Multiple pathways of risk taking in adolescence

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ABSTRACT

In this review, we describe multiple pathways that may lead to risk-taking in adolescence. We review behavioral and neuroimaging studies showing heightened risk-taking tendencies and associated neural reward activity in mid to late adolescence, but evidence points to risk taking as highly context and sample dependent. Here, we suggest that individual differences, specifically reward drive, may be a differential susceptibility factor that shows heightened sensitivity in adolescents and that makes some adolescents more sensitive to their environment. Furthermore, we review evidence that an elevated reward drive in mid-adolescence in interaction with prosocial and cognitive development can lead to various trajectories of risk taking. In this review we propose to extend existing models with individual-difference factors, specifically reward drive, and accompanying developmental processes, including cognitive control and prosocial development, that drive the development of multiple pathways of risk taking.

Introduction

Why do adolescents take risks? What motivates risk-taking? It is well conceptualized that adolescence, relative to childhood and adulthood, is period of increased reported and observed risk-taking behavior (Strang, Chein, & Steinberg, 2013), but the mechanisms for elevated risk-taking remain debated (Bjork & Pardini, 2015). Adolescence is defined as the developmental phase during which individuals transition from children with high dependency on parents and/or caregivers to adults who are independent members of society (Dahl, Allen, Wilbrecht, & Suleiman, 2018). Adolescence starts with the biological changes that are associated with pubertal development, but the end phase of adolescence is less clearly defined and depends on cultural and historical differences.

Here, we refer to three partly overlapping periods in adolescent development, but not all studies use similar definitions (for a more elaborate discussion, see van Duijvenvoorde, Peters, Braams, & Crone, 2016). Puberty, the first phase of adolescence between approximately ages 10–16-years, is characterized by physical, cognitive and social-emotional changes associated with a rapid increase in gonadal hormones which spur physical transitions, such as breast development in girls and voice changes in boys (Shirtcliff, Dahl, & Pollak, 2009) and changes in emotion variability (Peper & Dahl, 2013). The second phase of adolescence, between ages 16–24-years is accompanied by changing social goals and is strongly culturally dependent (Sawyer, Azzopardi, Wickremarathne, & Patton, 2018). The third phase in development defines the transition from adolescence to adulthood, which is emerging adulthood. This period from approximately ages 18–29-years defines a period during which individuals are adults by law, but are still developing in terms of
identity exploration, self-focus and possibilities to develop into multiple directions (Arnett, Zukauskiene, & Sugimura, 2014).

In parallel to behavioral research, in the last two centuries adolescent developmental has also been examined from the perspective of brain development. During the teenage years and early twenties, there is a pronounced change in cortical neural development, which has been interpreted as a post-natal growth spurt in the human brain. The first post-natal growth spurt takes place in the first 4–5 years of life during which grey matter increases and white matter connections grow, as is evident from Magnetic Resonance Imaging (MRI) studies (Gilmore, Knickmeyer, & Gao, 2018; Girault et al., 2019). Cortical gray matter is composed of neurons and glial cells, dendrites, synapses, as well as blood vessels. After a relative plateau period, the second phase of neural development consists of a reduction in grey matter leading to stability of grey matter neural density in the mid-twenties (Gilmore et al., 2018; Tamnes et al., 2017). White-matter connections continue to grow during the whole developmental phase from birth to adulthood, but growth accelerates during puberty (Menzies, Goddings, Whitaker, Blakemore, & Viner, 2015). The reduction in grey matter is thought to be related to a decrease in synaptic connections driven by a specialization in the adolescent brain. The increase in white volume is thought to reflect, at least partly, the strengthening of the connections between brain regions, leading to faster and more efficient information processing. These neural changes have led to a new direction of research on risk taking by examining how grey-matter change and white-matter connectivity of particularly subcortical-cortical brain connections are associated with an inclination to take risks (Peper & Dahl, 2013). In addition, research on task-related neural activity can be examined using functional Magnetic Resonance Imaging (fMRI), which is an indirect measure to examine Blood Oxygen Level Dependent (BOLD) changes in relation to specific events in time. The fMRI paradigms elucidated adolescent-specific neural sensitivity to rewards which occurs in the context of risk-taking paradigms (Silverman, Jedd, & Luciana, 2015).

One of the most challenging aspects when aiming the question why adolescents take risks is how to define risk taking. Risk taking has previously been described as an act of cultural rebelliousness (Arnett, 2000) or behaviors that lead to detrimental health consequences (Willoughby, Good, Adachi, Hamza, & Tavernier, 2014). In experimental behavioral paradigms, risk taking is often defined as the choice for which outcomes are more variable (Figner & Weber, 2011). These choices are often made in the context of tasks that aim to capture the dynamics of real-world risk taking. As will be evident in this research, aspects of behavioral risk-taking are examined in many different ways, with debates concerning when risk taking is optimal (or positive) versus detrimental (or negative) in economic terms, and whether risk taking is required for learning and exploration to make the ‘optimal’ (or socially adaptive) choice. Finally, what is optimal for an individual in terms of economic gains does not always align with social expectations. For example, risk taking can have personal benefits, such as financial gains, but can at the same time lead to negative social effects, such as peer rejection (Blakemore, 2018).

The various transitions of adolescents and young adults in the pathway to full adulthood are thought to require a certain amount of exploration and risk seeking, given that leaving ‘the safe nest’ is necessarily not without risks. The transition from childhood to adolescence is associated with a pronounced extension of an adolescent’s social environment. Not only do adolescents spend more time with peers relative to childhood (De Goede, Branje, Delsing, & Meeus, 2009), they also extend the diversity of social environments in which they engage, including the school, sports clubs, part-time jobs and social gatherings (Fuligni, 2019). Indeed, higher levels of exploration are also observed in rodent studies that reported higher levels of risk-seeking behavior in rats in puberty relative to adulthood (Sisk & Foster, 2004). Possibly, neural changes predict or accompany the changes in risk-taking behavior. Yet, the exact motivations of adolescents to take risks are more difficult to pinpoint as the expression of risk-seeking behavior seems contextually dependent. That is to say, whereas elevated levels of risk taking are observed in health statistics and self-reported sensation-seeking into the early twenties (Willoughby et al., 2014), the behavior has proved challenging to replicate in a laboratory setting and results have remained inconclusive in terms which adolescents more sensitive to risk taking and under which circumstances (Defoe, Dubas, Figner, & van Aken, 2015; van Duijvenvoorde, Blankenstein, Crone, & Figner, 2017).

In this review, we present a perspective on risk-taking that focusses on the multiple pathways of adolescents’ risk-taking by reviewing behavioral and neuroscientific studies. We first summarize recent behavioral studies that used a decomposition of risk-taking to specify developmental models of risk-taking in adolescence. We then suggest two extensions of existing perspectives. First, we address the question why some adolescents take more risks than others. We argue that individual differences in reward-drive tendencies may be a differential susceptibility factor that makes some adolescents more sensitive to the environment than others. Reward-drive tendencies is used as an umbrella term for various behaviors that are associated with dopaminergic-driven reward experiences, such as approaching rewards, valuing rewards, novelty seeking and sensation-seeking (Telzer, 2016). This adolescent specific differential reward drive may explain why some, but not all adolescents are more inclined to take risks, relative to childhood and adulthood (Crone et al., 2020). Second, we address the question on the outcomes of risk taking. We argue that whether risk taking leads to individual and/or societal optimal or detrimental outcomes depends on the interacting influence between cognitive and social development and reward processing. We will illustrate this by longitudinal behavior and brain imaging studies showing that developmental trajectories of risk taking co-occur with the development of social and cognitive processes. We argue that incorporating these elements in existing models will lead to a novel interpretation of risk taking as a component of learning to find one’s place in society.

Decomposing risk taking

Neurodevelopmental models

Risk taking, which in the behavioral economic literature is defined as the choice for which outcomes are more variable (Figner & Weber, 2011), can be examined as a composite measure that can be decomposed into processes underlying risky choice (Rosenbaum & Hartley, 2019; van Duijvenvoorde et al., 2015). Several theoretical frameworks have been influential in understanding the interacting
processes of adolescent risk taking.

Prior neurodevelopmental models on adolescent risk-taking have described that risk taking is driven by several interacting processes. Imbalance models of adolescent risk taking distinguish a cognitive control versus a social-emotional brain system that differ in their developmental trajectories. Whereas adolescents’ cognitive control system develops slowly, the social-emotional brain system is maturing earlier, possibly under influence of pubertal hormones (Casey, Jones, & Somerville, 2011; Somerville, Jones, & Casey, 2010). This temporary imbalance in the development of these brain-systems, results in a life phase of increased risk taking, particularly in emotionally-salient contexts, such as when immediate rewards, or peers are present. Dual-system models (Shulman et al., 2016; Steinberg, 2008) make a similar distinction in brain systems to explain adolescent risk taking, but focus on an adolescent-specific heightened reward system, and an eventually dominant cognitive-control system that increases in strength into adulthood. Note that this is not an extensive summary of neurodevelopmental models, and several alternative frameworks have been proposed (for an overview, see Shulman et al., 2016).

Another contemporary model on adolescent risk-taking is fuzzy-trace theory (FTT; Reyna & Farley, 2006; Rivers, Reyna, & Mills, 2008). FTT distinguishes verbatim-based and gist-based decision making. Whereas verbatim-based decision making uses literal information on gains, losses, and probabilities, gist-based decision making is oriented towards the gist of a situation, which reflects, among others, experience. FTT predicts that gist-based risk-aversion increases with age across development. Therefore, FTT predicts that adolescents show more risk taking than adults, but less so than children.

Romer, Reyna, & Satterthwaite (2017) suggested in the life-span wisdom model that at least three processes are involved in decomposing risk taking across adolescent development. The first refers to a gradual decrease in taking explicit risks, where all probabilities and time delays for reward are known. This type of risk taking gradually decreases as cognitive control increases over the course of adolescence and young adulthood. The second refers to a late-adolescence/young adult specific increase in risk taking in ambiguous situations. This type of risk taking is subsumed under sensation seeking, which is defined as a heightened attraction to novel and exciting situations. A third type of risk taking involves impulsive action, which appears in some youth early in development and also peaks for those youth during adolescence. It is this form of risk taking that is most clearly associated with harmful outcomes, such as substance use disorder. Together, these processes lead to an increase in exploration in some adolescents/young adults, which is replaced over the life span by making decisions based on cognitive control and wisdom. This model has many similarities with prior models such as the dual system models, FTT, and other models that specify interaction with contextual factors (such as the Developmental Neuro-Ecological Risk-taking Model; Defoe, Semon Dubas, & Romer, 2019), although it diverges from prior models in that it distinguishes exploration from impulsive risk taking, and it isolates impulsive action to a subset of youth. It converges with prior models in that all these models suggest adolescent-specific developmental patterns of risk taking.

Explicit and experience-based risk taking

In the next section, we summarize recent laboratory studies on risk taking to further understand the specific task and context dependency of risk-taking development. We categorize the risk-taking paradigms based on two experimental task-specific elements that may influence the processes underlying risk taking. First, whether adolescents take explicit (known) risks versus ambiguous (not all information on probabilities is known) in experimental tasks. Second, for each measurement, we also distinguish whether the measurement taps static (all information on probabilities is presented) or experience-based (information learned by experience) decision making (see also Garcia, Cerrotti, & Palminteri, 2021; Hertwig & Erev, 2009) for further discussion on the decision-making differences between descriptive and experience-based decision making). We summarize the various experimental tasks and processes in the section below.

Explicit risk-taking: Known probabilities

Several studies have examined risk-taking with known probabilities using gambling tasks that required a choice between a sure gain or a gamble, which could result in lower or higher gains (i.e., the risky choice). An important distinction that is made when studying adolescent risk taking, depends on the conditions under which risk taking occurs. That is, when risk taking occurs under conditions in which the potential outcomes and probabilities are fully known. Several studies have shown that in these contexts people are typically risk averse meaning they estimate the value of the risky choice to be less than the objective value. To illustrate, when asked to choose between a flip of a coin of 100 dollar or nothing versus a sure bet of 45 dollars, risk-averse people tend to prefer the sure (or safe) option. Across adolescence people tend to show large individual differences, and reports on age-related changes have been mixed. For instance, some studies observed adolescents to be more risk seeking compared to children and adults (van den Bos & Hertwig, 2017), others observed no differences (Blankenstein, Schreuders, Peper, Crone, & van Duijvenvoorde, 2018), or even a slight decrease in risk aversion across adolescence (Blankenstein & van Duijvenvoorde, 2019).

Ambiguous probabilities

Alternatively, risk taking in real-life often presents a more uncertain context in which the probabilities of risk are unknown, also referred to as risk taking under ambiguity (for an excellent review on risk taking under ambiguity, see Blankenstein, Huettel, & Li, 2021, this issue). Several studies have examined how tolerant people are to these uncertain risks in choice paradigms presenting a safe and an ambiguous risky choice. A study including participants between ages 10–25-years showed that ambiguity-attitude, but not risk-attitude, showed an age related change, such that ambiguity tolerance was higher in early adolescence and decreased linearly into
adulthood (Blankenstein, Crone, van den Bos, & van Duijvenvoorde, 2016). Higher ambiguity tolerance in adolescence was also associated with more self-reported reckless behavior (Blankenstein et al., 2016). A separate study showed that ambiguity tolerance was higher in adolescence (ages 12–17) compared to adulthood (ages 30–50) (Tymula et al., 2012), or even peaked in adolescence (van den Bos & Hertwig, 2017) when considering potential losses. These contradictory patterns suggest that there are large differences between individuals in tolerance to ambiguity. This may suggest that whether adolescent specific effects are observed depends on the age-range and sample under consideration.

**Experience-based risk taking**

Whereas the studies above examined ambiguity preferences on static choice behavior, dynamic, or experience-based, tasks involve repeated choices in which people experience outcomes and learn about the probabilities and reward-structure in the task. In this way these tasks present people with an initial ambiguous choice situation, but it may allow them to learn what is the most optimal response over trials. Thus, partly, how well people handle ambiguous risks may depend on individual’s learning abilities. That is, in real-life risk taking, we also experience the outcomes of our behavior directly (e.g., (not) getting into an accident when texting while driving). Over the past years there are a number of studies suggesting that these learning processes contribute to adolescents’ heightened risk taking (Mamerow, Frey, & Mata, 2016; Rosenbaum & Hartley, 2019; van Duijvenvoorde, Jansen, Bredman, & Huizenga, 2012).

Experience-based risk taking has previously been examined with the Balloon Analogue Risk Taking (BART) task (Lauriola, Panno, Levin, & Lejuez, 2014; Lejuez et al., 2002). In an accelerated longitudinal study using three waves across ages 8–29-years, a recent study showed a pattern of increasing levels of risk taking until mid-late adolescence after which risk-taking behavior showed a plateau and a slight decrease in adulthood (Peper, Braams, Blankenstein, Bos, & Crone, 2018). The BART task present participants with a risky choice (i.e., to pump a balloon) or a safe choice (cash out). Inflating the balloon is risky because although it results in increasing monetary gains for each pump, yet when the balloon explodes all gains are lost. It has been discussed that in the BART task people typically take too few risks, and that optimal levels of performance requires exploration. Interestingly, we observed in prior work that in mid-adolescence, participants took most risks but also earned most money whereas younger and older participants were more risk averse, possibly suggesting financially advantageous risk taking in mid-adolescence (Peper et al., 2018).

Other risk-taking tasks in the current literature are the Iowa Gambling Task (IGT) (Bechara, Damasio, Tranel, & Damasio, 1997) and the experience-based Columbia Card Task (CCT) (Figner, Mackinlay, Wilkening, & Weber, 2009). In the IGT participants are presented with four decks of cards and need to learn to sample from advantageous decks that present initial low gains, but also small losses, and refrain from the disadvantageous decks that present initial high gains, but also high losses. Characterizing risky-decision making in the IGT has been done based on the basis of how advantageous the decks are (i.e., learning the net outcome across time). Arguably this task therefore taps more strongly into reward-based learning than risky choice when defining risky choice as choosing the option with the greater outcome variability. Previous work has shown that people learn to choose more advantageously across adolescence (Cauffman et al., 2010; van Duijvenvoorde, Jansen, Visser, & Huizenga, 2010) and particularly to avoid disadvantageous decks (Icenogle et al., 2017).

Finally, the CCT is a sampling paradigm in which people are presented with a choice to either turn a card from a deck of cards presented on screen or stop flipping cards and cash out. Turning a card may lead to gains, but also potentially large losses (Figner et al., 2009; van Duijvenvoorde et al., 2015). In contrast to the other experiential risky decision-making tasks, it strictly does not reflect ambiguity since all choice information is explicitly presented. However, the experiential nature of the CCT is used to compare risky decision making under different affective loads, i.e., a more ‘hot’ (i.e., affectively driven) choice situation versus a ‘cold’ (more deliberative) choice situation. In contrast to the ‘cold’ CCT, only the ‘hot’ CCT includes immediately presented outcomes. Previous findings showed that adolescents from age 14 and older 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 (Figner et al., 2009).

Taken together, there is some evidence that behaviorally adolescents take more risks than children and/or adults, for example when ambiguity is higher (Blankenstein et al., 2016; Tymula et al., 2012; van den Bos & Hertwig, 2017), when risk taking is arousing because of a larger potential financial benefit or immediate outcomes (Braams, van Duijvenvoorde, Peper, & Crone, 2015; Defoe et al., 2015; Figner et al., 2009; Freeman, Dirks, & Weinberg, 2020), or because of avoidance of regret (Burnett, Bault, Coricelli, & Blake-more, 2010). On the other hand, a prior meta-analysis concluded that the overall age-trend in risk taking across adolescence on experimental tasks is downward (Defoe et al., 2015). There is currently discussion concerning whether age-differences in measured and observed risk taking are related to task-specific strategies (Frey, Pedroni, Mata, Rieskamp, & Hertwig, 2017; Mata, Josef, Samanez-Larkin, & Hertwig, 2011), and/or opportunity (Defoe et al., 2015). Possibly, risk-taking trajectories also depend on an interaction between individual reward-drive tendencies and environmental influences, such as the family in which children grow up or the presence of risk-taking peers.

**Reward drive as a potential differential susceptibility marker**

The summary presented above describes that, in specific contexts, adolescents take more risks in certain phases of development. However, it was demonstrated in various studies that not all adolescents take risks, yet, it is not yet well understood why some adolescents take more risks than others. Current models lack a specification of these individual differences.

Prior studies suggested that the interaction between reward-drive tendencies and environmental experiences may impact risk taking in adolescence. According to these findings, reward drive may act as a differential susceptibility marker such that individual
differences in heightened reward drive sensitivity in adolescence relative to childhood and adulthood, may impact adolescent development for better or for worse, therefore placing larger emphasis on interaction between individual reward-drive tendencies and the environment (Crone & Dahl, 2012; Do, Prinstein, & Telzer, 2020; Schriber & Guyer, 2015). That is to say, heightened reward drive in a supportive environment may result in personally or societally optimal risk taking (such as standing up for a friend), whereas the same heightened reward drive in a non-supportive environment may result in personally or societally detrimental risk taking (such as stealing under peer pressure). Below, we summarize studies describing whether adolescents show a heightened reward drive. Second, we summarize effects of the environment on reward drive and risk taking. The full differential susceptibility model has not yet been tested in adolescent development, but the studies described here provide initial evidence and starting points for incorporating this element in existing models.

Self-reported reward drive

Reward-drive as we specify it here refers to an individual’s general tendency to approach or pursue rewards and/or seek out novel experiences (Telzer, 2016). Reward-drive can be measured, for example, using the Behavioral Inhibition System/Behavioral Activation System (BIS/BAS) questionnaire (Carver & White, 1994). A prior 3-wave longitudinal study in participants ages 8–29-years observed that reward-drive peaked in mid-adolescence and declined in adulthood, particularly for approach behavior (Peper et al., 2018). A second way to measure reward drive is by testing the tendency to seek out novel experiences, such as sensation-seeking. Behavioral studies on sensation seeking development revealed an adolescent peak in the late teen-age years (Harden et al., 2017; Steinberg et al., 2008), a pattern that is found cross-culturally (Steinberg et al., 2008). Prior studies reported that adolescents who define themselves as thrill seeking in daily life also take more risks in various experimental task contexts (Blankenstein et al., 2016; Galvan, 2010). Thus, there seem to be a general elevated reward drive in adolescence but researchers have emphasized large individual differences in mid-adolescence (Bjork & Pardini, 2015). We suggest that reward drive may show a larger differential susceptibility in adolescence relative to childhood and adulthood. Differential indicates that reward drive is higher for some, but not all adolescents. Differential susceptibility models suggest that these individual differences may be driven by genetic differences, temperament or personality (Belsky, Bakermans-Kranenburg, & Van IJzendoorn, 2007; Crone et al., 2020; Van IJzendoorn, Bakermans-Kranenburg, Coughlan, & Reijman, 2020).

Brain correlates of reward drive

Brain imaging studies reporting on reward outcomes in adolescence have been relatively consistent, showing elevated activity in the ventral striatum to rewards in adolescents relative to adults as was confirmed in a meta-analysis (Silverman et al., 2015). Indeed, our own longitudinal work (not included in the meta-analysis) also showed that in a gambling task that required 8–29-year-old participants to make a heads or tails choice, followed by gains or losses, reward related activity in the ventral striatum peaked in mid-adolescence (Braams et al., 2015; Schreuders et al., 2018).

Moreover, in an adolescent sample ventral striatum activation in response to reward was related to individual’s changes in reward drive, such as self-reported fun-seeking (van Duijvenvoorde et al., 2014). In another adolescent sample the age-related rise in ventral striatum activity between childhood and mid-adolescence was again correlated with increasing reward drive, and the age-related decrease between mid-adolescence to adulthood correlated with reductions in hedonic reward pleasure (Schreuders et al., 2018). Thus, even though the general quadratic age trend in ventral striatum activity was confirmed, individual differences were explained by self-report reward drive and self-report hedonic reward pleasure. A separated report of the same dataset demonstrated that higher ventral striatum reward activity correlated with higher alcohol use (Braams, Peper, van der Heide, Peters, & Crone, 2016), suggesting that, similar as observed for self-reported reward drive, neural responses to rewards correlate with real-life risk-taking behavior.

Environmental influences on risk taking

A further requirement for a differential susceptibility marker is that this marker makes some adolescents more sensitive to the environment than others (Belsky et al., 2007).

Peer influence on risk taking

One environmental factor that may interact with reward drive to result in risk taking is the presence of peers. Interestingly, several studies have reported that risk taking in the laboratory increases when risks are taken in the presence of peers (Silva, Patrianakos, Chein, & Steinberg, 2017; Wagemaker et al., 2020), particularly when the peer monitors the participants decisions (Somerville et al., 2019) or reinforces risk taking (Harakeh & de Boer, 2019; LaSpada et al., 2020; Van Hoorn, Crone, & Van Leijenhorst, 2017). In contrast, in the presence of an older other, adolescents showed reduced risk-taking behavior (Silva, Chein, & Steinberg, 2016). Neuroimaging studies demonstrated that the neural response in the ventral striatum to the presence of peers is higher in adolescence than in adults, possibly indicating that peer presence elevates reward drive in adolescence (Chein, Albert, O’Brien, Uckert, & Steinberg, 2011). Peer effects however are not observed in all studies, possibly indicating that peer effects on reward sensitivity may be dependent on the specific sample, design and social contextual factors (Defoe et al., 2019).
Social-economic and harsh environment experiences

Long-term environmental influences may also interact with individual’s reward drive in shaping risk-taking tendencies. The social environment in which children and adolescents grow up indeed has also a pronounced impact on risk-taking development. Social-economic disparities can influence the development of risk-taking behaviors. A longitudinal study of four waves demonstrated that parent-reported socioeconomic variables predicted increases in self-reported risk taking in adolescence, an effect that was partly mediated by effects of socioeconomic risk on cognitive control development (Brieant, Peviani, Lee, King-Casas, & Kim-Spoon, 2020). Disadvantageous circumstances can also impair the expected trajectory of adolescent risk taking. A 12-year longitudinal study of children who were institutionalized after birth showed lower levels of risk-taking behavior and sensation seeking in adolescence (Kopetz et al., 2019). Similar results were observed that compared adolescents with a history of maltreatment. These adolescents also showed lower levels of risk taking compared to adolescents without a history of maltreatment (Hoffmann et al., 2018). These studies show that detrimental environmental circumstances can also significantly impair the natural tendency to explore and take risks in adolescence.

Together, the results show that experiences can shape or influence the development of the processes that drive subsequent risk taking. Therefore, we suggest for a richer assessment of the individual background variables, including socioeconomic opportunities, neighborhood, peer influence and parent–child relations, which may influence the development of behavioral and neurobiological reward sensitivity, and subsequently risk-taking behavior. According to the differential susceptibility hypothesis (Belsky et al., 2007), elevated reward drive (behaviorally or in terms of neural activity in the ventral striatum) may result in ‘optimal’ risk taking when in an environment that is warm and supportive, but may result in detrimental, or an absence of optimal risk taking when in an environment that is harsh and unsafe (see Fig. 1).

Multiple pathways of risk taking

The differential susceptibility framework suggests that a heightened reward drive in combination with environmental influences results in developmental outcomes, for better and for worse. But what is better and worse risk taking? Aspects that have remained relatively underrepresented in descriptive models on adolescent risk-taking are the definition of ‘optimal’ or ‘detrimental’ risk taking. These may depend on co-occurring developing processes that may contribute to the decision making processes, leading to multiple (i. e., positive and negative) developmental trajectories (Crone & Dahl, 2012). Therefore, in this second section, we switch our focus from environmental influences to individual developmental patterns that co-occur with reward drive, especially prosocial development and cognitive development.

It was previously demonstrated that risk taking can be separated in positive (socially accepted and constructive) and negative (illegal and dangerous) outcomes for the individual and society (Crone & Dahl, 2012; Duell & Steinberg, 2020). Risk taking has been typically linked to more negative health outcomes, such as trying out drugs or alcohol, and using a phone while driving. Positive risk-taking, on the other hand, has been defined to benefit adolescent wellbeing, is associated with mild potential costs, and is legal and societally acceptable (Duell & Steinberg, 2020). Examples may be taking a social risk such as helping out a peer at school, or trying out for a challenging class. Previous findings show that even though both positive as negative risk taking were associated with heightened sensation-seeking, negative risk-taking was associated with higher reward sensitivity and lower punishment sensitivity than positive risk taking (Duell & Steinberg, 2020). Thus, the same sensation-seeking tendencies may result in multiple pathways of risk taking. These findings fit well with a model suggesting that risk taking in combination with prosocial development my lead to a trajectory of prosocial risk taking (helping others in need even when this involves an element of risk) whereas the same risk-taking tendencies without prosocial motives may lead to anti-social risk taking (taking self-serving risks, such as shoplifting for fun) (Do, Guassi Moreira, & Telzer, 2017). Thus, co-occurring developmental processes may influence the direction of risk taking in variable ways (see Fig. 2).
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Prosocial risk-taking

We recently performed a longitudinal study to examine whether the elevated reward drive in adolescence can lead to multiple trajectories of risk taking. For this study, we included participants between ages 8–29-years who took part in a 3-wave longitudinal study. Self-reported reward drive peaked in mid-adolescence, consistent with prior studies that reported a peak in sensation-seeking (Steinberg et al., 2008). Two other behaviors were assessed; rebellious behavior and prosocial behavior. Interestingly, these behaviors both peaked in adolescence, and were positively correlated (see Fig. 2 a). Longitudinal comparisons revealed that current levels and longitudinal changes in self-reported reward drive (specifically fun seeking) predicted both rebellious and prosocial behavior uniquely, as well as the combination of both, where the combination indicates a unique profile of risk-takers (“prosocial risk-takers”) (based on Do et al., 2017). The study was complemented by analyses of structural brain development which revealed that structural longitudinal medial prefrontal cortex development predicted only additional variance in the development of rebellious behavior, but not for prosocial behavior (Blankenstein et al., 2019). Finally, prosocial behavior, but not rebellious behavior, was uniquely predicted by intention to comfort and perspective taking. This study suggests that rebelliousness and prosociality share a common predictor (reward drive) but also are sensitive to separable influences. Prosociality has previously been associated with the development of a separate network in the brain which includes the temporal-parietal junction, superior temporal sulcus and the midline cortical areas (Blakemore & Mills, 2014). Possibly, the development of this network should be included in future studies to test whether the trajectories of risk taking develop in directions of prosocial or antisocial behaviors (Do et al., 2020; Duell & Steinberg, 2019).

Cognitive development and flexibility

Multiple pathways of risk taking can also result from a complementary contribution of reward drive and cognitive control. Prior imbalance models have mainly described the role of cognitive control in terms of balancing between reward-oriented behavior and deliberate actions. However, very few behavioral studies are showing this affective approach-cognitive control balance in risk-taking paradigms. Recently, a novel perspective, the flexible dual system model, suggested that engagement of cognitive control depends on the availability of information when taking risks (Li, 2017). According to this model, cognitive control processes are engaged more

Fig. 2. A multi-panel figure of interactions between individual difference factors and multiple pathways of risk taking. Panel A presents data from Blankenstein et al. (2019). Data from this study shows that tendency of rebellious behavior and prosocial behavior correlate positively, and results showed that rebelliousness and prosocial behavior were predicted by reward drive (specifically fun seeking). Panel B presents data from Peters & Crone (2017). Data from this study shows that prefrontal cortex activation in response to learning from informative feedback increases and peaks in adolescence/young adulthood, a similar pattern was observed for ventral striatum activation. Both studies contain longitudinal-data analyses and represent that the interaction between these individual difference values (prosocial behavior and rebelliousness; cognitive control and reward drive related to future risk taking and learning. We suggest that these interacting pathways can result in personal positive or societally contributing risk-taking behavior, as well as impulsive or antisocial risk taking.

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We recently performed a longitudinal study to examine whether the elevated reward drive in adolescence can lead to multiple trajectories of risk taking. For this study, we included participants between ages 8–29-years who took part in a 3-wave longitudinal study. Self-reported reward drive peaked in mid-adolescence, consistent with prior studies that reported a peak in sensation-seeking (Steinberg et al., 2008). Two other behaviors were assessed; rebellious behavior and prosocial behavior. Interestingly, these behaviors both peaked in adolescence, and were positively correlated (see Fig. 2 a). Longitudinal comparisons revealed that current levels and longitudinal changes in self-reported reward drive (specifically fun seeking) predicted both rebellious and prosocial behavior uniquely, as well as the combination of both, where the combination indicates a unique profile of risk-takers (“prosocial risk-takers”) (based on Do et al., 2017). The study was complemented by analyses of structural brain development which revealed that structural longitudinal medial prefrontal cortex development predicted only additional variance in the development of rebellious behavior, but not for prosocial behavior (Blankenstein et al., 2019). Finally, prosocial behavior, but not rebellious behavior, was uniquely predicted by intention to comfort and perspective taking. This study suggests that rebelliousness and prosociality share a common predictor (reward drive) but also are sensitive to separable influences. Prosociality has previously been associated with the development of a separate network in the brain which includes the temporal-parietal junction, superior temporal sulcus and the midline cortical areas (Blakemore & Mills, 2014). Possibly, the development of this network should be included in future studies to test whether the trajectories of risk taking develop in directions of prosocial or antisocial behaviors (Do et al., 2020; Duell & Steinberg, 2019).

Cognitive development and flexibility

Multiple pathways of risk taking can also result from a complementary contribution of reward drive and cognitive control. Prior imbalance models have mainly described the role of cognitive control in terms of balancing between reward-oriented behavior and deliberate actions. However, very few behavioral studies are showing this affective approach-cognitive control balance in risk-taking paradigms. Recently, a novel perspective, the flexible dual system model, suggested that engagement of cognitive control depends on the availability of information when taking risks (Li, 2017). According to this model, cognitive control processes are engaged more
strongly when information available is high (making risk taking a deliberate choice), whereas cognitive control processes decrease when information available is low, such as in ambiguous or experience-based risk-taking paradigms. This flexibility in cognitive control recruitment was suggested to develop between childhood and adulthood, with larger flexibility at younger ages.

Other studies suggested flexible cognitive control recruitment specifically in adolescence, when cognitive control is functionally well in high information contexts, but is more flexible in ambiguous or learning contexts (see Crone & Dahl, 2012, for a descriptive meta-analysis of flexible prefrontal cortex recruitment in adolescence). We previously observed in a cognitive learning task that adolescents outperformed children and adults when exploring new rules which was associated with increased activity in both the ventral striatum and the dorsolateral prefrontal cortex (Peters & Crone, 2017), possibly suggesting that reward drive may aid in recruiting cognitive-control processes, supporting learning. It remains to be determined in future research how cognitive control influences positive and negative risk taking. The life-span model puts forward an interesting perspective on the interaction between reward drive and cognitive control. This model suggests that when cognitive control is weak, reward drive leads to impulsive risk-taking (Romer et al., 2017). Interestingly, a recent study showed that adolescents who took reasoned, deliberated risks showed higher levels of sensation seeking compared to adolescents who took reactive risks. However, reasoned risks were also associated with higher working memory and cognitive control. Moreover, reasoned risk taking was associated with greater future orientation and these adolescents perceiving risk as beneficial rather than risky (Maslowsky, Owotomo, Huntley, & Keating, 2019). Thus, rather than examining cognitive control as a process that inhibits risk taking, as suggested by imbalance models, cognitive control may also aid in determining when risk taking is worthwhile.

Subgroups and interacting developmental processes

Taken together, we suggest here that future models of risk taking should include also the interacting developmental processes that may exaggerate or buffer the relation between reward drive and risk-taking behavior and that may predict unique developmental outcomes. It was recently found that the differences in subtypes of risk-taking behaviors was largest in mid to late adolescence (Peeters, Oldehinkel, Veenstra, & Vollebergh, 2019), suggesting that this is an important developmental period for defining separable trajectories of risk taking (Dahl et al., 2018; Peeters et al., 2019). Clusters that are identified at age 16 years can even predict health compromising risk taking patterns up to age 42 years (Akasaki, Ploubidis, Dodgeon, & Bonell, 2019). The separable contributions of self-regulation and reward seeking on risk taking were previously observed in a cross-sectional study in 5200 10–30 participants across 11 cultures (Duell et al., 2016). An important consideration for future longitudinal studies in testing risk-taking is to move beyond group-level estimates. For instance, the use of methods such as growth mixture models can help to identify subgroups with distinct developmental trajectories that aid our understanding of individual-level development (Becht & Mills, 2020; Becht et al., 2020). One prior study showed that classification in subtypes predicts future levels or risk-taking trajectories across multiple domains (Meeus et al., 2021).

Neuroscience studies can be helpful in distinguishing trajectories of individual’s risk taking, but to date few studies have examined how interactions between networks of brain regions over time predict separable trajectories or subclusters of risk taking. These studies can take three directions. First, structural cortical brain development shows relative within-person stability in slope suggesting that these trajectories may predict long term outcomes. Evidence for this approach was recently demonstrated in a study showing that structural development slope of social brain areas predicts friendship quality (Becht et al., 2020) and identity commitment (Becht et al., 2018). Combining measures of cognitive control, social and reward sensitive brain areas in clusters may together prove valuable to predict multiple patterns of risk taking. Second, connectivity between cortical and subcortical brain areas such as assessed through white matter connectivity or resting state connectivity can provide useful for examining how joint contribution of brain areas predicts change in behavior over time (Achterberg, Peper, van Duijvenvoorde, Mandler, & Crone, 2016; van Duijvenvoorde, Achterberg, Braams, Peters, & Crone, 2016). White matter connections and resting state connectivity connections have previously shown both age and puberty related changes (Goddings, Beltz, Peper, Crone, & Braams, 2019; van Duijvenvoorde, Westhoff, de Vos, Wierenga, & Crone, 2019). Therefore, these connections are useful for studying the joint contribution of neurobiological influences and social-environmental risk taking on reward drive and risk taking. Finally, task-based functional neuroimaging studies have proven highly useful for decomposing risk taking subprocesses associated with risk learning and risky choice. Stability of MRI measures have shown to be lower over time, indicating that MRI measures are more context-sensitive (Braams et al., 2015; Herting, Gautam, Chen, Mezher, & Vetter, 2017), although this depends on the specific paradigm and brain regions (Peters, van Duijvenvoorde, Koolschijn, & Crone, 2016). Therefore, these measures are highly useful for detecting contextual sensitivity and providing mechanistic explanations.

Future directions

A next step for research on risk taking is to formalize predictive research designs (preceding outcomes in times) theoretically distinguish prediction and causality (Hamaker, Mulder, & van, 2020). Several longitudinal studies have highlighted the potential predictive (Peters, Van der Meulen, Zanolie, & Crone, 2017) and mediating role of functional brain imaging measures (Li et al., 2019), but the specific role in predicting future outcomes will need to be resolved in future research. That is, many of the reviewed studies here on adolescent’s risk taking, including our own, formalize descriptive research goals. Descriptive research is a valuable approach for theory formation and finding factors that eventually may be able to explain or predict the behavior of interest. Including predictive research designs in upcoming work on adolescent risk taking will allow to further delineate who is most at risk, and eventually enhance our understanding of how to stimulate optimal development for that specific individual.

Finally, an important direction for future research is to extend the summary in this review to cross-cultural comparisons (see Duell et al., 2019).
et al., 2018; Icenogle et al., 2019, for excellent cross-cultural work on adolescent risk taking). It is well documented that the developmental period of adolescence differs between cultures and across history (Arnett et al., 2014). An important direction for future research is also to examine the influences of large societal changes, as the definition of risk taking is for a large part defined by societal expectations. For example, adolescents and young adults may experience the consequences of the COVID-19 crisis differently from older individuals, given that their natural tendencies to explore were significantly restricted (Orben, Tomova, & Blakemore, 2020). Moreover, during a pandemic, risk taking by a very small group of adolescents and young adults can have wide scale consequences for health in the population, which can lead to stigmatization and, possibly, self-fulfilling prophecy (Qu, Galvan, Fuligni, Lieberman, & Telzer, 2015). All these aspects were not part of this review but are crucial to take into account when generalizing the results across populations.

Conclusion

This review examined risk taking in adolescence from a behavioral and neurocognitive perspective. We demonstrated that risk taking places in a dynamic environment, which involves short term contextual influences, such as the extent to which risks can result in pay-offs or social benefits, or contexts in which risk taking can aid in learning the outcomes of behavior. Here we suggest that heightened reward drive may explain why some adolescents are more inclined to take risks than others. Whereas prior models acknowledge that not all adolescents are similarly inclined to take risks, there is no clear mechanistic explanation. We suggested in the first part of this review that the differential susceptibility model that is often used to explain individual differences in sensitivity to child rearing experiences (Belsky & van IJzendoorn, 2017), may also be a useful model to test the hypothesis that individual differences in reward drive in combination with long-term social experiences influence the way adolescents respond to risks, for example because they grew up in supporting versus unpredictable environments (Do et al., 2020). Thus, both contextual and accumulated social experiences influence the way adolescent develop risk taking tendencies and these experiences may interact with biologically driven sensitivities that emerge in adolescence. This is an important question for future research.

In the second part of this review, we shifted attention from differential susceptibility to buffering and/or compensating developmental processes. To understand when risk taking is societally accepted versus detrimental, we propose to extend existing models to understand the interplay between various developmental processes. The development of risk taking can be influenced by protective (buffering) or activating (enhancing) developmental processes, such as cognitive control or prosocial tendencies (Do et al., 2017). We hope these novel perspectives provide a richer basis for examining the various interrelations in biological and social-cultural contexts in which adolescents grow up in today’s societies.

CRediT authorship contribution statement

Eveline A. Crone: Conceptualization, Writing – original draft. Anna C.K. van Duijvenvoorde: Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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