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

Leijenhorst, L. van

1.

General introduction

1.1 The scope of this thesis

This thesis aims to gain insight into risky behavior in adolescence by contributing to our knowledge about the development of decision-making skills in relation to brain development. Adolescence is a fascinating period in life. In a relatively short period of time, roughly between 10 and 20 years of age (Dahl, 2004; Spear, 2000), children transform into adults. This transformation has implications for the way teens look and behave, and for their cognitive and psychosocial functioning. Adolescents are often characterised as impulsive and prone to take risks. Already at the beginning of the 20^{th} century G. S. Hall, who is often regarded as the founder of adolescent psychology, described an increase in risky behavior and sensation seeking in adolescence. He saw adolescence as a period of "storm and stress"; characterized by conflict with parents, mood swings, and impulsive behavior (Hall, 1904). Similarly, more recent studies show that adolescents report a greater need for sensation seeking compared to children and adults (Arnett, 1996; Zuckerman, 1994), and that more teens than children or adults end up in emergency rooms because of (traffic) accidents, or because of problems related to experimentation with drugs or alcohol (Furby & Beyth-Marom, 1992; Steinberg, 2004). While the consequences of adolescent risk-taking can be grave, most children pass through adolescence relatively calmly (Arnett, 1999; Dahl, 2004; Masten et al., 1999). Nevertheless, during adolescence many decisions are made that will have long term consequences; smoking for example, often starts during adolescence, and adolescents' choices with regards to their education can have consequences in adulthood. These possible negative consequences underline the importance of understanding the developmental changes that characterize adolescent risky behavior.

Even though the development of risk-taking behavior has been studied from different perspectives, and using different methods (for an extensive review see Boyer, 2006), the stereotypical adolescent risky behavior has been difficult to capture in experiments. The development of non invasive neuroimaging techniques such as Magnetic Resonance Imaging (MRI) and *functional* MRI (fMRI) have enabled us to study structural and functional brain maturation in children, adolescents and adults in vivo. These techniques have transformed both our understanding of the neurological changes that occur during adolescence and the way in which we think about adolescent development. Neuroimaging data can reveal age related changes in brain function, which are not always apparent based on behavioral measures. When combined with behavioral experiments, the ability of these imaging techniques to increase our understanding of the development of risk-taking behavior is promising. However, because this approach is new, many questions still need to be answered. In addition to behavioral measures (accuracy, choice and reaction time data), we used measures of heart rate changes and fMRI to gain insight into the development of the neural correlates of decision-making during development. In the absence of differences in behavior, these measures can reveal age related differences in the processes that underlie this behavior. The remainder of this chapter will give a short overview of the theoretical background of the studies that are presented in this thesis.

1.2 Imaging the developing brain

The results from a large scale longitudinal study on the structural development of normal developing brains in which 145 healthy children and adolescents ranging in age from 4 to 22 years participated revealed a more protracted developmental trajectory than was previously thought. Important changes still take place throughout adolescence (Giedd et al., 1999; Gogtay et al., 2004; Sowell et al., 2004). Even though the overall size of the brain of a 9-year-old is comparable to the size of an adult's brain, there are important differences in brain structure. MRI studies have shown that gray matter volume, or the total amount of neurons and connections between neurons, follows an inverted U shaped developmental trajectory (Giedd et al., 1999). The number of neurons and connections increases from birth on and reaches a peak at the beginning of adolescence; from this point on the amount of gray matter will decrease. The adolescent brain begins to change, neurons and connections that are not necessary disappear, and important connections are strengthened, allowing the brain to function more efficiently. In contrast, the volume of white matter, which is made up of myelin that supports communications between neurons, shows a linear increase which continues into adulthood (Giedd et al., 1999). Importantly, the rate at which the brain matures differs between brain regions (Shaw et al., 2008). Regions in the prefrontal cortex (PFC) and parietal cortex are among the last regions in which gray matter volume reaches its peak. These regions continue to change throughout adolescence, which is much later than was previously thought (Casey et al., 2005; Gogtay et al., 2004; Sowell et al., 2004).

In addition to these measures of structural brain maturation, the emergence of fMRI has enabled us to see the brain in action. fMRI's high spatial resolution has vastly increased the ability to map cognitive functions on different brain regions. Importantly, because healthy children and adolescents can participate in fMRI studies, hypotheses about the relation between brain development and cognitive development could be tested. The first developmental fMRI studies revealed that children and adults recruit similar brain regions when they perform cognitive tasks (Casey et al., 1995; Thomas, 1999; Nelson, 2000). Functional brain development mirrors structural brain development, and follows a different developmental trajectory in different regions. Brain regions associated with basic (motor and sensory) processes mature before regions associated with more complex cognitive processes (for a review see, Casey et al., 2005). While children and adults recruit similar brain regions, the way in which these regions are recruited changes with development. That is, brain activation seems to reflect more efficient processing with development (Casey et al. 2005). For example, some studies have found activation in prefrontal brain regions that are associated with a specific task in adults to increase with development, suggesting that these regions are engaged more with age (Crone , Wendelken, Donohue, Van Leijenhorst, & Bunge, 2006; Klingberg et al., 2002; Kwon, 2002). In addition, other studies have found that with development activation in brain regions that are not correlated with task performance decreases (Casey et al., 1997, 2000; Durston et al., 2006; Luna, 2001). Because cognitive functions map onto similar brain regions across development, age related differences in the patterns of brain activation can help gain insight into developmental changes in cognitive processes that underlie age related changes in behavior. Even when participants from different age groups show similar behavior, the patterns of brain activation associated with this behavior can differ. Because of this, fMRI holds the potential to reveal differences between children, adolescents and adults in experimental tasks of decision-making in the absence of behavioral differences in risk-taking. Differences in brain activation patterns between children and adolescents from different ages may provide insight into the seemingly conflicting findings from observation and experimental studies on risk-taking in adolescence.

1.3 Examining decision-making development to understand risk-taking

While studies using self-report and observation methods report a peak in risk-taking and sensation seeking in adolescence (Arnett, 1996; Furby & Beyth-Marom, 1992; Steinberg, 2004; Zuckerman, 1994), studies using experiments have provided almost no evidence of this peak. In contrast, the results from these studies generally show a decrease in risk-taking from childhood to adulthood (Boyer, 2007). It has been argued that during development learning to avoid excessive risks is one of the most important skills that has to be acquired (Byrnes, 1998; Boyer, 2007; Garon & Moore, 2004; Steinberg & Scott, 2003). An influential approach to the study of human behavior in risky or uncertain situations is the study of decision-making. In this thesis, decision-making is defined as the process of choosing between competing courses of action. Often these choice alternatives are associated with possible undesirable consequences, and therefore involve risk. These undesirable consequences can range from mild (e.g. not winning 5 cents in a gambling task) to severe (being in a traffic accident). Decision-making is a complex construct and age-related changes in numerous cognitive abilities contribute to its development. This thesis will focus on the development of three abilities that are requirements for mature decision-making. *First*, the probabilities of positive and negative outcomes associated with a risk have to be judged. *Second*, the potential negative consequences of a risk have to be weighed against the potential benefit associated with it given these probabilities. And *Third,* to allow behavior to be oriented towards reaching long term goals, impulses have to be controlled, or cognitive control has to be applied.

The development of these three abilities has been studied by developmental psychologists, using different experimental paradigms. The literature on the development of the ability to judge probabilities shows mixed results. Piaget and Inhelder argued that children are unable to use probability information in their decisions until they reach the stage of formal operations around early adolescence (Piaget and Inhelder, 1975). However, the results of more recent studies suggest that well before puberty children, as young as 5 years old, have at least a basic understanding of probabilities, and can use this information when making decisions (Acredolo, O'Connor, Banks & Horobin, 1989; Schlottmann, 2001). In contrast, the ability to weigh short-term rewards against long-term rewards has been shown to improve throughout adolescence (Crone & Van der Molen, 2004; Hooper, Luciana, Conklin & Yarger, 2004) in studies in which participants were asked to complete age appropriate versions of the Iowa Gambling Task (IGT). The IGT is a widely used neuropsychological task that simulates real-life decision making in the way rewards, punishments and future consequences of decisions need to be considered. Young children's behavior has been shown to be primarily driven by the magnitude of immediate rewards (Crone & Van der Molen, 2004). In sum, the behavioral literature to date suggests that in straightforward risky situations children as young as 5 years of age can accurately estimate risks when making decisions, but decision-making in more complex situations increases gradually during development, which suggests that mature decision-making emerges over the course of adolescence. With age, participants are more able to choose the behavior that is most advantageous in the long run and focus on their long term goals.

Cognitive control, refers to the cognitive processes that enable us to control our behavior and perform goal-directed actions. It encompasses processes such as working memory (WM), inhibition, and selective attention. Cognitive control has been shown to improve with age (Eigsti et al., 2006; Mischel, Shoda & Rodrigues, 1989), and has been shown to continue to mature during adolescence (Davidson, Amso, Anderson & Diamond, 2006; Diamond, 2002; Huizinga, Dolan & Van der Molen, 2006). It is associated with late maturing brain regions in the prefrontal and parietal cortex (Casey, Galvan & Hare, 2005), and an influential view in the literature on the development of risk-taking behavior suggests that the increase in cognitive control over the course of childhood and adolescence, enables an increase in the ability to make decisions and control impulses. As a consequence, the development of cognitive control would lead to a decrease in risk-taking with age.

1.4 The insufficient cognitive control hypothesis of adolescent risk-taking

Adolescents' immature cognitive control abilities have been proposed to underlie their impulsivity, risky behavior, and sometimes seemingly irrational decisions. For example, the ability to reject an immediate reward (such as chatting with friends on MSN) in favor of a larger but delayed reward (getting a good grade because you did not chat with friends but did your homework) develops slowly. This ability begins to develop in pre-school aged children. In a classic series of experiments Mischel et al. gave 4 year olds a small reward (e.g. a cookie or marshmallow), and told them that they would receive another reward (an additional cookie or marshmallow) when they managed not to eat the cookie until the experimenter, who left the room for 15 minutes, would return. When 4 year old children are faced with this choice between a small immediate reward, and a larger, more desirable reward, many (approximately 70%) are unable to wait (Mischel et al., 1989). Similarly, when given a choice between a small immediate reward, and a larger delayed reward, children are more likely to prefer the delayed reward with age. This increase in the preference for larger delayed rewards and the ability to wait for rewards has been reported until adolescence (Scheres et al., 2006). The ability to delay gratification at age 4 appears to be predictive of inhibition abilities (Eigsti et al., 2006), and school performance (Shoda, Mischel & Peake, 1990). Children who are more able to control themselves at an early age perform better in adolescence. Several studies have shown that the ability to resist the need for immediate reward improves throughout adolescence (Crone & Van der Molen, 2004; Garon & Moore, 2004; Hooper et al., 2004; Overman et al., 2004). Indirect neuroscientific support for this theory comes from developmental fMRI studies on cognitive control abilities which show that brain regions associated with cognitive control are among the last to mature (Casey et al., 2005). In adults, damage to PFC regions, that are implicated in cognitive control, has been shown to result in impaired decision-making (e.g. Bechara, Damasio, Tranel & Damasio, 1997; Bechara, Tranel & Damasio, 2000). Taken together these findings suggest that immature cognitive control, as a consequence of the protracted development of PFC brain regions contributes to immature decision-making, and possibly to adolescent risky behavior. However, few fMRI studies examined the role of these PFC regions in the development of risk-taking directly. The studies that did have not included children; May et al. (2004) examined the neural correlates of decision-making in a group of adolescents, and Ernst et al. (2005) and Bjork et al. (2004) compared adolescents to adults. However, these studies focused on brain regions that were implicated in the processing of rewards, not on regions associated with cognitive control. A limitation of the insufficient cognitive control account of risky behavior is that it would predict that children, who have the least mature reasoning skills and cognitive control abilities, should show *even more* risk-taking behavior than adolescents. This would be in contrast to the self-report data which suggest an increase in risk-taking in adolescents compared to children. Therefore, the cognitive control hypothesis can only account for the change in behavior that occurs with the transition from adolescence to adulthood, but cannot explain why risk-taking would increase from childhood to adolescence. A second view explains adolescent risky behavior not as a consequence of the ability to control behavior, but emphasizes the increased sensation-seeking that has been reported by adolescents.

1.5 The increased arousal hypothesis of adolescent risk-taking

Adolescence can roughly be subdivided into two phases; the beginning of adolescence is marked by the onset of puberty around 10 years of age and lasts until about 15 years of age. During puberty the physical transformation from child to adult occurs under the influence of gonadal hormones; children undergo growth spurts and the secondary sex characteristics develop (Spear, 2000; Dahl 2004). The second phase of adolescence follows puberty and lasts until approximately 20 years of age. This phase is characterised by the maturation of psychological and psychosocial abilities (Steinberg, 2005). While physical changes are most apparent during puberty, important developmental changes in both brain structure and function take place throughout adolescence. Biological and physiological changes that start at the onset of puberty have been proposed to underlie the increase in sensation seeking and risky behavior in adolescence. At the onset of puberty gonadal hormones influence the brain, especially neurotransmitter systems in brain areas that are important for the processing of rewards (Spear, 2000). These areas are part of the brain's limbic system which is implicated in the experience of excitement, arousal and emotions (Nelson, Leibenluft, McClure & Pine, 2005). When these regions are more sensitive to appetitive stimuli in adolescents, this would make them more sensitive to the potential benefits associated with a risk, and as a consequence, adolescents would be more willing to try something new, and explore their environment. On the one hand, this gives them the opportunity to develop skills they need as adults (Kelley et al., 2004), but on the other hand leaves them vulnerable to risks. Because these hormonal changes are specific to adolescence, the increasing emotion and arousal hypothesis predicts a non linear pattern of risk-taking behavior, with a peak in adolescence, which is consistent with the findings from self-report and observation studies.

One of the first developmental imaging studies focusing on adolescent risk-taking examined adolescents in a guessing task in which participants could win money by guessing whether a playing card would be higher or lower than five (May et al., 2004). This study reports more activation in the ventral striatum (VS) and orbitofrontal cortex (OFC) in response to rewards compared to losses. While the May et al. study did not include adults, the VS had previously been shown to play an important role in processing rewards and in motivating behavior in adults (Knutson, Adams, Fong & Hommer, 2001; McClure, Berns, Montague, 2003). Similar findings have been reported by Ernst et al. (2005). In this study activation of brain regions associated with the processing of gains and losses was compared between adolescents and adults in a decision-making task. The VS response to rewards was larger in adolescents than adults. Together these findings suggests that reward related regions in the brain are more activate in adolescence, and this supports the hypothesis that adolescents take more risks because they are more sensitive to the potential benefits associated with that risk. In contrast, a study by Bjork et al. (2004) reported the opposite pattern. In this study reward processing was examined in adolescents and adults in the context of a monetary incentive delay task. Adolescents showed less activation in the VS in response to rewards compared to adults. These authors explained the increase in sensation seeking and risky behavior in adolescence as a consequence of this diminished sensitivity of reward systems. According to these authors, adolescents need more exciting experiences to achieve the same sense of reward as adults, and therefore take risks. It could be that differences in the behavioral requirements between the tasks used in the studies reported above account for differences in the observed patterns of brain activation. Adolescents' risk-taking behavior could be influenced by differences in the strategies used by participants from different ages when they approach a risky situation. For example, the task used by Bjork and colleagues was more difficult compared to the tasks used by May et al (2004) and Ernst et al. (2005), in that it required more cognitive control. Taken together, these findings show that we cannot explain adolescent risk-taking when we study the development of reward related brain regions, or neuroimaging results in isolation. The studies described in this chapter suggest that in order to fully understand adolescent risky behavior the development of risk estimation, reward processing, cognitive control and age related changes in brain regions associated with these functions should be studied separately, and once it is possible to investigate how these processes can be isolated, it is important to examine how they work together.

Real-world adolescent risk-taking behavior is sometimes extreme and potentially fatal, but usually more subtle. Most adolescents engage in more accepted forms of risky behavior, such as listening to loud music, wearing "extreme clothing", engaging in dangerous sports, or studying for a test at the very last minute. In addition to experiments that can capture subtle age related differences in risk-taking in the scanner, fMRI studies require testable hypotheses on the development of the neural correlates of cognitive processes that underlie the changes observed in behavioral ad self-report studies. The studies discussed in this chapter form a starting point to tackle these questions.

1.6 Outline of this thesis and publications

This chapter has given an overview of the theoretical background of the studies that are presented in this thesis. The six chapters that report empirical studies (Chapters 2-7) aimed to examine the developmental trajectory of decision-making, in order to gain insight into risky behavior in adolescence. Chapters 2 and 3 describe two developmental fMRI experiments that each focus on the neural correlates of cognitive processes that are considered basic components of decision-making under risk; the ability to judge probabilities (Chapter 2), and reward sensitivity (Chapter 3). **Chapter 2** describes the first fMRI study that examined age differences in brain activation patterns in control related regions, between children and young adults (9-12 and 18-26 years old) in a decision-making context. In this chapter we introduce a new child friendly two-choice decision-making paradigm; "the Cake Gambling Task". **Chapter 3** describes a second developmental fMRI study in which neural responses between early adolescents, middle adolescents, and young adults (10-12, 14-15, and 18-25 years old) were studied in response to rewards. This study examined the hypothesis that adolescence is characterised by a peak in the brain's responsiveness to rewards, and aimed to resolve conflicting findings of earlier studies.

While these first two chapters each focus on one of the processes that underlie decision-making; Chapters 4, 5 and 6 describe experiments in which these processes were combined and participants had to weigh risks against potential rewards. **Chapter 4** describes a behavioral study on the development of decision-making under risk, using a modified version of the Cake Gambling Task that was introduced in Chapter 2. Children, adolescents and adults from five age groups (8-9, 11-12, 14-15, 17-18, and 25-30 years old) participated in this study, in which both the probability of winning and the size of the reward that could be gambled with were manipulated. The results from this study motivated the experiments described in Chapter 5 and 6, in which we examine the relative contributions of reward sensitivity and cognitive control to decision-making under risk. In the study described in **Chapter 5** we used behavioral and psychophysiological measures to test the hypothesis that adolescent decision-making is biased towards taking risks because of an increased sensitivity to possible rewards paired with immature cognitive control. Adolescent participants from three age groups (11-12, 14-15, and 17-18 years-old) were included, and the Cake Gambling task was modified to enable us to measure heart rate changes. In addition, we introduced monetary rewards. **Chapter 6** describes the third developmental fMRI study in which we directly test the hypothesis that brain regions associated with reward processing and cognitive control follow different developmental trajectories, and underlie adolescent risk-taking. Children, adolescents and young adults from 4 age groups (8-10, 12-14, 16-17 and 19-26 years old) gambled for monetary reward in an adapted version of the Cake Gambling Task. In addition, this study examined the relation between brain activation patterns and individual differences in risk-taking behavior.

The final empirical chapter does not focus on decision-making directly. **Chapter 7** focuses on the development of an important cognitive control component, and describes a behavioral study on the development of working memory for object and spatial information in children, adolescents and young adults (6-7, 9-10, 11-12 and 18-26 years old). In addition to behavioral measures this study describes measures of heart rate changes, which provide an index of covert cognitive processes. Finally in **Chapter 8** the findings described in the empirical chapters are summarized and discussed.

All empirical chapters that this thesis consists of have been published in, or submitted to peer reviewed journals, to acknowledge the contributions of the co-authors the full references to these papers are presented below:

Van Leijenhorst, L., Crone, E. A., & Bunge, S. A. (2006). Neural correlates of developmental differences in risk anticipation and feedback processing. *Neuropsychologia, 44,* 2158-2170. (Chapter 2)

Van Leijenhorst, L., Zanolie, K., Van Meel, C. S., Westenberg, P. M., Rombouts, S. A. R. B. & Crone, E. A. (*in press*) What motivates the adolescent? Brain regions mediating reward sensitivity in adolescence. *Cerebral Cortex.* (Chapter 3)

Van Leijenhorst, L., Westenberg, P. M. & Crone, E. A. (2008) A developmental study of risky decisions on the Cake Gambling Task; Age and gender analyses of probability estimation and reward evaluation. *Developmental Neuropsychology, 33,* 179-196. (Chapter 4)

Van Leijenhorst, L., Westenberg, P. M., Crone, E. A. (*manuscript in revision*) A heart rate analysis of risky decision-making, reward sensitivity and outcome monitoring in adolescence. (Chapter 5)

Van Leijenhorst, L., Gunther Moor, B., Op de Macks, Z. A., Rombouts, S. A. R. B., Westenberg, P. M., & Crone, E. A. (*manuscript in revision*) Adolescent risky decision-making: neurocognitive development of affective and control regions. (Chapter 6)

Van Leijenhorst, L., Crone, E. A. & Van der Molen, M. W. (2007). Developmental changes in object and spatial working memory: A psychophysiological analysis. *Child Development, 78,* 987-1000. (Chapter 7)

Chapters 1 & 8 are based on a book chapter and paper (in Dutch) that were published as:

Van Leijenhorst, L. & Crone, E. A. (2009). Paradoxes in adolescent risk-taking. In: Zelazo, P. D, Chandler, M. & Crone, E. A. (Eds). *Developmental Social Cognitive Neuroscience.* Oxford University Press.

Van Leijenhorst, L. & Crone, E. A. (2009). Het adolescentenbrein: Inzichten in risicovol gedrag in de adolescentie uit de cognitieve neurowetenschappen. *Neuropraxis, 1,* 3-7.