Towards a better understanding of adolescent risk taking: Contextual moderators and model-based analysis

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Adolescence is the transition period between childhood and adulthood during which individuals gain independence and develop mature social goals. The age range of adolescence differs between countries and cultures, but it is generally agreed upon that, in Western societies, adolescence encompasses the period of approximately ages 10 to 22 years (Blakemore, & Robbins, 2012; Crone, & Dahl, 2012). The onset of adolescence commences at the start of puberty, which is the phase in life during which rapid increases in gonadal hormones result in changes in physical appearance, such as voice changes in boys and breast development in girls, but also behavioral and brain changes (Blakemore, Burnett, & Dahl, 2010). That is, it has been found previously that pubertal hormones have a massive influence on the developing brain structure and function (Peper, & Dahl, 2013). Puberty thus marks the first phase of adolescence and starts approximately around ages 10-11-years, on average 1.5 years earlier for girls than for boys, and lasts until approximately age 15-16 years (Blakemore et al., 2010). The second phase of adolescence (16-22 years) is characterized by the development of mature goals and gaining independence from parents. The end of adolescence is mostly culturally defined, and is dependent on when individuals obtain a mature role in society (Crone, & Dahl, 2012).

Adolescence often has been described as a period of increased risk taking (Reyna, & Farley, 2006). Risk taking is typically referred to behaviors or decisions in which outcomes are uncertain, and in which at least one negative consequence could occur. A more formal description has been used in economics and the decision sciences, in which risk taking is defined as choosing the option with the largest outcome variability (Figner, & Weber, 2011). Adolescent risky behavior is consistent with both conceptualizations of risk taking, as often these behaviors can result in potentially large rewards for adolescents (such as obtaining high status with peers when stealing an exam), but also in large costs (such as being suspended because for being caught when stealing the exam). Epidemiological reports have observed an increase in risk taking behavior in adolescence, such as for traffic accidents, delinquency, and substance abuse (see Willoughby, Good, Adachi, Hamza, & Tavernier, 2013). Therefore, it is often assumed that adolescents take more risks than children and adults, which may come at a substantial individual and societal costs. Since there is evidence that this is a universal characteristic of all known human societies—and also shared with other mammal species—there is reason to believe that this may have evolutionary adaptive value. For example, because risk taking is necessary for exploring new environments, achieving high social ranks, or experimenting with new social roles in society (Crone & Dahl, 2012; Wilson & Daly, 1985). However, others have argued that adolescents merely have more opportunity for risk taking, because they are less supervised compared to young children (e.g., Willoughby et al., 2013).

Several studies used a controlled experimental environment (with equal opportunity for risk taking in all age groups) to test the question whether there is a unique adolescent signature of risk taking. Such laboratory studies have remained elusive with respect to whether risk taking is reliably observed in adolescence, and under which circumstances. Some studies have shown that children, adolescents and adults take similar levels of risk (van Duijvenvoorde et al., 2015; van Leijenhorst, Westenberg, & Crone, 2008). Others have observed that adolescents take more risks than adults but less than young children, suggesting a monotonic decrease across adolescence in risk taking (Crone, & van der Molen, 2004; van Duijvenvoorde, Jansen, Bredman, & Huizenga, 2012). Finally, some studies have shown that adolescents take more risks than children and adults, especially in 'hot' contexts that trigger affective-emotional processes (Burnett, Bault, Coricelli, & Blakemore, 2010; Figner, Mackinley, Wilkening, & Weber, 2009a), such as when rewards are high (Braams, Peters, Peper, Guroglu, & Crone, 2014), or under socially arousing situations (Chein, Albert, O'Brien, Uckert, & Steinberg, 2011). A recent meta-analysis (Defoe, Dubas, Figner, & van Aken, 2015) examined the evidence for heightened levels of risk taking in adolescence (compared to childhood and adulthood) on laboratory tasks. This meta-analysis showed that risk taking decreased between adolescence and adulthood, but that children and adolescents showed similar levels of risk tasking, although contextual factors of the decision making situation could influence this pattern. A question for further research is therefore *when, i.e., under which circumstances*, adolescent risk taking is triggered and when it is not. That is, to what extent does adolescent risk taking depend on different contextual factors? In the following sections of this chapter we will focus particularly on the decision domain and the level of experienced decision-uncertainty as two specific contextual moderators.

Another important question is *what* drives adolescent risk taking, i.e., what are the mechanisms underlying different levels of overt risk taking. One way to better understand potential mechanisms is to decompose the different components of risk taking with experimental designs suited for this purpose. In the decision sciences and behavioral economics, several model-based approaches exist that allow to decompose overt risk-taking levels into underlying mechanisms. This approach, which so far has been mostly applied to adult risk-taking, may prove valuable for understanding risk taking in adolescence as well. That is, some adolescents may be more inclined to focus on the rewarding feeling of positive outcomes when taking risks (such as, in our earlier example, focusing on gaining peer status when stealing an exam), whereas others may focus more on the potential negative outcomes (such as being suspended). Therefore, we will also describe several prominent—and promising—decision models and highlight the potential of such decomposition approaches for studying adolescent risk taking.

Taken together, there is a clear societal need to have a better understanding of risk taking in adolescence, and experimental studies have made tremendous progress in understanding the determinants of risk taking in the laboratory. This increase use of experimental approaches also has led to several important lingering questions particularly focusing on the questions (1) under which circumstances do adolescents take more risks than adults and children, and (2) what drives adolescent risk-taking. Research on these questions has benefited much from experimental behavioral studies, but also from physiological measures, such as brain activity when individuals take risks or when individuals obtain rewards (e.g., Crone, van Duijvenvoorde, & Peper, 2016). That is, across adolescence, and into early adulthood, several studies have shown that there are large functional and structural changes in the brain, such as ongoing increases in myelination and a gradual decrease in synaptic density (e.g., Gogtay et al., 2004; Huttenlocher, 1990; Tamnes et al., 2010). In this chapter we will therefore also take into account neural changes that help to pinpoint changes in adolescent risk-taking.

The *when* of adolescent risk-taking

Domain-specific risk taking

It has been debated in the psychological literature whether risk taking is a unidimensional construct. That is, a dominant view states that risk taking represents either a single personality trait or a small cluster of traits (e.g., impulsivity and sensation seeking; Hansen & Breivik, 2001). However, the relation between trait like impulsivity and real-world risk taking is relatively complex, and a single trait typically will not predict risk taking across different domains or situations very well (Fox & Tannenbaum, 2011; Weber, Blais, & Betz, 2002).

One way to unpack risk taking is to focus on the potential domain-specificity of individuals' risk taking. Domain-specific risk taking means that somebody's risk taking in one domain (e.g., recreational risk taking, such as bungee-jumping) may not be highly correlated with his or her risk taking in another domain (e.g., financial risk taking, such as investment behavior). The Domain Specific Risk Taking scale (DOSPERT; see Blais, & Weber, 2006; Weber et al., 2002) is an instrument that assesses individuals' risk taking across five broad domains: Social (e.g., asking an employer for a raise), Recreational (e.g., skydiving), Financial (sometimes split into an investment and a gambling component; investment: e.g., investing in a speculative stock; gambling: e.g., betting money on a sporting event), Health/Safety (e.g., drinking too much alcohol at a party), and Ethical (e.g., cheating on a tax return). The adult DOSPERT scale has shown evidence of construct validity in a full (Weber et al., 2002) and a shortened version (Blais, & Weber, 2006), and DOSPERT self-reports have been related to real-life risk-taking behavior. For instance, Markiewicz and Weber (2013) found that individuals reporting more risk taking propensity specifically on the DOSPERT gambling component were also more likely to engage in excessive stock trading.

Within the DOSPERT scale, risk taking—the self-reported likelihood of engaging in a risky activity—is measured separately from two additional scales that measure perceived risks and expected benefits of engaging in risky activities in each domain. Thus, an important advantage of the DOSPERT is that it assesses not just domain-specific risk taking propensities but also two important motivators of such behavior, namely perceived risks and benefits. This builds on a risk-return framework, in which risk taking is predicted by both perceived risks (alternatively described as 'fear') and perceived benefits (alternatively described as 'greed') (Weber et al., 2002). Thus, risk behavior will vary across domains if there are differences in the subjective perception of risks and/or expected benefits. Although most people will dislike risks and like benefits, important individual differences in risk- and benefit-perception exist, which may explain differences in overt risk taking.

Emerging evidence indeed suggests that risk taking is a domain-specific construct. For instance, it has been found that smokers take more risks that concern their health compared to non-smokers, but do not take more risks in other domains such as financial or social risk taking (Hanoch, Johnson, & Wilke, 2006). Similarly, documented recreational risk takers (e.g., skydivers) have only average risk-averse scores in other domains (e.g., Hanoch et al., 2006). Also, greater decision making competence—which reflects individual differences in rational responding across several classic behavioral decision-making tasks—has been related to less risk taking, but only for domains which are more maladaptive in nature, such as health and gambling risks (Weller, Ceshi, & Randolph, 2015). Additionally, HEXACO personality factors have been shown to be related to common and distinct aspects of risk taking. That is, 'openness' specifically related to risk taking in social and recreational domains, whereas lower 'honesty/humility' has been associated with greater health and ethical risk taking (Weller, & Tikir, 2011). Finally, Rolison and colleagues (Rolison, Hanoch, Wood, & Liu, 2014) observed—besides a pattern of normative age-related decline in risk taking—that financial and recreational risk taking showed steeper declines into old age than social, ethical and health domains (see for a longitudinal approach Josef et al., 2016). Collectively, these findings suggest some level of domain-specificity in adults' risk taking. A next question for research is whether different risk-taking domains exhibit different developmental trajectories.

In adolescence research, there is no comparable research on domain-specificity in risk taking, but there is some evidence that this might be the case. For instance, different addictive behaviors (substance use, gambling, gaming) have been specifically related to characteristics such as depression and extraversion (for substance use) and to irritability/aggression, social anxiety, and low self-esteem (for gaming) (Walther, Morgenstern, & Hanewinkel, 2012). To test individual's domain-specific risk-taking behavior further, an adolescent-version of the DOSPERT recently has been developed (although not yet evaluated in a large sample). The adolescent DOSPERT (originally developed by Bernd Figner and Elke Weber) includes similar decision domains as the adult DOSPERT and similarly builds on a risk-return framework, yet includes adolescent-appropriate domain-specific questions. A functional magnetic resonance imaging (MRI) study has used a tentative version of the adolescent DOSPERT in adolescents (ages 13-17, n = 18) and adults (ages 25-30, n = 16) to test the relation between neural activation during risky choice and real-life reported risk taking (Barkley-Levenson, van Leijenhorst, & Galvan, 2013). To this end, this study used a choice paradigm with mixed gambles presenting a 50-50 probability of winning or losing a certain amount of money, and a choice to accept (i.e., play) or reject this gamble (see for a similar paradigm in adults studying loss-aversion: Tom, Fox, Trepel, & Poldrack, 2007. Results showed that greater activation in the dorsal medial prefrontal cortex (PFC) during risk-avoidant choices was related to less self-reported risk taking, but only in adolescents. Because the medial PFC has been implicated in the representation of value during risky decision-making (e.g., Levy et al., 2010), the authors interpreted this finding as a lower reliance of value-assessments when evaluating choices for adolescents who were more inclined toward real-world risk taking. These results highlight the possible application of the adolescent DOSPERT to study individual differences and age-related change in adolescent risk-taking. However, it was not yet investigated to what extent brain-behavior relations of risk taking may be domain-specific across adolescence, nor to what extent risks and benefits influence risk-taking levels. Moreover, these findings will need to be supported by further (larger) studies. In ongoing studies, we are currently validating the adolescent DOSPERT scale in several large developmental samples. Moreover, we currently investigate the domain-specificity and factors underlying (risk and benefit perception) in adolescent's self-reported risk-taking.

Decision making under uncertainty

Another important construct that may drive individuals' risk taking is the level of uncertainty encountered in the decision environment. That is, although the magnitudes of the outcomes of risky choices are usually known (e.g., the pleasure one derives from smoking a cigarette), the probabilities of those outcomes may often not be known exactly or be even completely unknown (for example whether one will develop lung cancer because of smoking). First, risk can occur under conditions in which the probabilities of the outcomes are completely known. This has been defined as explicit risk (Knight, 1921; Tversky & Kahneman, 1979), and examples include a coin toss (for which the chances are 50:50), or a roulette wheel (for which the chance of the wheel stopping at the color red, for instance, is also just below 50:50). However, real-life often does not present exact probabilities. Consider the example of driving through a red light. One may know that a traffic accident is possible, but unlike a coin toss, one cannot be certain of the probability that this outcome may occur. The level of uncertainty (sometimes referred to as ambiguity) has been found to have differential effects on risk taking across the life span (Tymula, Rosenberg Belmaker, Ruderman, Glimcher, & Levy, 2013) and adolescents seem to be particularly ambiguity-tolerant (Blankenstein, Crone, van den Bos, & van Duijvenvoorde, 2016; Tymula et al., 2012).

Prior studies have shown that people generally have an aversion to both explicit risk (known probabilities; Von Gaudecker, Van Soest, & Wengström, 2011) and ambiguous risk (unknown/uncertain probabilities; Ellsberg, 1961), but people show an even stronger aversion to ambiguous than known risk. This can be illustrated by the famous Ellsberg paradox (Ellsberg, 1961), in which two urns are presented: one urn with 50 red and 50 black balls, and one urn with 100 red and black balls in an unknown distribution. People typically prefer the first urn when asked to bet between urns for grabbing a red ball. Yet when asked to bet on a black ball from one of the urns, they again bet on the first urn with the known distribution of balls. This continuous betting on the urn with the known probabilities contradicts individuals' earlier beliefs about the distribution of the second urn (i.e., that there are more black balls in the second urn), and illustrates people's aversion to unknown distributions (i.e., ambiguity).

Most risk taking studies in adolescents have either investigated risk alone with explicit risky decision tasks, such as the Game of Dice task, or the Columbia Card Task (e.g. Donati, Panno, Chiesi, & Primi, 2014; Figner et al., 2009a; Schiebener, Zamarian, Delazer, & Brand, 2011; van Duijvenvoorde et al., 2015; van Leijenhorst et al., 2008), or have used paradigms in which risk and ambiguity were inseparable using paradigms such as the Iowa Gambling Task or the Balloon Analogue Risk Task (e.g., Crone, & van der Molen, 2004; Lejuez, Aklin, Zvolensky, & Pedulla, 2003; van Duijvenvoorde et al., 2010; 2012). Adult studies have also examined decisions under conditions of risk and ambiguity separately (see Gilboa & Schmeidler, 1989; Huettel, Stowe, Gordon, Warner, & Platt, 2006; Hsu, Bhatt, Adolphs, Tranel, & Camerer, 2005; Levy, Snell, Nelson, Rustichini, & Glimcher, 2010; Tymula et al., 2013). Risk-and ambiguity attitudes are typically unrelated, suggesting they are distinct elements of risk taking (Huettel et al., 2006; Levy et al., 2010; Tversky & Kahneman, 1992). Given that risk-taking situations in daily-life typically include more ambiguous prospects—and adolescents are also more likely to make decisions detrimental to their health, well-being, and financial situation—it is of interest to study how ambiguity influences adolescents' risk-taking. That is, ambiguous risk situations may provide a potential context in which adolescents are particularly likely to take more risks than adults (Defoe et al., 2015).

One way to study risk- and ambiguity-attitudes is to include both risky gambles (known probabilities) and ambiguous gambles in a choice task. For instance, the study of Li and colleagues (Li, Brannon, & Huettel, 2014) included a two-choice task that presented a choice between a risky gamble with a 50-50 probability and an ambiguous gamble with unknown probabilities. A rational (i.e., ambiguity- and risk-neutral) decision maker should treat these gambles similarly and therefore choose both options equally often. When comparing children (8-9 years) with adults (19-27 years), children were indeed equally likely to choose the ambiguous and the risky option, whereas adults chose the risky option more often than the ambiguous option (see Figure 1). On a separate task, children were willing to pay as much to play out an ambiguous than a risky gamble, whereas adults were willing to pay more to play out the risky than the ambiguous gamble. Both findings highlight that children, in contrast to adults, did not yet differentially respond to risk versus ambiguity (Li et al., 2014). This suggests that only in adolescence, ambiguity-aversion might start to develop into the pattern typically observed in adulthood.

Adolescents' risk- and ambiguity-aversion has been studied recently using a two-choice paradigm with varying conditions of risk and ambiguity to estimate risk- and ambiguity-attitude across the life span from ages 12 to 90 (Tymula et al., 2013). Participants were recruited from four different age groups: adolescence (12-17 years), young adulthood (21-25 years), midlife adulthood (30-50 years), and older adulthood (65-90 years). One choice option was a consistent sure gain, whereas the other option was a lottery, that varied systematically in the amount that could be won, and either the probability of winning (in the case of a risky trial), or the level of ambiguity (in the case of an ambiguous trial) (Tymula et al., 2012; 2013). The level of ambiguity was varied by changing the size of an occluder that could cover more or less of the probabilities.

This study observed pronounced differences across age groups in risk- and ambiguity-attitude. That is, all age groups were risk-averse, with the older adults being most risk-averse (Tymula et al., 2013), and surprisingly adolescents being more risk-averse than adults (Tymula et al., 2012). Moreover, young adults, mid-life adults, and older adults were all similarly ambiguity-averse, suggesting that from adulthood, people remain relatively stable in their attitude towards ambiguity. However, when comparing ambiguity-attitude between adolescents (12-17 years) and adults (30-50 years) it was observed that adolescents were less ambiguity-averse than the adults (Figure 1). The authors interpreted this as a unique tolerance to ambiguity in adolescence. Note that in this study, risk- and ambiguity-attitude were uncorrelated in the adolescents, suggesting that risk and ambiguity indeed reflect different elements of adolescent risk-taking. This was further demonstrated by the finding that ambiguity-attitude, but not risk-attitude, was related to the frequency of self-reported reckless behavior in daily life. Specifically, less ambiguity-aversion was related to more frequent reckless behavior such as drinking and driving, and having unprotected sex. These findings suggest that tolerance to ambiguity may particularly change across adolescence, and could drive changes in real-life risk taking.

Finally, to further test the age-related change in risk- and ambiguity-attitude across adolescence, Blankenstein and colleagues (2016) studied these attitudes in a larger adolescent sample (*N*=157) with a continuous age range between ages 10 and 25. Although individual differences were prominent, most participants were risk-averse, and risk-aversion did not change with age. Most participants were also ambiguity-averse, but contrary to risk-aversion, ambiguity-aversion increased linearly across adolescence (Figure 1). Furthermore, Blankenstein et al. replicated the relation between ambiguity-attitude and the frequency of real-life reckless behavior, in which a greater ambiguity, but not risk-tolerance, was related to more reckless daily-life behavior.

Taken together, these studies highlight that risk (known probabilities) and ambiguity (uncertainty about probabilities) are distinct elements of risk taking, which show different developmental patterns. Particularly, ambiguity-aversion seems to only emerge from age 10, increase across adolescence, and relate to real-life risk taking. Suggestively, a long-lasting tolerance to ambiguity in adolescence may be adaptive, given that adolescence is a period of increased novelty seeking which requires a certain tolerance to uncertain outcomes (e.g. Crone, & Dahl, 2012). A tolerance to uncertainty may thus be a mechanism that allows for accomplishing these goals, exploring new environments, and gathering information about the world (e.g., Hartley, & Somerville, 2015). A next step would be to relate tolerance to ambiguity not only to maladaptive risk taking in adolescence, but also to the more adaptive properties of risk taking behavior such as adolescents' novelty-seeking and exploration-tendencies.

The *what* of adolescent risk-taking

Until now, we have only described a small proportion of possible moderators in adolescent risk-taking (e.g., domain-specificity, risk and expected benefit perception, and risk- and ambiguity-attitude). Obviously adolescent risk-taking is a multifaceted phenomenon with a large array of underlying causes and drivers (for thorough overviews, see e.g., Boyer, 2006; Reyna & Farley, 2006). Nevertheless, we believe there is much potential by making more use of the tools and insights that the decision sciences (and related disciplines such as behavioral economics, decision neuroscience, neuroeconomics, and reinforcement-learning theory) provide to study adolescent risk-taking. In particular, we think that a better mechanistic understanding of psychological and neural processes can be gained by both taking advantage of the methodological tools and—at the theory level—by increasing specificity of our theoretical frameworks (e.g., Pfeifer, & Allen, 2016; van den Bos, & Eppinger, 2016). Thus, we propose that adopting methods and modeling approaches to decompose overt risk taking levels promises to advance our insights of adolescent risk-taking at a mechanistic level. Such a mechanistic understanding in turn promises to lead to more efficient prevention, intervention, and perhaps even treatment approaches in the future.

In this section of our chapter, we will focus mostly on a selection of formal risky choice models and how they may help to improve our understanding of the mechanisms and drivers underlying adolescent risk-taking. As we (e.g., Figner, & Weber, 2011; van Duijvenvoorde, & Crone, 2013) and others have pointed out before, adopting a formal modeling approach is one promising avenue to advance the field. Within risky decision making research, different types of formal models exist. In the next section, we focus on main models that have been predominantly applied to adults' risk-taking. We first describe these main model types, and subsequently their potential applicability for understanding adolescent risk-taking.

Expectation models

A prominent class of models can be referred to as *expectation models* (e.g., Pachur, Hertwig, Gigerenzer, & Brandstätter, 2013): Individuals are assumed to compute some kind of subjective value of the available choice options by multiplicatively integrating information on outcome magnitudes and outcome probabilities. In a next step, the option with the highest subjective value is then chosen (more details, including a historical overview, can be found for example in Weber & Johnson, 2008).

The earliest of such models were expected value models, i.e., the sum of each objective outcome magnitude multiplied with its objective outcome probability. In a next step, an important refinement was then to assume that the subjective representation of outcome magnitudes can differ from the objective outcome magnitude, and that the subjective value ("expected utility," thus Expected Utility Theory, EUT) can be modeled with marginally decreasing sensitivity (Von Neumann & Morgenstern, 1944; Savage, 1954), e.g., by a power function with an exponent smaller than 1. EUT can explain why most people are typically risk averse. For example, given a choice between EUR 45 for sure versus a 50% chance to win EUR 100 and otherwise EUR 0, most individuals would choose the riskless EUR 45 for sure, although the objective expected value of the risky option is higher (e.g., the objective EV = .50 * 100 = 50). This behavior would indicate that the value function is not linear, but modified with an exponent (e.g., $0.5 * 100^{0.88} = 0.5 * 57.54 = 28.77$), creating a concave value function indicating risk aversion. Note that the work by Tymula and colleagues (2012; 2013) and Blankenstein and colleagues (2016) that we discussed earlier in this chapter, addresses a modelling approach using a type of EUT framework. These studies demonstrate the usefulness of combining developmental work with formal models of risky choice in disentangling influences of risk and ambiguity.

Another prominent example of a further refined subjective expected utility model is Daniel Kahneman and Amos Tversky's Prospect Theory (PT) (Kahneman, & Tversky, 1979) and cumulative PT (Tversky, & Kahneman, 1992). In brief, PT models risky choice (as well as individual and situational differences therein) by a set of parameters that translate objective attributes (probabilities, gain amounts, loss amounts) into subjective representations, allowing for deviations of subjective representations from their objective counterparts. In typical PT specifications, this is represented by a so-called value function (e.g. a function that is assumed to be typically steeper for losses than gains, reflecting what is often referred to as loss-aversion, i.e, that losses loom larger than gains), and a probability weighting function which defines the deviation from objective probabilities (i.e., people typically overweight small probabilities and underweight large probabilities). An example of the use of PT in adolescent decision making is a recent study testing to what extent advice from an adult expert influences risky decision making in early adolescents (ages 12-14), late adolescents (ages 15-17), and adults (ages 18-45) (Engelmann, Moore, Capra, & Berns, 2012). While undergoing functional MRI participants made decisions with real financial outcomes between sure wins and risky lotteries. On half the trials, risk-averse advice from a financial expert was displayed, which participants were free to ignore. On the other half of the trials, participants made choices without advice. Results indicated significantly more adult-like behavior in both adolescent groups in the presence of advice. By using cumulative prospect theory, the authors observed that advice particularly influenced the weighting of probabilities in adolescence. In addition advice increased the correlation strength between activity in the lateral PFC and behavioral valuation of safe choices in adolescents. In contrast, in adults advice decreased the correlation strength between activity in ventral medial PFC (vmPFC) and risky choice valuation. Thus, social advice may modulate adolescents' behavior via valuation-specific enhancement of cognitive-control processes (as reflected by lateral PFC activation).

Related but simpler approaches to decomposition in an expectation-model framework investigate the impact of the *objective* properties of risky choices on risk-taking levels. In our own work, we developed the Columbia Card Task (CCT; Figner & Voelki, 2004; Figner, Mackinlay, Wilkening, & Weber, 2009a; 2009b) for exactly this purpose, namely to be able to assess not only overt risk-taking levels in different age groups, but to investigate the impact of variations in "economic primitives" of risky choice, namely the potential gains, potential losses, and their probabilities (e.g., Figner et al., 2009a; Panno, Lauriola, & Figner, 2013)[1]. With the CCT we have observed that adolescents from age 14 on adequately adjusted their risk taking towards changing levels of gains, losses, and probabilities, but particularly so in a 'cold' (more deliberative) choice situation compared to a 'hot' (affectively-driven) choice situation.

These recent studies illustrate that the use of such models may allow us to move from describing whether there are changes in risky choice across development, to what choice processes drive these observed changes. That is, these decomposition approaches—ranging from the relatively simple models investigating objective properties to the more sophisticated models that account for subjective representations—thus allow to not only test *when* adolescent risk-taking is more likely to occur (such as when comparing 'hot' versus 'cold' decision-making), but also *what* is changing (such as reduced control, or reduced information processing, or changes in sensitivity to gains, losses, probabilities, etc.) and how that might explain changes in adolescents risk-taking levels.

Risk-Return Models

There is a variety of other formal risky choice models besides expectation models. Of those, the most similar to the expectation models are the so-called *risk-return models* (e.g., Weber, 2010) (this model type is also the basis of the DOSPERT scale discussed earlier). The risk-return framework decomposes risky choices into a return and a risk component. The return component can be modeled by the expected value of the risky choice option (i.e., an integration of probability and outcome magnitudes), and the risk component by its outcome variability (often operationalized via the variance or the standard deviation of the outcome distribution). Thus, in contrast to the expectation models, risk-return models contain an explicit component of risk, making them attractive from a psychological perspective. The main idea is that, when making a risky choice, decision-makers trade-off possible returns against possible risks: Most individuals like increasing returns and thus increasing returns are associated with approach (i.e., an increasing likelihood to choose the risky option). On the other hand, most individuals dislike increasing risks, and therefore increasing risks are often associated with avoidance (i.e., a decreasing likelihood to choose the risky option).

[1] Nevertheless, to adopt a more advanced decomposition approach, we recently have developed and tested in adults an adjusted CCT version that allows estimation of prospect theory parameters.

As we discussed in more detail in Figner and Weber (2011) and van Duijvenvoorde et al. (2015), this decomposition allows for a metric of individuals' sensitivity to returns, their sensitivity to risks, and the tradeoffs between the risks and returns. In our own work, we developed an fMRI-CCT version to investigate risk-return tradeoffs in children, adolescents, and adults while they make dynamic risky choices in the MRI scanner (van Duijvenvoorde et al., 2015). While we did not observe any age-related differences in overt risk-taking levels, we observed pronounced individual and age-related differences in behavioral and neural sensitivities to returns and risks. That is, neural activation in response to expected value increased monotonically with age in a valuation network including the vmPFC and posterior cingulate cortex (see Figure 2). Neural activation in response to risk, on the other hand, peaked in adolescents, as reflected in increased activation in the insula and dorsal medial prefrontal cortex. Moreover, we observed that adolescents' behaviorally estimated risk- and return-sensitivity was related to these neural activations (Figure 2).

Risk-return decompositions have been used successfully in adults, but only rarely in developmental work (e.g. Burnett et al., 2010; Paulsen et al., 2011; 2012). To the best of our knowledge, all of these developmental studies (including our own) investigated only the effects of *objective* risk. That is, these analyses assume (at least implicitly) that subjective risk does not differ systematically from objective risk. For future work, it might be fruitful to investigate whether subjective and objective risk might differ in systematic ways, and perhaps so differently across different age groups.

Piagetian and heuristic models

Besides expectation and risk-return models, the decision sciences, behavioral economics, and other disciplines developed other decision-making models relevant for risk taking. For example, there are a wide range of lexicographic and other heuristic models that do not assume that decision-makers always take into account all the relevant information about outcome magnitudes and outcome probabilities. In developmental psychology, these models have been fruitfully combined with thinking and methodology in Jean Piaget's and Robert Siegler's tradition (e.g., Jansen, van Duijvenvoorde, & Huizenga, 2011). This work is based on the assumption that younger children might first not take into account all relevant pieces of information, but only focus on some of it, like for example loss magnitude (though see Wilkening, & Anderson, 1982). That is, a Piagetian framework states that children's problem solving is a progression through a series of suboptimal stages before the "correct" or "normative" strategy is used. This resembles the use of decision heuristics, or strategies that simplify the decision process by comparing options based on a limited set of attributes. The use of verbatim (e.g., normative and mathematical reasoning) and gist-based (e.g., intuitive and heuristic) strategies across development has also been prominently outlined in fuzzy-trace theory (Reyna, & Rivers, 2008). This theory, however, states that children rely more on verbatim processes, whereas across development we would increasingly rely on gist. This increased use of gist predicts a greater susceptibility to biases in decision-making across development, yet similarly an increase in risk-averse behavior (see for a detailed description Reyna & Farley, 2006; Reyna, & Rivers, 2008). A study by Jansen and colleagues (Jansen, van Duijvenvoorde, & Huizenga, 2011) supports both accounts by observing that a more normative decision strategy (combining outcomes and probability into expected value) was increasingly adopted with age, although the use of more complex heuristics also increased. Yet predominantly large individual differences were observed in decision strategy between children of the same age group.

Recent neuroimaging findings further tested such individual differences and observed that adults may differ in their tendency to engage in different (non)-heuristic decision strategies, which was reflected in distinct underlying neural signals during choice (van Duijvenvoorde, Figner, Weeda, van der Molen, & Huizenga, 2016; Venkatraman, & Huettel, 2012). Additionally, a recent study observed that adolescents who used a more complicated reasoning strategy showed greater activation in cognitive-control regions such as the PFC and parietal cortex, over and above age (Peters, Koolschijn, Crone, van Duijvenvoorde, & Raijmakers, 2014). The acknowledgement of different decision strategies within, and between, age groups is particularly important for illustrating the level of individual differences across distinct developmental phases.

Reinforcement learning

Another class of modeling frameworks have their origins in reinforcement-learning theory and often focus more on the involved dynamics over time, for example how individuals in different age groups might differentially learn from probabilistic positive and negative feedback, and how that can affect their decisions and decision strategies (Hämmerer & Eppinger, 2012). A more detailed and formal analysis of sensitivity to positive feedback (i.e., gains) and negative feedback (i.e., losses) can be made by examining outcomes in relation to prior expectations. When decision outcomes do not match expectations formed on the basis of previous trials, they trigger a learning signal that is referred to as a prediction error. A prediction error signals a mismatch between expected and obtained outcomes, and is therefore positive if outcomes are better than expected and negative if outcomes are worse than expected. Adolescents may show heightened prediction error signals to both positive (Cohen et al., 2010) and negative outcomes (Hauser, Iannaccone, Walitza, Brandeis, & Brem, 2015), although these developmental differences in prediction-error coding are not consistently observed (van den Bos, Cohen, Kahnt, & Crone, 2012).

The extent to which a prediction error alters subsequent subjective valuation of choice options depends on one's estimated learning rate. High learning rates give heavy weighting to recent outcomes, whereas lower learning rates lead to more integration over a longer feedback history. It has been observed that children weight recent negative feedback more heavily (van den Bos et al., 2012), and are more responsive to occasional losses. That is, in a probabilistic learning task, children and young adolescents have been found to continue updating behavior after receiving an occasional loss, which—in a stable choice environment—results in lower overall outcomes (van Duijvenvoorde et al., 2012). On the other hand, learning rates for gains may increase across adolescence (van der Schaaf, Warmerdam, Crone, & Cools, 2011). These opposite developmental patterns could lead to variable weighting of positive and negative outcomes in adolescents' behavior (Hartley, & Somerville, 2015). Future studies should examine in which ways such learning signals might differ as a function of task context and how these factors might contribute to adolescent risk-taking.

Summary of model-based approaches

To summarize, in this chapter we tried to show that the adoption of formal modeling approaches that allow decomposition of overt risk-taking levels into underlying processes is a still underused tool in developmental studies. These promising approaches have shown to not only lead to novel and highly relevant insights, but to also substantially advance the developmental (neuroscience) field as it moves to more concrete and specific models. For instance, if we observe an adolescent's reckless behavior, is this driven by a heightened tolerance to ambiguity, a lower sensitivity to risk, or a heightened focus on possible benefits? The question of what model to use is partly an empirical question. That is, explicit model fits allow a researcher to compare (nested) sets of models in order to test which model best describes the data. On the other hand, if the specific research interest and the methodological paradigm is focused towards a particular aspect (such as the learning or processing of outcomes), this will of course also determine what type or class of model is the most appropriate.

However, we also want to point out that when such a formal modeling approach is adopted, it is important to critically evaluate the used model. Adult research has shown that there is both substantial inter-individual and intra-individual variation in risky choice strategies. On the one hand, different individuals may habitually tend to differ in how they make risky decisions (van Duijvenvoorde et al., 2016). On the other hand, decision-makers can also adaptively adjust their strategies as a function of context and the task at hand (e.g., Payne, Bettman, & Johnson, 1993). This means that the same formal model might be able to explain one participant's risky decisions very well while it fails to capture and model the relevant processes of another decision maker. In developmental studies, this problem might be aggravated given that children and adolescents go to multiple phases of transitions, resulting in age-related systematic differences. So, if for example a study uses prospect theory as a model framework, one should not only estimate the relevant parameters and compare them across age groups, but should also test whether prospect theory is equally able to explain the choices of all age groups equally well. This additional investigational step is not only important to safeguard interpretations but is likely to contribute by itself to a better understanding of how and why different age groups may differ in their risky choices.

Conclusion and Future Directions

In this chapter, we have discussed the “when” and “what” of adolescent risk-taking, by considering contextual moderators of adolescent risk-taking and by considering several formal model approaches that may be used to advance our knowledge of what drives and underlies adolescent risk-taking. Specifically, we addressed the importance of testing the domain-specificity of adolescent risk-taking, the type of uncertainty of the decision-context, and described how these factors may drive adolescents’ daily-life risky choice. Besides purely describing levels of risk taking by different individuals in different situations (e.g., Figner & Weber, 2011), an important goal of studying adolescent risky choice is to understand what drives risk taking, especially when the ultimate goal is to help adolescents make better decisions, or to understand the adaptive nature of risk taking behaviors. For these goals, a model-based approach is an interesting starting point to decompose the processes that contribute to adolescent risk-taking. Here, we have laid out a set of models that could be applied to adolescent behavior.

Finally, we want to highlight two research topics in adolescent risk-taking for which the approaches in this chapter may be particularly useful (and are increasingly being utilized). First, changes across adolescence in overt or decomposed risk taking may be influenced by levels of pubertal hormones (Blakemore et al., 2010; Crone, & Dahl, 2012). Studies that aim to disentangle age- and puberty-related changes provide important information which developmental process (age or hormones) steers neural and behavioral changes in adolescent risk-taking (Braams et al., 2015; Peper & Dahl, 2013; de Water et al., 2013), and can be easily combined with a model-based perspective. Second, a vast number of studies have tested how social context influences adolescent risk-taking, including manipulations of peer presence, peer advice, or peer pressure (Somerville 2013; Albert, Chein, & Steinberg, 2013). Note that most risk-taking paradigms in this chapter are well-suited for creating a social decision-context that can be combined with social-valuation and social-learning models (see Ruff & Fehr, 2014, for an overview).

Advancing our understanding of developmental changes in risky decision-making is important for providing crucial input such as to optimize adolescents' decisions or providing interventions for problematic choice behaviors when necessary. Although adolescence is often described as a period of heightened risk taking, the flexible nature of adolescence can also have several advantages for rapid learning and adjustment to changing context. A better conceptualization of adolescents' sensitivities will be an important step toward understanding adolescent advantages in decision-making, as well as specific behaviors with negative outcomes, such as excessive and maladaptive risk taking.

References

Albert, D., Chein, J., & Steinberg, L. (2013). The teenage brain peer influences adolescent decision making. *Current Directions in Psychological Science, 22,* 114-120.

Barkley-Levenson, E.E., Van Leijenhorst, L., & Galvan, A. (2013). Behavioral and neural correlates of loss aversion and risk avoidance in adolescents and adults. *Developmental Cognitive Neuroscience, 3,* 72-83.

Blais, A.R., & Weber, E.U. (2006). A domain-specific risk-taking (DOSPERT) scale for adult populations. *Judgment and Decision Making, 1,* 33–47.

Blakemore, S-J. Burnett, S., & Dahl, R. (2010). The role of puberty in the developing adolescent brain. *Human Brain Mapping, 31*, 926-933.

Blakemore, S-J., & Robbins, T.W. (2012). Decision-making in the adolescent brain. *Nature Neuroscience, 15,* 1184-1191.

Blankenstein, N.E., Crone, E.A., van den Bos, W., & van Duijvenvoorde, A.C.K. (2016). Dealing with uncertainty: Testing risk- and ambiguity-attitude across adolescence. *Developmental Neuropsychology.*

Boyer, T.W. (2006). The development of risk-taking: A multi-perspective review. *Developmental Review, 26*, 291–345.

Braams, B.R., Peters, S., Peper, J.S., Guroglu, B., & Crone, E.A. (2014). Gambling for self, friends, and antagonists: Differential contributions of affective and social brain regions on adolescent reward processing. *NeuroImage, 100*, 281–289.

Braams, B.R., van Duijvenvoorde, A.C.K., Peper, J.S., & Crone, E.A. (2015). Longitudinal changes in adolescent risk-taking: A comprehensive study of neural responses to rewards, pubertal development, and risk-taking behavior. *Journal of Neuroscience, 35,* 7226–7238.

Burnett, S., Bault, N., Coricelli, G., & Blakemore, S.-J. (2010). Adolescents' heightened risk seeking in a probabilistic gambling task. *Cognitive Development, 25,* 183-196.

Chein, J., Albert, D., O'Brien, L., Uckert, K., & Steinberg, L. (2011). Peers increase adolescent risk-taking by enhancing activity in the brain's reward circuitry. *Developmental Science*, *14,* F1 –F10.

Cohen, J.R., Asarnow, R.F., Sabb, F.W., Bilder, R.M., Bookheimer, S.Y., Knowlton, B.J., & Poldrack, R.A. (2010). A unique adolescent response to reward prediction errors. *Nature Neuroscience, 13,* 669-671.

Crone, E.A., & Dahl, R.E. (2012). Understanding adolescence as a period of social-affective engagement and goal flexibility. *Nature reviews. Neuroscience, 13,* 636–650.

Crone, E.A., van Duijvenvoorde, A.C.K., & Peper, J.S. (2016). Annual Research Review: Neural contributions to risk taking in adolescence - Developmental changes and individual differences. *Journal of Child Psychology and Psychiatry and Allied Disciplines, 57*, 353–368.

Crone, E.A., & van der Molen, M.W. (2004). Developmental changes in real life decision making: Performance on a gambling task previously shown to depend on the ventromedial prefrontal cortex. *Developmental Neuropsychology, 25*, 251–279.

Defoe, I.N., Dubas, J.S., Figner, B., & van Aken, M.A. (2015). A meta-analysis on age differences in risky decision making: Adolescents versus children and adults. *Psychological Bulletin, 141,* 48 –84.

Donati, M.A., Panno, A., Chiesi, F., & Primi, C. (2014). A mediation model to explain decision making under conditions of risk among adolescents: The role of fluid intelligence and probabilistic reasoning. *Developmental Neuropsychology, 36,* 588-595.

Ellsberg, D. (1961). Risk, ambiguity, and the Savage axioms. *The Quarterly Journal of Economics*, 643-669.

Engelmann, J.B., Moore, S., Capra, M., & Berns, G.S. (2012). Differential neurobiological effects of expert advice on risky choice in adolescents and adults. *Social Cognitive and Affective Neuroscience, 7,* 557-567.

Figner, B., Mackinlay, R.J., Wilkening, F., & Weber, E.U. (2009a). Affective and deliberative processes in risky choice: Age differences in risk taking in the Columbia Card Task. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *35*, 709–730.

Figner, B., Mackinlay, R.J., Wilkening, F., & Weber, E.U. (2009b). *Risky choice in children, adolescents, and adults: Affective versus deliberative processes and the role of executive functions*. Paper presented at the Society for Research in Child Development, Denver, CO.

Figner, B., & Voelki, N. (2004). Risky decision making in a computer card game: An information integration experiment. *Polish Psychological Bulletin, 35,* 135–139.

Figner, B., & Weber, E.U. (2011). Who takes risks when and why? Determinants of risk-taking. *Current Directions in Psychological Science, 20,* 211–216.

Fox, C.R., & Tannenbaum, D. (2011). The Elusive Search for Stable Risk Preferences. *Frontiers in Psychology, 2,* 298.

Gilboa, I., & Schmeidler, D. (1989). Maxmin expected utility with non-unique prior. *Journal of Mathematical Economics, 18,* 141-153.

Gogtay, N., Giedd, J.N., Lusk, L., Hayashi, K.M., Greenstein, D., Vaituzis, A.C., Nugent, T.F. 3rd., Herman, D.H., Clasen, L.S., Toga, A.W., Rapoport, J.L., & Thompson, P.M. (2004). Dynamic mapping of human cortical development during childhood through early adulthood. *PNAS, 101,* 8174-8179.

Hämmerer, D., & Eppinger, B. (2012). Dopaminergic and prefrontal contributions to reward-based learning and outcome montioring during child development and aging. *Developmental Psychology, 48,* 862-874.

Hanoch Y., Johnson J.G., & Wilke A. (2006). Domain specificity in experimental measures and participant recruitment: an application to risk-taking behavior. *Psychological Science, 17,* 300–304.

Hansen, E.B., & Breivik, G. (2001). Sensation seeking as a predictor of positive and negative risk behaviour among adolescents. *Personality and Individual Differences, 30*, 627–640.

Hartley, & Somerville (2015). The neuroscience of adolescent decision-making. *Current opinion in Behavioral Sciences, 5,* 108-115.

Hauser, T.U., Iannaccone, R., Walitza, S., Brandeis, D., & Brem, S. (2015). Cognitive flexibility in adolescence: neural and behavioural mechanisms of reward prediction error processing in adaptive decision making during development. *NeuroImage, 104,* 347-354.

Hsu, M., Bhatt, M., Adolphs, R., Tranel, D., & Camerer, C. (2005). Neural systems responding to degrees of uncertainty in human decision-making. *Science, 310,* 1624-1625.

Huettel, S.A., Stowe, C.J., Gordon, E.M., Warner, B.T., & Platt, M.L. (2006). Neural signatures of economic preferences for risk and ambiguity. *Neuron, 49,* 765-775.

Huttenlocher, P.R. (1990). Morphometric study of human cerebral cortex development. *Neuropsychologia, 28,* 518-527.

Jansen, B.R.J., van Duijvenvoorde, A.C.K., & Huizenga, H. M. (2012). Development of decision making: sequential versus integrative rules. *Journal of Experimental Child Psychology, 111*, 87-100.

Josef, A. K., Richter, D., Samanez-Larkin, G. R., Wagner, G. G., Hertwig, R., & Mata, R. (2016). Stability and Change in Risk-Taking Propensity Across the Adult Lifespan. *Journal of Personality and Social Psychology*.

Kahneman, D., & Tversky, A. (1979). Prospect Theory: An Analysis of Decision under Risk. *Econometrica, 47*, 263-291.

Knight, F. (1921). *Risk, Uncertainty, and Profit*. New York: Houghton, Mifflin.

Lejuez, C., Aklin, W.M., Zvolensky, M.J., & Pedulla, C.M. (2003). Evaluation of the Balloon Analogue Risk Task (BART) as a predictor of adolescent real-world risk taking behaviours. *Journal of Adolescence, 26,* 475-479.

Levy, I., Snell, J., Nelson, A.J., Rustichini, A., & Glimcher, P.W. (2010). Neural representation of subjective value under risk and ambiguity. *Journal of Neurophysiology, 103,* 1036–1047.

Li, R., Brannon, E.M., & Huettel, S.A. (2014). Children do not exhibit ambiguity aversion despite intact familiarity bias. *Frontiers in Psychology, 5,* 1519.

Markiewicz L., & Weber E.U. (2013). DOSPERT's Gambling Risk-Taking Propensity Scale predicts excessive stock trading. *Journal of Behavioral Finance, 14,* 65–78.

Pachur, T., Hertwig, R., Gigerenzer, G. &, Brandstätter, E. (2013). Testing Process Predictions of Models of Risky Choice: A Quantitative Model Comparison Approach. *Frontiers in Psychology, 4, 646*.

Panno, A., Lauriola, M., & Figner, B**.** (2013). Emotion regulation and risk taking: Predicting risky choice in deliberative decision making. *Cognition & Emotion*, *27*, 326-334.

Paulsen, D.J., Platt, M.L., Huettel, S.A., & Brannon, E.M. (2011). Decision-making under risk in children, adolescents, and young adults. *Frontiers in Psychology, 2,* 72.

Paulsen, D.J., Carter, R.M., Platt, M.L., Huettel, S.A., & Brannon, E.M. (2012). Neurocognitive development of risk aversion from early child- hood to adulthood. *Frontiers in Human Neuroscience, 5,* 178.

Payne, J.W., Bettmann, J.R., & Johnson, E.J. (1993). *The adaptive decision maker*. Cambridge University Press.

Peper, J.S., & Dahl, R.E. (2013). Surging hormones: Brain-behavior interactions during puberty. *Current Directions in Psychological Science, 22,* 134–139.

Peters, S., Koolschijn, P.C.M.P., Crone, E.A., van Duijvenvoorde, A.C.K., Raijmakers, M.E.J. (2014). Strategies influence neural activity for feedback learning across child and adolescent development. *Neuropsychologia, 62,* 365-374.

Pfeifer, J.H, & Allen, N.B (2016). The audacity of specificity: Moving adolescent developmental neuroscience towards more powerful scientific paradigms and translatable models. *Developmental Cognitive Neuroscience, 17,* 131-137.

Reyna, V. F., & Farley, F. (2006). Risk and rationality in adolescent decision making: Implications for theory, practice, and public policy. *Psychological Science in the Public Interest, 7,* 1–44.

Reyna, V. F., & Rivers, S. E. (2008). Current theories of risk and rational decision making. *Developmental Review, 28,* 1–11.

Rolison J.J., Hanoch Y., Wood S., & Liu P. (2014). Risk-taking differences across the adult life span: a question of age and domain. *J. Gerontol. B Psychol. Sci. Soc. Sci., 69,* 870–880.

Ruff, C.C., & Fehr, E.F. (2014). The neurobiology of rewards and values in social decisionmaking. *Nature Reviews Neuroscience, 15*, 549-562.

Savage, L.J. (1954). *The Foundations of Statistics*. New York: Wiley

Schiebener, J., Zamarian, L., Delazer, M., & Brand, M. (2011). Executive functions, categorization of probabilities, and learning from feedback: what does really matter for decision making under explicit risk conditions? *J Clin Exp Neuropsychol, 33,* 1025-1039.

Somerville, L.A., (2013). The teenage brain: Sensitivity to social evaluation. *Current Directions in Psychological Science, 22,* 129-135.

Tamnes, C.K., Ostby, Y., Fjell, A.M., Westlye, L.T., Due-Tonnessen, P., & Walhovd, K.B. (2010). Brain maturation in adolescence and young adulthood: regional age-related changes in cortical thickness and white matter volume and microstructure. *Cerebral Cortex, 20,* 534-548.

Tom, S., Fox, C.R., Trepel, C., & Poldrack, R.A. (2007). The neural basis of loss aversion in decision-making under risk. *Science, 315,* 515-518.

Tversky, A., & Kahneman, D. (1992). Advances in prospect theory: Cumulative representation of uncertainty. *Journal of Risk and Uncertainty, 5,* 297–323.

Tymula, A., Rosenberg Belmaker, L. A., Roy, A. K., Ruderman, L., Manson, K., Glimcher, P. W., & Levy, I. (2012). Adolescents' risk-taking behavior is driven by tolerance to ambiguity. *PNAS, 109*, 17135-17140.

Tymula, A., Rosenberg Belmaker, L. A., Ruderman, L., Glimcher, P. W., & Levy, I. (2013). Like cognitive function, decision making across the life span shows profound age related changes. *PNAS, 110,* 17143-17148.

van den Bos, W., Cohen, M.X., Kahnt, T., & Crone, E.A. (2012). Striatum-Medial Prefrontal Cortex Connectivity Predicts Developmental Changes in Reinforcement Learning. *Cerebral Cortex, 22*, 1247-1255.

van den Bos, W., & Eppinger, B. (2016). Developing developmental cognitive neuroscience: From agenda setting to hypothesis testing. *Developmental Cognitive Neuroscience, 17,* 138-144.

van der Schaaf, M.E., Warmerdam, E., Crone, E.A., & Cools, R. (2011). Distinct linear and non-linear trajectories of reward and punishment reversal learning during development: Relevance for dopamine's role in adolescent decision making. *Developmental Cognitive Neuroscience, 1,* 578-590.

van Duijvenvoorde, A.C.K., & Crone, E.A. (2013). A Neuroeconomic Approach to Adolescent Decision Making. *Current Directions in Psychological Science, 22,* 108-113.

van Duijvenvoorde, A.C.K., Figner, B., Weeda, W.D., van der Molen, M.W., & Huizenga, H.M. (2016). Neural mechanisms underlying compensatory and non-compensatory strategies in risky choice. *Journal of Cognitive Neuroscience.*

van Duijvenvoorde, A.C.K, Huizenga, H.M., Somerville, L.H., Delgado, M.R., Powers, A., Weeda, W.D., Casey, B.J., Weber, E.U., & Figner, B. (2015). Neural correlates of expected risks and returns in risky choice across development. *Journal of Neuroscience, 35,* 1549–1560.

van Duijvenvoorde, A.C.K., Jansen, B.R.J., Bredman, J.C., & Huizenga, H.M. (2012). Age-related changes in decision making: Comparing informed and noninformed situations. *Developmental Psychology, 48*, 192–203.

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.

Venkatraman, V., & Huettel, S.A. (2012). Strategic control in decision-making under uncertainty. *European Journal of Neuroscience, 35*, 1075-1082.

Von Gaudecker, H.M., Van Soest, A., & Wengström, E. (2011). Heterogeneity in risky choice behavior in a broad population. *The American Economic Review*, 664-694.

Von Neumann, J., & Morgenstern, O. (1944). *Theory of Games and Economic Behavior*, Princeton: Princeton University Press.

Walther, B., Morgenstern, M., & Hanewinkel, R. (2012). Co-occurrence of addictive behaviours: personality factors related to substance use, gambling, and computer gaming. *Eur Addict Res, 18,* 167-174.

de Water, E., Braams, B.R., Crone, E.A., & Peper, J.S. (2013). Pubertal development and sex steroids are related to alcohol use in adolescents. *Hormones and Behavior, 63*, 392-397.

Weber, E. U. (2010). Risk attitude and preference. *Wiley Interdisciplinary Reviews: Cognitive Science, 1*, 79-88.

Weber E. U., Blais A. R., & Betz N. E. (2002). A domain-specific risk-attitude scale: measuring risk perceptions and risk behaviors. *Journal of Behavioral Decision Making, 15,* 263–290.

Weber, E. U., & Johnson, E. J. (2008). "Decisions under uncertainty: Psychological, economic, and neuroeconomic explanations of risk preference*"* In: P. Glimcher, C. Camerer, E. Fehr, & R. Poldrack (Eds.), *Neuroeconomics: Decision making and the* brain (pp. 127-144). New York: Elsevier.

Weller, J. A., Ceschi, A., & Randolph, C. (2015). Decision-making competence predicts domain-specific risk attitudes. *Frontiers in Psychology*, 6.

Weller, J.A., & Tikir, A. (2015). Predicting Domain-Specific Risk Taking with the HEXACO domain-specific risk attitudes. *Journal of Behavioral Decision Making, 24,* 180-201.

Wilkening, F., & Anderson, N.H. (1982). Comparison of two rule-assessment methodologies for studying cognitive development and knowledge structure. *Psychological Bulletin, 92,* 215-237.

Willoughby, T., Good, M., Adachi, P.J.C., Hamza, C., & Tavernier, R. (2013). Examining the link between adolescent brain development and risk-taking from a social-developmental perspective. *Brain and Cognition, 89,* 70 –78.

Wilson, M., & Daly, M. (1985). Competiveness, risk-taking, and violence: The young male syndrome. *Ethology and Sociobiology, 6,* 59–73.

Figure 1: A three-panel figure of developmental results on ambiguity-aversion. Left panel displays adults, in contrast to children, prefer a risky compared to an ambiguous prospect (adopted from Li et al., 2014; *Frontiers in Psychology*). Middle panel displays larger ambiguity aversion in adults (adopted from Tymula et al., 2012; *PNAS*); Right panel displays an increase in ambiguity aversion across adolescence (adopted from Blankenstein et al., 2016; *Developmental Neuropsychology*)

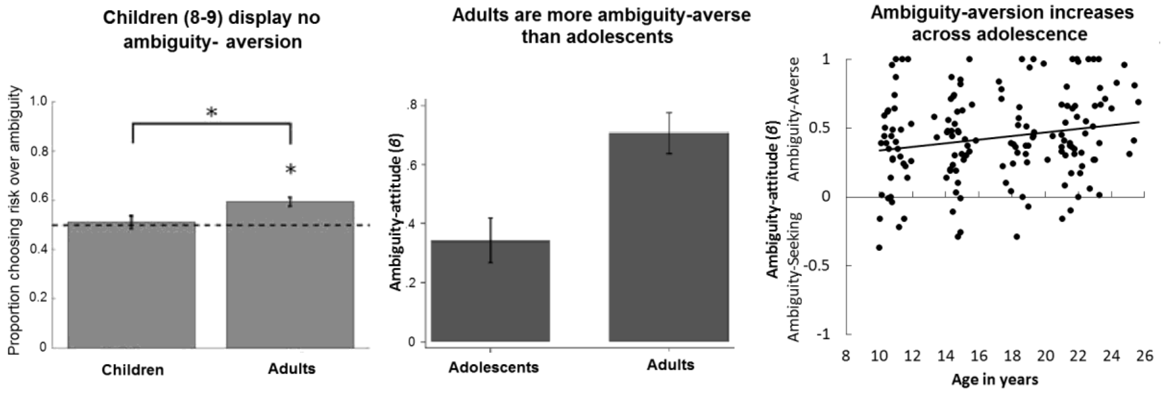

Figure 2: Adopted from van Duijvenvoorde et al., 2015, *Journal of Neuroscience*: Age-related changes in neural activation in response to return (upper panel) and risk (lower panel). Upper panel: Return activation increases across childhood, adolescence, and adulthood in the ventral medial PFC and posterior cingulate cortex. Greater neural activation is associated with greater behavioral sensitivity (approach) to return. Lower panel: Risk activation peaks in adolescence in the dorsal medial PFC and the insula. Greater neural activation to risks is associated with greater behavioral sensitivity (aversion) to risk, but only for adolescents.