higher following loss feedback than following reward feedback (Main effect Feedback, $F(1, 68) = 7.75, p < .01$). A Feedback \times Gain interaction, $F(1, 68) = 12.31, p < .005$, demonstrated

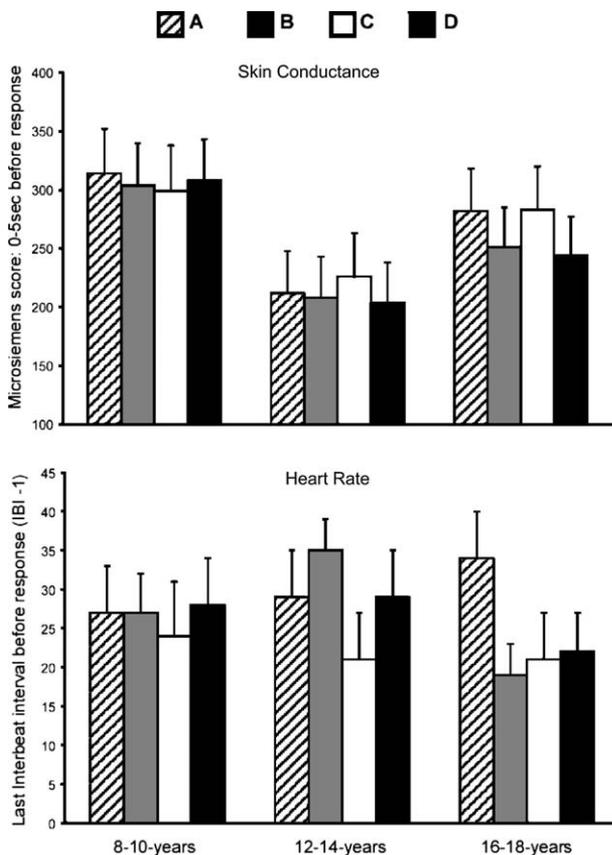


Figure 3. Skin conductance (A) and heart rate (B) responses preceding the response choice for each deck and each age group. Differences were only significant for 16-18-year-olds. Skin conductance responses were higher for choices that could result in frequent punishment (A&C) relative to infrequent punishment (B&D). No anticipation differences were observed for heart rate responses.

that this effect was only present for loss following disadvantageous choices, $F(1, 68) = 17.90, p < .001$, but not for loss following advantageous choices, $F(1, 68) = .07, p = .78$. A Feedback \times Frequency interaction, $F(1, 68) = 6.7, p < .05$, showed that the feedback effect was only present for trials with infrequent (and high magnitude) punishment, $F(1, 68) = 10.43, p < .05$, but not for trial with frequent (lower magnitude) punishment, $F(1, 68) = 1.23, p = .27$ (Figure 4). These effects were not modulated by Age group (all p 's $> .20$).

For the heart rate analysis, we selected the first interbeat interval (IBI) following the presentation of the feedback, where feedback effects are largest

(Crone et al., 2004b; Crone et al., 2003a). This IBI was referenced to the IBI preceding the presentation of the feedback, in order to provide a baseline corrected score. The IBI values were submitted to an Age Group (3) \times Gain (2) \times Frequency (2) \times Feedback (reward, loss) ANOVA. Again, heart rate slowing was largest following loss relative to reward (Main effect Feedback, $F(1, 68) = 45.84, p < .001$), but there were no significant differences between the gain and frequency of this effect (Figure 4). Also for this analysis, there were no significant differences between age groups (all p 's $> .30$).

Gender differences. The analyses reported above were reanalyzed with gender included, but gender

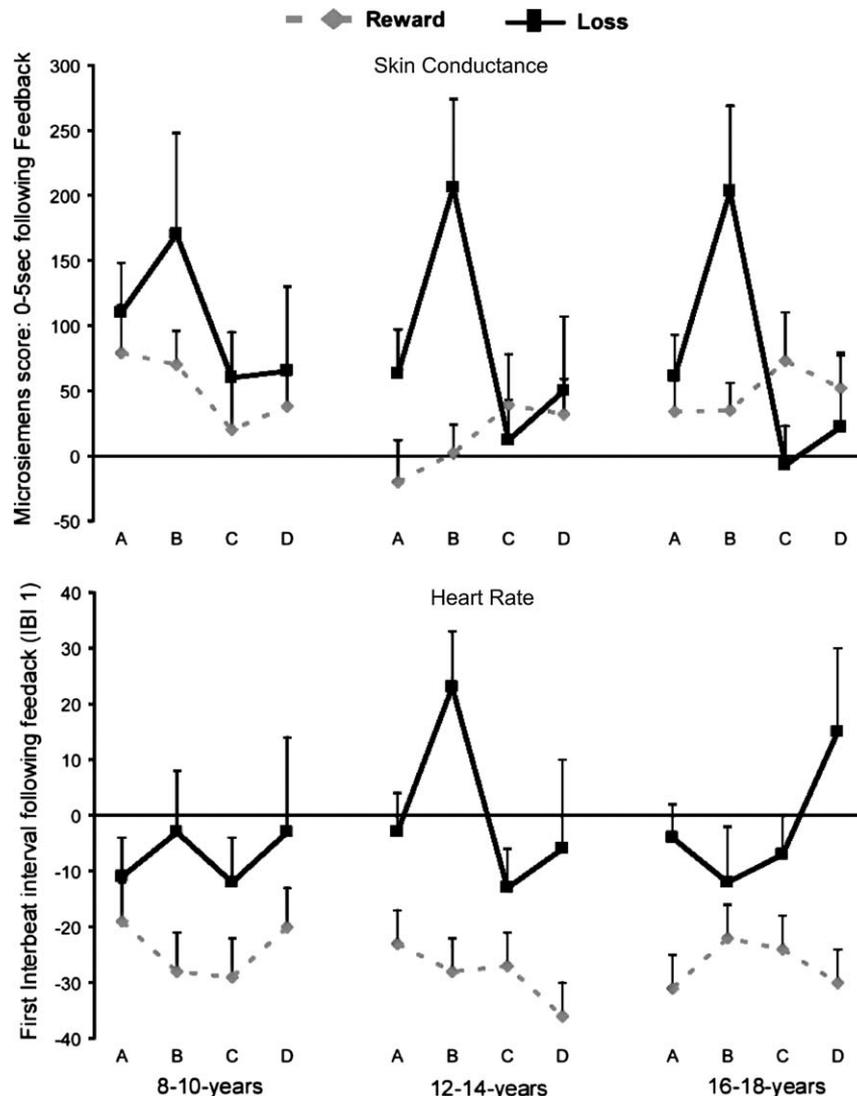


Figure 4. Skin conductance (A) and heart rate (B) responses following reward and punishment for each deck and each age group. Skin conductance increased and heart rate slowed following higher magnitude punishment, and these differences were observed for all age groups.

did not interact with any of the feedback effects, all p 's $> .20$ (see Figure 5).

Together, these results show that both skin conductance and heart rate slowing increased following loss, and skin conductance rise was additionally sensitive to the magnitude and frequency of loss. None of the effects differentiated between children of different age groups, or between boys and girls, indicating that all age groups and genders were similarly sensitive to the magnitude of loss. For all analyses above, we also correlated number of advantageous choices with autonomic signals within age groups, but these correlation analyses failed to reach significance.

Discussion

The current study yielded three main results: (a) The current results are a replication of previously reported behavioral differences showing that the ability to make long-term advantageous choices on the IGT does not develop until late adolescence (Crone, Vendel, & Van der Molen, 2003b; Hooper et al., 2004; Overman et al., 2004); (b) these changes were accompanied by developmental differences in anticipation, but not outcome-related autonomic responses, mainly reflected in skin conductance activation; (c) the results replicate previously reported gender differences, with boys outperforming girls in number of advantageous choices

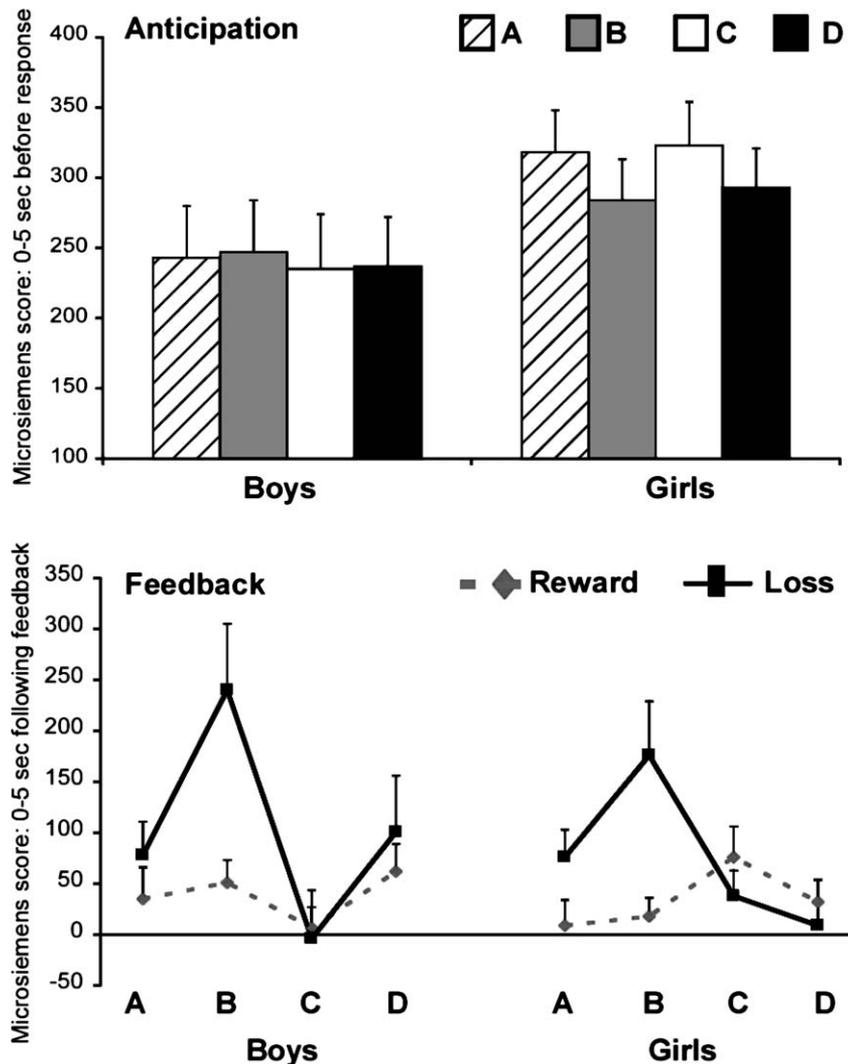


Figure 5. Skin conductance responses preceding choices (A) and following reward and punishment (B) for boys and girls, averaged across age groups. Anticipatory skin conductance increase was larger preceding choices that could result in frequent relative to infrequent punishment, but only for girls and not for boys. Skin conductance increase following punishment was observed for both boys and girls.

across age groups, and 16-18-year-old girls showing a preference for decks that result in infrequent (high magnitude) punishment (Overman, 2004).

The analysis of actual choices shows that 16-18-year-old participants display an increase in the number of advantageous choices over task blocks, although they still do not make as many advantageous choices as observed in adults in prior studies (Bechara et al., 2000a; Reavis & Overman, 2001). These results suggest that the ability to make future oriented choices continues to develop in late adolescence. Children aged 8-10-years and children aged 12-14 did not learn to make advantageous choices but sampled from both advantageous and disadvantageous decks across task blocks. Their response pattern, however, was not random, because they had a preference for choices with infrequent (but high magnitude) punishment (10% of the trials) in comparison to frequent (but low magnitude) punishment (50% of the trials). These findings indicate that punishment frequency may be a more dominant dimension in children's decision making than magnitude of punishment (Dunn et al., 2006). Huizenga, Crone, & Jansen (in press) recently reanalyzed behavioral data (reported in Crone et al., 2004a), to examine whether age differences in IGT performance can be explained in terms of using more complex proportional reasoning rules. Using mixture analysis, they showed that performance of young children is dominated by the frequency of punishment in children aged 6-9 years. It is not until late adolescence that children learn to combine frequency and magnitude into a higher proportional reasoning rule (Huizenga et al., in press). Thus, it is possible that children use different information when completing the IGT than adolescents and adults (see also Falk & Wilkening, 1998).

Analysis of heart rate and skin conductance responses demonstrates that children of all age groups process the outcomes of their choices in a similar way. Analysis of outcomes shows that heart rate slows, and skin conductance rises when participants receive loss. Prior studies have argued that the slowing of the heart rate and skin conductance increase following loss is associated with a monitoring system that indicates that performance should be adjusted on subsequent trials (Hajcak, McDonald, & Simons, 2003; Somsen et al., 2000). This monitoring system may involve a network of brain regions including the ACC and the insula (Critchley, 2005). The current results show that heart rate and skin conductance responses following reward and loss do not differ between age groups, even though the 16-18-year-olds perform more advantageously than 8-10-year-olds and 12-14-year-olds. This dissociation between performance and

autonomic outcome activity is consistent with prior studies showing that patients with VMPFC also fail to learn to make advantageous choices but show similar autonomic responses to punishment as healthy adults (Bechara et al., 1996). In contrast, patients with damage to the amygdala, a region important for fear learning (Phelps, 2006), do not learn to make advantageous choices and show no autonomic response following punishment (Bechara, Damasio, Damasio, & Lee, 1999). These results suggest that autonomic responses to punishment can be associated with a general system that responds to aversive situations. The dissociation between the processing of punishment information and using this information on subsequent trials may indicate a developmental dissociation between knowing and doing (Zelazo, 2004). In future studies, the role of outcome processing and subsequent performance adjustments should be examined more closely, in addition to physiological learning effects across trials. Possibly, autonomic responses can be used to adjust performance on subsequent trials in simple tasks in which the appropriate strategy is already known (Hajcak et al., 2003; Somsen et al., 2000). However, when the task is complex, autonomic responses to punishment alone cannot direct behavior towards an advantageous strategy.

An alternative system that can assist in learning to make advantageous choices makes use of anticipatory autonomic signals preceding the choice (Bechara et al., 1996; Damasio, 1996). The current results demonstrate that 16-18-year-old adolescents, but not 12-14-year-olds or 8-10-year-olds, show a differentiating autonomic response preceding choices, as reflected in skin conductance activity. In a prior study using the Hungry Donkey Task including only adults, we found that good performing adults develop anticipatory skin conductance responses preceding disadvantageous choices, but this response was largest for choices that could result in frequent punishment (Crone et al., 2004b). In the current study, 16-18-year-olds failed to differentiate between advantageous and disadvantageous choices in their autonomic responses but showed higher skin conductance responses preceding choices that could result in frequent punishment relative to infrequent punishment. These results are consistent with the hypothesis that 16-18-year-olds are more sensitive to the frequency of punishment than the magnitude of punishment and that the integration of these two dimensions does not occur until early adulthood (Dunn et al., 2006; Huizenga et al., in press).

Developmental changes in decision making have been associated with a slow functional maturation of the VMPFC. This hypothesis is based on the striking

similarity in performance of young children and VMPFC patients (Crone & van der Molen, 2004; Hooper et al., 2004). However, it is also possible that performance and physiological differences are associated with the development of other brain regions that work together with VMPFC, such as the dorsal prefrontal cortex (Manes et al., 2002). Recent empirical data indicate that the IGT is a well-validated and extensively applied task to study differences in decision-making, but it is unclear whether the somatic marker theory, which argues that the VMPFC is important for the development of somatic markers that guide decision making (Damasio, 1994), suffices as single mechanism to explain differences in task performance. It is also possible that the changes in task performance, and the associated psychophysiological manifestation, are related to changes in interactions between mechanisms that guide future orientation, working memory, and risk-taking (Dunn et al., 2006). These exact contributions should be studied in future research.

Recently, the notion of slow prefrontal cortex development vis-à-vis decision making was confirmed in an fMRI study including children, adolescents, and adults. Galvan et al. (2006) had participants of three age groups (7-11 years, 13-17 years, and 23-29 years) perform a delayed response two-choice task in which a cue indexed whether the response would be followed by a small, medium, or large reward. Prior fMRI studies in adults (Galvan et al., 2005) and animal studies (Winstanley, Theobald, Cardinal, & Robbins, 2004) have shown that the orbitofrontal cortex, which is a broader region of the lower prefrontal cortex that includes VMPFC, is important for updating incentive values during delay-response evaluations. Galvan et al. (2006) demonstrated that increases in reward resulted in increased activity in nucleus accumbens and lateral orbitofrontal cortex in all age groups, but adolescents showed a larger increase in nucleus accumbens relative to children and adults (Ernst et al., 2005; May et al., 2004), whereas both children and adolescents showed more activity in lateral orbitofrontal cortex relative to adults. These results were interpreted in terms of protracted maturational changes in top-down control systems (orbitofrontal cortex) relative to subcortical regions (nucleus accumbens) implicated in appetitive behaviors. Therefore, adolescents may be more driven by appetitive systems than control systems, leading to suboptimal choices in decision-making tasks.

Finally, as in prior studies, boys outperformed girls in number of advantageous choices (Crone et al., 2005; Garon & Moore, 2004; Overman, 2004; Reavis & Overman, 2001). This pattern of results was observed

across age groups and could not account for the developmental changes that were observed. Consistent with Overman (2004), 16-18-year-old girls were more sensitive to the frequency of punishment than boys were (avoiding decks with frequent punishment). These results suggest that girls are informed by the trial-to-trial changes in the task, rather than the future outcomes of their choices. These findings are confirmed in the skin conductance analyses, showing that girls had higher skin conductance responses preceding choices that could result in frequent punishment, independent of whether these choices were associated with advantageous or disadvantageous doors. Thus, it is possible that girls avoided doors with frequent punishment, because they experienced autonomic warning signals when choosing from these doors. This pattern of results cannot be explained by a higher sensitivity to loss, because girls showed similar autonomic responses following loss as boys. In a neuroimaging study using Positron Emission Tomography (PET) in adults, men were found to activate lateral orbitofrontal cortex bilaterally and right DLPFC, whereas women only activated a small region in medial orbitofrontal cortex and left DLPFC during IGT performance. These findings were interpreted in terms of greater dependence on right hemisphere activation in orbitofrontal cortex for successful IGT performance, which may explain why men perform more advantageous on the task than females (Bolla, Eldreth, Matochik, & Cadet, 2004). It should be determined in future research whether these differences in brain activation also apply to younger participants.

Overman et al. (2006) considered, but rejected, the possibility that gender differences result from boys being better in reversal learning. Instead, they demonstrated that the gender difference in IGT performance disappears when girls are asked to contemplate moral dilemma's while playing the IGT. According to the authors, the contemplation of moral dilemma's results in increased activation in DLPFC, a brain region important for rational decision making (Greene, Nystrom, Engell, Darley, & Cohen, 2004). The authors concluded, consistent with Bolla et al.'s (2004) results, that women may utilize different cognitive strategies and alternative neural networks when performing this specific task. In future studies, it would be interesting to use a similar approach in a developmental context and investigate whether children can be taught to make advantageous choices by training them on tasks that are regulated by DLPFC and VMPFC networks. It should be noted that, even though there was no significant difference in gender distributions across age groups, the number

of boys was relatively low in the oldest age group. It is possible that for this reason we lacked power to find Age \times Gender interactions. In future studies, it will be important to examine gender differences systematically in adolescence.

In conclusion, the current study demonstrates that the ability to anticipate future outcomes of decisions continues to develop until late adolescence. The data support the hypothesis that 8-10-year-old and 12-14-year-old children perform like patients with VMPFC damage, because they fail to anticipate outcomes prior to making a decision. The data reject the hypothesis that 8-10-year-old children and 12-14-year-old children perform disadvantageously, because they fail to process the outcomes of their decisions. In future studies, it will be important to examine gender differences in adolescence (Overman, 2004), the training potential of DLPFC, and VMPFC (Overman et al., 2006), and to test developmental changes using brain imaging techniques in order to understand the neural correlates of developmental changes in decision making (Casey, Tottenham, Liston, & Durston, 2005; Crone, Wendelken, Donohue, Van Leijenhorst, & Bunge, 2006a; Van Leijenhorst, Crone, & Bunge, 2006).

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