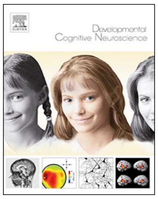
Developmental Cognitive Neuroscience 27 (2017) 91–98

Contents lists available at ScienceDirect

Developmental Cognitive Neuroscience

journal homepage: www.elsevier.com/locate/dcn



Review

Flexing dual-systems models: How variable cognitive control in children informs our understanding of risk-taking across development

Rosa Li[a,b,c,d,*]

[a] Department of Psychology and Neuroscience, Duke University, Durham, NC, USA
[b] Center for Cognitive Neuroscience, Duke University, Durham, NC, USA
[c] Center for Interdisciplinary Decision Sciences, Duke University, Durham, NC, USA
[d] Institute for Brain Sciences, Duke University, Durham, NC, USA

ARTICLE INFO

Keywords:
Decision-making
Risk
Ambiguity
Risk-taking
Dual systems
Adolescence
Childhood
Cognitive control

ABSTRACT

Prevailing models of the development of decision-making propose that peak risk-taking occurs in adolescence due to a neural imbalance between two processes: gradual, linearly developing cognitive control and rapid, nonlinearly developing reward-processing. Though many studies have found neural evidence supporting this dual-systems imbalance model, its behavioral predictions have been surprisingly difficult to document. Most laboratory studies have not found adolescents to exhibit greater risk-taking than children, and public health data show everyday risk-taking to peak in late adolescence/early adulthood. Moreover, when adolescents are provided detailed information about decision options and consequences, they evince similar behavior to adults. Such findings point to a critical feature of the development of decision-making that is missed by imbalance models. Specifically, the engagement of cognitive control is context dependent, such that cognitive control and therefore advantageous decision-making increases when available information is high and decreases when available information is low. Furthermore, the context dependence of cognitive control varies across development, such that increased information availability benefits children more than adolescents, who benefit more than adults. This review advances a flexible dual-systems model that is only imbalanced under certain conditions; explains disparities between neural, behavioral, and public health findings; and provides testable hypotheses for future research.

1. Introduction

Adolescence is popularly characterized as a turbulent time period in which raging hormones drive reckless teenagers to engage in risky behaviors. Public health data broadly support such a characterization, as progressing from childhood to adolescence more than triples one's likelihood of dying, and the leading causes of adolescent deaths are accidents/unintentional injuries and homicide/assault (Heron, 2013). Current prevailing models have taken a dual-systems approach to suggest that adolescence is a developmental time period of peak risk-taking due to three factors: 1) reward processing and its associated limbic neural circuitry (including but not limited to ventral striatum; VS) peak in adolescence, 2) cognitive control and its associated prefrontal cortex (PFC) circuitry develop linearly from childhood to adulthood, and 3) reward-processing overwhelms cognitive control most prominently in adolescence, thereby driving adolescents to take more undue risks than both adults and children (Casey et al., 2008; Shulman et al., 2016b; Somerville et al., 2010; Steinberg, 2007; Fig. 1). While these dual-systems imbalance accounts have fostered much fruitful research in the fields of developmental cognitive neuroscience and decision-making, their behavioral predictions have not been well-supported by laboratory findings or public health data.

According to dual-systems imbalance models, risk-taking should peak when VS response to reward does, in early adolescence around ages 14–16 (Braams et al., 2015; Galván et al., 2006; Padmanabhan et al., 2011; van Leijenhorst et al., 2010a,b; but see Bjork et al., 2004; Bjork et al., 2010; Paulsen et al., 2012; and see Galván, 2010; Richards et al., 2013 for review). To the contrary, a recent meta-analysis of laboratory developmental risk-taking studies found no differences in risk-taking between children (ages 5–10) and adolescents (ages 11–19), and mid-late adolescents (ages 14–19) were actually found to take *fewer* risks than early adolescents (ages 11–13; Defoe et al., 2015). In fact, *only three laboratory studies have found adolescents to take more risks than both adults and children* (Braams et al., 2015; Burnett et al., 2010; van den Bos and Hertwig, 2017). In one particularly illustrative study, reward processing in VS was found to peak in adolescence, and activity in

---

* Correspondence to: PO Box 90999, Durham, NC 27708, USA.
E-mail address: rosa.li@duke.edu.

http://dx.doi.org/10.1016/j.dcn.2017.08.007
Received 27 April 2016; Received in revised form 8 June 2017; Accepted 14 August 2017

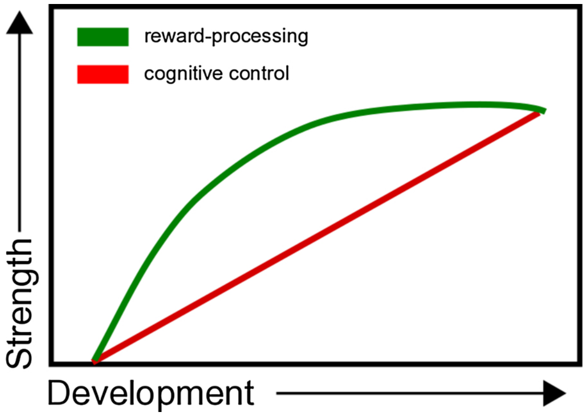


Fig. 1. The classic dual-systems imbalance model, in which cognitive control develops linearly while reward-processing peaks in adolescence. Adapted from Casey et al. (2008).

PFC regions varied linearly with age, but the two factors did not combine to generate behavioral risk-taking differences across different age groups (van Leijenhorst et al., 2010a). This study, and the broader literature (see Boyer, 2006; Defoe et al., 2015 for review), highlights the striking disconnect between developmental changes in neural activity, which often support dual-systems imbalance models, and risky decision-making as measured in the laboratory, which rarely does.

The behavioral predictions of dual-systems imbalance models are also not borne out in public health data. Many everyday risky behaviors such as binge drinking, drug use, and criminal activity actually peak in late adolescence/early adulthood, around ages 18–21 (Steinberg, 2013; Willoughby et al., 2013), well beyond the developmental peak in VS response to reward around ages 14–16. Thus, there are two major shortcomings of the predictive validity of dual-systems imbalance models: 1) laboratory studies generally find that risk-taking decreases or is developmentally constant up to and including the ages of 14–16, and 2) public health data suggest that everyday risk-taking increases after the ages of 14–16.

Proponents of the dual-systems imbalance model have suggested that laboratory studies do not find risk-taking to peak in adolescence because such studies do not account for the various social, affective, and cultural factors that alter behavior in everyday decision contexts. They further note that studies that vary contextual factors to more strongly resemble everyday decisions, such as by reducing the amount of available decision information (Tymula et al., 2012) or adding the presence of peers (Chein et al., 2011; Gardner and Steinberg, 2005), do find adolescents to take more risks compared to adults. Finally, they suggest that the lag between the timing of the dual-systems imbalance model-predicted peak in risk-taking (ages 14–16) and real world peaks (ages 18–21) is due to greater legal access to everyday risk-taking opportunities in late adolescence/early adulthood (Shulman et al., 2016b).

Studies that manipulate decision contexts for adolescents and adults, however, only go halfway towards probing the prediction of dual-systems imbalance models that adolescents take more risks than both adults *and children*. Without studies comparing children to adolescents and adults, we cannot discern whether a developmental difference from adolescence to adulthood represents a peak in adolescence, a linear trend across development, or a trait that is already present prior to adolescence (Fig. 2).

Unfortunately, developmental risky decision-making studies that manipulate social and affective contexts have only included adolescents and/or adults (Chein et al., 2011; Figner et al., 2009; Gardner and Steinberg, 2005; O'Brien et al., 2011; Smith et al., 2014; Smith et al., 2015; Weigard et al., 2013), so we do not yet know how such emotionally-arousing contexts affect risk-taking in children (but see Knoll, Magis-Weinberg, Speekenbrink, & Blakemore, 2015 for a study of how social-influence affects stated risk perception in children, adolescents, and adults). Fortunately, there are a small number of studies that examine how the amount of available decision information affects children, compared to adolescents and/or adults. These studies shed light on why current dual-systems imbalance models fall short and how such models can be amended to provide more predictive power.

In this review, I will note that studies with children that use paradigms that reduce the amount of available decision information, either by offering ambiguous gambles (Section 2) or using experience-based tasks in which decision contingencies must be learned through experience (Section 3), find that children gamble more and/or are worse decision-makers compared to adolescents and adults. In Section 4, I will show that studies that use description-based paradigms providing full decision information often find that children are comparable to adolescents and adults in their ability to make advantageous decisions, or that risk-taking linearly decreases with age from childhood to adolescence to adulthood, rather than peaking in adolescence.

Taken together, these studies suggest that learning demands differentially affect decision-makers across development. This results in different developmental risk-taking trajectories depending on whether decisions are description-based (high information environments with low learning demands) or experience-based (low information environments with high learning demands). In Section 5, I will posit that the recruitment of cognitive control systems is flexible based on a decision-environment's information availability, such that cognitive control and therefore advantageous decision-making increases when information is high and decreases when information is low. Furthermore, this flexible recruitment of PFC also interacts with age, such that children are disproportionately poor decision-makers in low information environments but also show the greatest improvements in decision-making when moving to high information environments (Fig. 3). Finally, in Section 6, I will integrate the idea of flexible recruitment of cognitive control into existing dual-systems imbalance models, resulting in a flexible dual-systems model that is only imbalanced under certain conditions, thereby explaining disparities between neural, behavioral, and public health findings and providing testable hypotheses for future research.

For the purposes of this review, I will generally consider adolescence as the teenage years (ages 13–19), or approximately the time period between the onset of puberty and the attainment of adult status in Western societies (Crone and Dahl, 2012). These bounds are loosely construed, however, as the literature on the development of decision-making has no clean definitions of when adolescence begins and ends. Thus, whenever possible, I note the age ranges of adolescents, adults, and children when referencing previous studies and generally follow the grouping nomenclature used by each study. When referring to laboratory paradigms, I define risk as the coefficient of variation (CV; a standardized measure of outcome variability), risk-taking as choosing the option with the greater CV (Weber et al., 2004), advantageous decision-making as choosing the option with the greater expected value (EV; a metric of the average outcome of a gamble), description-based paradigms as those that provide participants with full information about a decision's potential outcomes and their probabilities, and experience-based paradigms as those that require participants to learn about outcomes and probabilities through experienced feedback (Hertwig and Erev, 2009). With regards to everyday decision-making, I use risk-taking in the colloquial sense, to refer to engaging in behaviors with potentially harmful outcomes.

2. Risk-taking under ambiguity

In description-based laboratory tasks, potential outcomes and their probability contingencies are explicitly given (i.e. when playing a wheel of fortune, the exact probabilities of each outcome are visually provided). In contrast, most everyday decisions feature outcomes with unknown exact probabilities (i.e. when running a red light, the exact probabilities of causing an accident are unknown). As a result, decisions

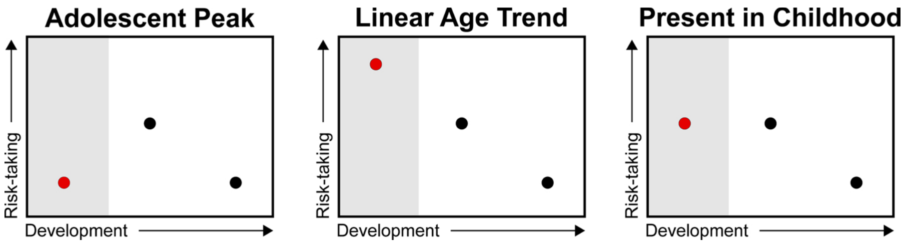


Fig. 2. When childhood is not studied (grey regions), greater risk-taking in adolescence compared to adulthood could represent one of three developmental trends. Knowledge of risk-taking in childhood is needed in order to distinguish between an adolescent peak, a linear age trend, or a trait that is already present in childhood.

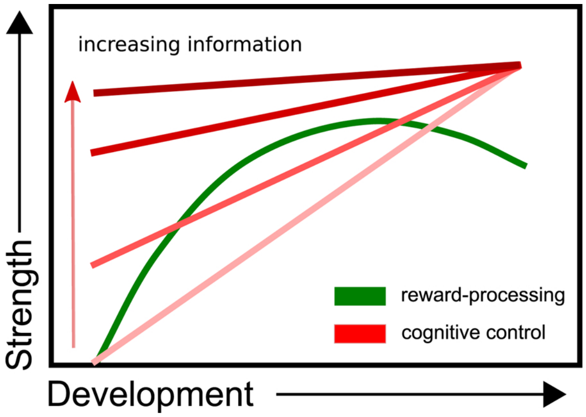


Fig. 3. In the proposed flexible model, increasing available information (and therefore lowering learning demands) changes the slope of the strength of cognitive control to drive advantageous decision-making. Children receive the greatest boost in cognitive control strength from increased information, followed by adolescents and then adults. Increasing color saturation indicates increasing information available in the decision environment.

regarding “ambiguous risk” or “ambiguity”, when outcome probabilities are unknown, are likely a better proxy for real world decision-making than those regarding “known risk”, when outcome probabilities are provided by the experimenters.

The study of ambiguity preferences in adults dates back to 1961 (Ellsberg, 1961; see Camerer and Weber, 1992; Trautmann and van de Kuilen, 2015 for review), but developmental work on ambiguity preferences was not published until 2012, when Tymula and colleagues reported that adolescents (ages 12–17), compared to adults (ages 30–50), were more willing to take ambiguous gambles for potential gains. This first study has been taken to support dual-systems model predictions of peak risk-taking in adolescence (Shulman et al., 2016b), despite the fact that it compared only adolescents to adults and did not include children.

More recent work, however, has found that children as young as 5-year-olds (Li et al., 2017) and 8-year-olds (Li et al., 2015) are also more willing to take ambiguous gambles than are adults (ages 18–32). In fact, while adolescents were still found to exhibit some aversion to ambiguity (Tymula et al., 2012), 5- and 8-year-olds exhibited no ambiguity aversion on tasks that evoked ambiguity aversion in adults (Li et al., 2015, 2017). Furthermore, a study of ambiguity preferences of participants between the ages of 10 and 25 found ambiguity seeking in the gain domain to decrease linearly with age, with no evidence of a quadratic relationship between age and ambiguity preferences (Blankenstein et al., 2016; but see van den Bos and Hertwig, 2017, which found age and ambiguity preferences to exhibit no significant relationship when playing for gains but a quadratic relationship when playing for losses in participants ages 8–22; and Tymula et al. (2013), which found no relationship between age and ambiguity preferences when playing for losses in participants ages 12–50).

The finding that adolescents are more ambiguity tolerant compared to adults (Tymula et al., 2012) initially appeared to support dual-systems model predictions of peak risk-taking in adolescence, but findings from children showed such predictions to be incorrect. Instead, developmental studies of ambiguity preferences suggest that ambiguity seeking, at least when playing for potential gains, decreases linearly with age (though much more work is needed to fully understand the development of ambiguity preferences in different domains). The example of risk-taking under ambiguity underscores the importance of including children before drawing conclusions about developmental trajectories. Future developmental neuroimaging studies of ambiguity preferences are needed in order to determine how neural activity underlying ambiguous decision-making corresponds with dual-systems imbalance models.

3. Comparing risk-taking in experience- and description-based paradigms

Everyday decisions can become less ambiguous over time through repeated exposure to a decision and its outcomes—but only if one can effectively learn about those outcomes and their probabilities through experience. The ability to learn from experience likely plays a role in explaining disparate findings between laboratory tasks using description-based paradigms and public health data on everyday experience-based decisions. A meta-analysis comparing younger (ages 18–35) and older (ages 65–85) adults has already found that learning demands interact with age to influence risk-taking: in described tasks, younger and older adults exhibited similar behavior, while in experienced tasks, risk-taking differences varied depending on how older adults’ poorer working memory and learning abilities interacted with task designs and demands (Mata et al., 2011).

Though a meta-analysis of risk-taking studies of children, adolescents, and adults did not find whether a task was experience- or description-based to significantly moderate any age differences (or lack thereof) in risk-taking (Defoe et al., 2015), very few studies have explicitly compared across ages on experience- and description-based versions of the same risky decision-making tasks. As summarized below, the findings of the few studies that do make such comparisons suggest that, as with older adults, learning demands affect risk-taking and interact with age in children, adolescents, and adults.

3.1. The Iowa Gambling Task

The Iowa Gambling Task (IGT) requires participants to learn which card decks lead to net gains and net losses through experienced feedback. Advantageous decks generally contain small and/or more frequent gains and smaller and/or less frequent losses, thus leading to net gains. Disadvantageous decks generally contain large gains but even larger losses, making them attractive in the short term but a costly net loss in the long run. Numerous studies using various iterations of the IGT have found that the ability to learn from experienced feedback and overall winnings on the IGT increase with age from childhood to adulthood (Cauffman et al., 2010; Christakou et al., 2013; Crone and van der Molen, 2004, 2007; Huizenga et al., 2007; Prencipe et al., 2011; but see Smith et al., 2012).

Studies comparing performance on a traditional IGT to one in which deck contingencies are explicitly labeled highlight how children and adolescents are able to increase advantageous decision-making when additional information is provided and learning demands are removed.

Children (ages 7–11) playing a description-based IGT chose significantly more often from the advantageous decks than the disadvantageous decks, compared to children playing an experience-based IGT. Furthermore, explicit contingencies ameliorated children's and adolescents' tendency to use a maladaptive lose-switch strategy (van Duijvenvoorde et al., 2012). Adolescents (ages 13–15) were also able to use more complex advantageous decision strategies when playing a description-based IGT, noting frequency, amount of loss and gain, and deck EV when making decisions. In contrast, in a traditional experience-based IGT, most adolescents only used frequency of loss to guide their decisions and thus performed worse (van Duijvenvoorde et al., 2010).

3.2. *The description-experience gap*

The "description-experience gap" refers to the difference in choice behavior when the same payoff contingencies are described versus experienced. Smaller description-experience gaps suggest more accurate learning, as preferences derived from experience more closely resemble those regarding fully described contingencies. Though the description-experience gap has been well-studied in adults (see Hertwig and Erev, 2009 for review), it has rarely been measured in developmental populations.

One study found that the description-experience gap was larger in younger participants (ages 11–17) than in adults (mean ages of 21.6 and 20.7), suggesting better learning in adults than in children and adolescents. Though this difference did not reach statistical significance, it was present across several experiments, and the authors suggest that a task with greater working memory demands may reveal greater developmental differences (Rakow and Rahim, 2010). Intriguingly, another experience-based study found that adolescents, compared to children and adults, chose to experience fewer samples of unknown gambles before making a choice and made riskier choices compared to both adults and children (van den Bos and Hertwig, 2017), suggesting that learning ability may interact with information-seeking or impulsivity to influence choice across development.

3.3. *Summary of comparing risk-taking in experience- and description-based paradigms*

Studies using experience-based paradigms generally find that the ability to optimize decision-making from feedback increases with age (but see Peters et al., 2014, which shows that there is individual variability within general age trends, such that some children use more complex learning strategies than do some adults), and that, understandably, those who struggle the most to make advantageous experience-based decisions stand to benefit the most from explicitly provided information that removes learning demands (van Duijvenvoorde et al., 2012). Consequently, some of the risk-taking discrepancies between laboratory tasks and everyday decisions may be due to the impact of reduced information availability and higher learning demands in the latter, relative to the former. Further developmental studies comparing description- and experience-based versions of the same tasks are needed to fully elucidate how such differences in available information affects decision-making across development.

4. Risk-taking in description-based tasks

Most developmental studies of risk-taking have used description-based decision-making paradigms featuring known probabilities and outcomes. Contrary to the predictions of dual-systems imbalance models, such tasks generally find risk-taking to linearly decrease with age when EV is held constant, while advantageous EV use is generally found to increase with age and learning abilities.

4.1. *Risk-taking decreases and advantageous decision-making increases with age*

A number of description-based studies providing participants with explicit probability contingencies and reward amounts have found that the ability to accurately use EV increases with age, especially in childhood. Children as young as 5 were found to be able to integrate both the probability of winning and win outcome when deciding whether to gamble, but 5- and 6-year-olds incorrectly added values. It was not until age 8 that probabilities and outcomes were multiplicatively integrated in decision-making (Schlottmann and Anderson, 1994). In a variety of described economic gambling tasks, EV-advantageous decision-making has been found to increase with age from 8 to 18 (Crone et al., 2008), from 9 to 35 (Burnett et al., 2010), from 5 to 64 (Harbaugh et al., 2002), and from 5 to 11 compared to adulthood (Levin et al., 2007). In these studies, risk-taking similarly linearly decreased with age, as children were more likely to take risks even when risks were disadvantageous.

In another study that held a gamble's EV constant but allowed CV to vary, increasing CV drove children (ages 6–8) to take more risks. In contrast, increasing CV drove adults (ages 18–32) and adolescents (ages 15–16) to take fewer risks. At the highest level of CV, risk-taking was found to decrease with age from childhood to adulthood (Paulsen et al., 2011). In another version of this study, children (ages 5–8) were found to be riskier than both adults (ages 18–35) and adolescents (ages 14–16), while adolescents did not differ from adults in their risk-taking behavior (Paulsen et al., 2012). Taken together, these behavioral findings suggest that when there is no EV-advantageously "correct" choice, risk-taking linearly decreases with age.

4.2. *Risk-taking does not vary with age when advantageous options are obvious*

A number of studies have also found no differences in gambling and EV use with age (Barkley-Levenson et al., 2013; Keulers et al., 2011; van Leijenhorst et al., 2010a, 2006). It may be that in some cases, perhaps when EV differences between options are relatively easy to distinguish, providing explicit probabilities and outcomes can bring children's and adolescents' abilities to make advantageous decisions on par with those of adults. For example, risk-taking on a Wheel of Fortune task decreased with age from 9 to 40 at the more moderate (7:3 odds) of two levels of risk, but behavior was similar across ages at the more obviously risky 9:1 odds gamble (Eshel et al., 2007). Similarly, a Cake Gambling Task found a linear decrease in gambling with age from 8 to 26 at the lowest risk level when gambles were EV equivalent, but no difference in behavior across ages when the risky gambles were EV-advantageous (van Leijenhorst et al., 2010a). These latter two studies run counter to the meta-analytic findings that tasks including unequal EVs find adolescents to take more risks than children, with no moderating effects of EV-advantageousness (Defoe et al., 2015). It should be noted, however, that the meta-analysis collapsed across description- and experienced-based designs, so it cannot be determined if that meta-analytic result also holds when restricted to description-based tasks.

4.3. *Advantageous decision-making interacts with cognitive control*

The ability to make EV-advantageous decisions has been found to interact with age and various measures of cognitive control. In a Game of Dice Task, in which reward contingencies were explicit and the EV-advantageous strategy was to avoid risk, overall risk-taking linearly decreased with age from 8 to 19. The relationship between age and risk-taking, however, significantly interacted with cognitive flexibility, as measured by performance on a card-sorting task. Older participants took similar risks regardless of cognitive flexibility, while younger participants showed differential risk-taking based on cognitive flexibility. Young children with high cognitive flexibility took fewer risks, and therefore made more EV-advantageous choices, performing on par with older participants. In contrast, young children with poor cognitive flexibility took more risks and performed worse (Schiebener et al., 2014). Another study using the Game of Dice task also found that advantageous decision-making positively correlated with fluid intelligence and probabilistic reasoning abilities in adolescents and young adults (ages 14–22; Donati et al., 2014). These studies suggest that increased cognitive control abilities support advantageous decision-making, especially for young children.

4.4. *Summary of risk-taking in description-based tasks*

It is notable that one of the three laboratory studies to find a true adolescent peak in risk-taking also found advantageous EV use to linearly increase with age from 9 to 35, with no evidence of a quadratic relationship with age (Burnett et al., 2010). This study highlights the need for paradigms that separate or orthogonalize EV and CV so that advantageous decision-making and risk-taking can be fully disentangled. As the two appear to have divergent developmental trajectories, with advantageous decision-making generally increasing with age (Burnett et al., 2010; Crone et al., 2008; Harbaugh et al., 2002; Levin et al., 2007) and risk-seeking generally decreasing with age (Eshel et al., 2007; Paulsen et al., 2012, 2011; Schiebener et al., 2014; van den Bos and Hertwig, 2017; van Leijenhorst, Gunther Moor et al., 2010), unpacking their dueling influences can help pinpoint the causes of decision-making differences across development.

5. Flexible recruitment of cognitive control systems

As reviewed above, the amount of available decision information differentially affects decision-making at different stages of development. When information is held constant and learning from experience is unavailable or unnecessary, willingness to take ambiguous risks and choose the riskier of described equal-EV options linearly decreases with age. When information is provided via an experimental paradigm, the boost in advantageous decision-making when shifting from experience- to description-based decisions interacts with age and cognitive control abilities. Together, these findings suggest that the recruitment of cognitive control systems in guiding advantageous decision-making is flexible based upon information availability.

In experience-based tasks, the role of cognitive control systems in guiding advantageous decision-making may follow dual-systems imbalance model predictions and linearly increase with age. In description-based tasks with high information availability, however, the strength of cognitive control systems may experience a slope change that disproportionately boosts the cognitive control of children relative to adolescents, relative to adults, with the shift in slope varying depending on the amount of decision information available (Fig. 3). In this proposed flexible dual-systems model, the disparities between neural findings and behavioral predictions of the dual-systems imbalance model can be resolved. Studies that find no age differences in risk-taking but neural findings consistent with dual-systems imbalance models (van Leijenhorst et al., 2010a) can be explained by a large slope shift in the developmental trajectory of cognitive control, thereby increasing cognitive control above the inverted-U of reward-processing and out of imbalance.

Though plentiful behavioral evidence suggests that the deployment of cognitive control to dictate advantageous decision-making is flexible based upon information availability, the neural basis of this flexible deployment of cognitive control remains speculative. The literature lacks developmental neuroimaging studies directly comparing experience- and description-based versions of the same risky decision-making task. There are, however, developmental neuroimaging studies in high information environments that support the idea of flexible PFC recruitment. When adolescents (ages 13–17) and adults (age 25–30) were given the chance to accept or reject described mixed economic gambles, there were no age-related behavioral differences. At the neural level, however, adolescents, compared to adults, exhibited more activity in frontal pole when choosing to reject trials, suggesting that choosing to reject gambles required more effort for adolescents (Barkley-Levenson et al., 2013). Similarly, on a described Cake Gambling Task, in which participants chose which of two colors to bet on for a reward, children (ages 9–12) and adults (ages 18–26) showed similar choice behavior, but children exhibited greater dACC activity on high-risk (color ratios of 6:3 or 5:4) versus low-risk (color ratios of 8:1 or 7:2) trials. Adults, in contrast, showed no difference by trial type. This study's findings suggest that children required more effort to implement optimal, advantageous decision-making on the more difficult high-risk trials (van Leijenhorst et al., 2006). It may be that high information availability boosts children's and adolescents' ability to call on PFC regions, perhaps by reducing learning demands and thus freeing cognitive resources for advantageous decision-making. Future work is needed to fully understand how such developmental differences in PFC activity during risky decision-making should be interpreted as signs of effort or efficiency (Pfeifer and Allen, 2012; Poldrack, 2015).

6. Conclusions and future directions

An existing interpretation of the dual-systems imbalance model suggests that limbic regions are flexibly recruited depending on whether a decision context is “hot” (affectively arousing) or “cold” (affectively neutral; A. R. Smith, Chein, & Steinberg, 2013; Steinberg, 2010; Fig. 4A), as several studies have found that “hot” contexts increased risk-taking and/or VS response to reward in adolescents (Chein et al., 2011; Figner et al., 2009; Gardner and Steinberg, 2005; Smith et al., 2015). In this review, I suggest that the recruitment of PFC and cognitive control is also developmentally flexible based on information availability. Moving from a static model of dual-systems imbalance towards a flexible model that accounts for interactions between decision-makers, information availability, and emotional arousal results in a framework that can account for some of the discrepancies between behavioral and neural findings (Fig. 4B). Still, much work remains to better capture the developmental trajectory of this flexible framework and rigorously test its predictions (Pfeifer and Allen, 2016; van den Bos

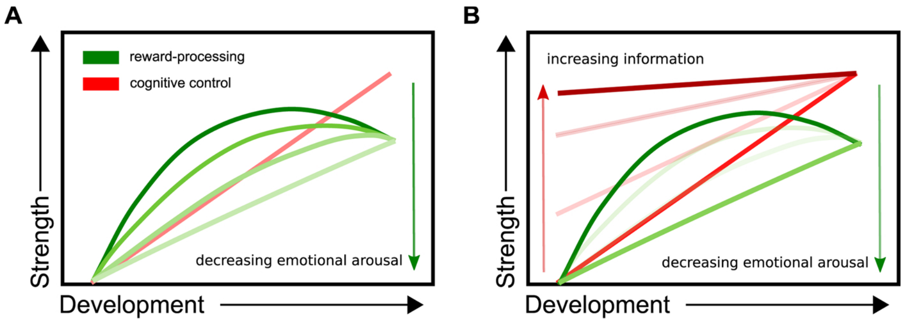


Fig. 4. Flexing dual-systems imbalance models. A) Decreasing emotional arousal decreases the strength of reward-processing in driving decision-making. Decreasing color saturation indicates decreasing emotional arousal. B) In a fully flexible model, the relative strengths of cognitive control and reward-processing in driving decision-making vary based upon information availability and emotional arousal in the decision environment (trajectories of intermediate levels of information and emotional arousal are faded for visual clarity).

and Eppinger, 2016).

As previously noted, the neural underpinnings behind the flexibility of cognitive control and advantageous decision-making remain unexplored, as there have been no developmental neuroimaging studies comparing risk-taking under different learning demands or cases of varying information availability. Additionally, the interactions between cognitive control and reward processing, and the developmental trajectory of those interactions, warrant further exploration. Self-report data suggest that impulse control and sensation-seeking develop independently (Shulman et al., 2016a), but emotional states have been found to enhance cognitive control performance and increase related neural activity in adults (ages 21–25; Cohen et al., 2016). Furthermore, adolescent (ages 13–17) risk-taking on a simulated driving game was correlated with their performance on a "hot" cognitive control task but uncorrelated with performance on a "cold" version of the same cognitive control task (Botdorf et al., 2016). Much more research is needed to unpack if, when, and how control and reward processes interact to influence risky decision-making.

The influences of control and reward on decision-making across development can be explicitly tested by comparing performance on high and low information and/or "hot" and "cold" versions of the same paradigm. For example, one commonly used measure of risk-taking is the BART (Balloon Analog Risk Task), in which participants pump up—but risk popping—virtual balloons to earn money (Lejuez et al., 2002). One of the three studies to find a true adolescent peak in risk-taking used this task (Braams et al., 2015). Because the BART is both experienced (participants are not told of the popping probabilities) and "hot" (each choice to continue pumping the balloon is incrementally made), it is difficult to untangle the influences of control and reward on risk-taking behavior. Comparing behavior on a high information version of the BART that labels balloons with their popping probabilities, or a "cold" version of the BART that has participants declare the number of desired pumps at the start of each balloon, could help determine whether risk-taking on a traditional BART is due to a lack of cognitive control that precludes learning about balloons' popping contingencies, an abundance of reward-seeking when one is caught up in the "heat" of incrementally pumping the balloon, or some combination of the two.

Our understanding of the influence of emotional arousal on risk-taking across development is still incomplete. Many "hot" versus "cold" context studies only investigated adolescents/late adolescents without a comparison group of adults (O'Brien et al., 2011; Smith et al., 2014; Weigard et al., 2013), and most studies comparing adolescents and adults do not include children (Chein et al., 2011; Figner et al., 2009; Gardner and Steinberg, 2005; Smith et al., 2015). It is important to remember that it is premature to draw conclusions about the full developmental trajectory of a process when only adults and adolescents have been studied. As the example of risk-taking under ambiguity illustrates, additional datapoints of children's behavior may overturn existing interpretations of incomplete developmental data. In fact, one study found that the effect of social influence on stated risk-perception linearly decreased with age from 8 to 59, suggesting that children could be more affected by social contexts than are adolescents and adults (Knoll et al., 2015). Further research comparing decision-making in children, adolescents, and adults under a variety of decision contexts is needed to capture the full developmental trajectories of how context affects behavior.

Finally, additional work is needed to understand how everyday access to different decision contexts changes across development, so that labaratory work can better translate to everyday decision-making. Age-dependent legal access to risky scenarios likely explains some developmental differences in everyday risk-taking (Boyer and Byrnes, 2009; Shulman et al., 2016b), but not all—for example, heavy drinking peaks around ages 21–25 in both U.S. and Swiss samples, despite the fact that the legal drinking age is younger in Switzerland (16 years) than in the U.S. (21 years; Substance Abuse and Mental Health Services Administration, 2013; Brodbeck et al., 2013). Cross-cultural studies (c.f. Steinberg et al., 2017) are needed to elucidate which aspects of age-related differences in everyday risk-taking are universal and which are determined by sociocultural norms and legal policies regulating access.

Increasing experience with risky scenarios likely also influences everyday decision-making. It may be that older adolescents/young adults take more everyday risks because they are disproportionately experiencing unfamiliar decision contexts due to sociocultural norms promoting greater independence at these ages, and risk-taking decreases with age due to increased information gained through life experience, rather than the passing of peak reward sensitivity. Cross-cultural and individual difference studies can also play a role here, by allowing the comparison of risk-taking in participants of similar ages but with differing levels of experience with a particular decision context. Additional research on whether and how the relative strengths of control and reward change through repeated experience or education could be fruitful for guiding public health interventions to reduce maladaptive risk-taking in adolescence.

The relatively young field of developmental risky decision-making has made many important discoveries about the adolescent brain with far-reaching implications for public health (Simpson, 2003) and the law (Steinberg, 2013). Yet much remains to be uncovered. Allowing existing dual-systems imbalance models additional degrees of freedom to vary with decision contexts provides a flexible framework for promoting further exploration and understanding of the development of risk-taking in a variety of scenarios, from the laboratory to everyday life.

Conflict of Interest

None.

Acknowledgements

A version of this paper served as partial fulfillment of the author's preliminary exam for a master's degree and qualification for doctoral candidacy in the Department of Psychology and Neuroscience at Duke University. The author would like to thank Scott Huettel, Elizabeth Brannon, Gráinne Fitzsimons, Adriana Galván, and Eveline Crone for their guidance and feedback on earlier drafts of the paper. The author was supported by a National Science Foundation Graduate Research Fellowship during the preparation of this manuscript.

References

Barkley-Levenson, E.E., van Leijenhorst, L., Galván, A., 2013. Behavioral and neural correlates of loss aversion and risk avoidance in adolescents and adults. Dev. Cogn. Neurosci. 3, 72–83. http://dx.doi.org/10.1016/j.dcn.2012.09.007.

Bjork, J.M., Knutson, B., Fong, G.W., Caggiano, D.M., Bennett, S.M., Hommer, D.W., 2004. Incentive-elicited brain activation in adolescents: similarities and differences from young adults. J. Neurosci. 24 (8), 1793–1802. http://dx.doi.org/10.1523/JNEUROSCI.4862-03.2004.

Bjork, J.M., Smith, A.R., Chen, G., Hommer, D.W., 2010. Adolescents, adults and rewards: comparing motivational neurocircuitry recruitment using fMRI. PLoS One 5 (7), e11440. http://dx.doi.org/10.1371/journal.pone.0011440.

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. Dev. Neuropsychol. 5641 (March), 1–16. http://dx.doi.org/10.1080/87565641.2016.1158265.

van den Bos, W., Eppinger, B., 2016. Developing developmental cognitive neuroscience: from agenda setting to hypothesis testing. Dev. Cogn. Neurosci. 17, 138–144. http://dx.doi.org/10.1016/j.dcn.2015.12.011.

van den Bos, W., Hertwig, R., 2017. Adolescents display distinctive tolerance to ambiguity and to uncertainty during risky decision making. Sci. Rep. 7, 40962. http://dx.doi.org/10.1038/srep40962.

Botdorf, M., Rosenbaum, G.M., Patrianakos, J., Steinberg, L., Chein, J.M., 2016. Adolescent risk-taking is predicted by individual differences in cognitive control over emotional, but not non-emotional, response conflict. Cogn. Emot. 9931 (April), 1–8. http://dx.doi.org/10.1080/02699931.2016.1168285.

Boyer, T.W., Byrnes, J.P., 2009. Adolescent risk-taking: integrating personal, cognitive, and social aspects of judgment. J. Appl. Dev. Psychol. 30 (1), 23–33. http://dx.doi.org/10.1016/j.appdev.2008.10.009.

Boyer, T.W., 2006. The development of risk-taking: a multi-perspective review. Dev. Rev. 26 (3), 291–345. http://dx.doi.org/10.1016/j.dr.2006.05.002.

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. J. Neurosci. 35 (18), 7226–7238. http://dx.doi.org/10.1523/JNEUROSCI.4764-14.2015.

Brodbeck, J., Bachmann, M.S., Croudace, T.J., Brown, A., 2013. Comparing growth trajectories of risk behaviors from late adolescence through young adulthood: an accelerated design. Dev. Psychol. 49 (9), 1732–1738. http://dx.doi.org/10.1037/a0030873.

Burnett, S., Bault, N., Coricelli, G., Blakemore, S.-J., 2010. Adolescents' heightened risk-seeking in a probabilistic gambling task. Cogn. Dev. 25 (2), 183–196. http://dx.doi.org/10.1016/j.cogdev.2009.11.003.

Camerer, C.F., Weber, M., 1992. Recent developments in modeling preferences: uncertainty and ambiguity. J. Risk Uncertain. 5 (4), 325–370. http://dx.doi.org/10.1007/BF00122575.

Casey, B.J., Getz, S., Galván, A., 2008. The adolescent brain. Dev. Rev. 28 (1), 62–77. http://dx.doi.org/10.1016/j.dr.2007.08.003.

Cauffman, E., Shulman, E.P., Steinberg, L., Claus, E.D., Banich, M.T., Graham, S., Woolard, J., 2010. Age differences in affective decision making as indexed by performance on the Iowa Gambling Task. Dev. Psychol. 46 (1), 193–207. http://dx.doi.org/10.1037/a0016128.

Chein, J.M., Albert, D., O'Brien, L., Uckert, K., Steinberg, L., 2011. Peers increase adolescent risk taking by enhancing activity in the brain's reward circuitry. Dev. Sci. 14 (2), F1–F10. http://dx.doi.org/10.1111/j.1467-7687.2010.01035.x.

Christakou, A., Gershman, S.J., Niv, Y., Simmons, A., Brammer, M., Rubia, K., 2013. Neural and psychological maturation of decision-making in adolescence and young adulthood. J. Cogn. Neurosci. 1–17. http://dx.doi.org/10.1162/jocn_a_00447.

Cohen, A.O., Breiner, K., Steinberg, L., Bonnie, R.J., Scott, E.S., Taylor-Thompson, K.A., Rudolph, M.D., Chein, J., Richeson, J.A., Heller, A.S., Silverman, M.R., Dellarco, D.V., Fair, D.A., Galván, A., Casey, B.J., 2016. When is an adolescent an adult? Assessing cognitive control in emotional and nonemotional contexts. Psychol. Sci. http://dx.doi.org/10.1177/0956797615627625. (0956797615627625-).

Crone, E.A., Dahl, R.E., 2012. Understanding adolescence as a period of social-affective engagement and goal flexibility. Nat. Rev. Neurosci. 13 (9), 636–650. http://dx.doi.org/10.1038/nrn3313.

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. Dev. Neuropsychol. 25 (3), 251–279. http://dx.doi.org/10.1207/s15326942dn2503_2.

Crone, E.A., van der Molen, M.W., 2007. Development of decision making in school-aged children and adolescents: evidence from heart rate and skin conductance analysis. Child Dev. 78 (4), 1288–1301. http://dx.doi.org/10.1111/j.1467-8624.2007.01066.x.

Crone, E.A., Bullens, L., van der Plas, E.A.A., Kijkuit, E.J., Zelazo, P.D., 2008. Developmental changes and individual differences in risk and perspective taking in adolescence. Dev. Psychopathol. 20 (4), 1213–1229. http://dx.doi.org/10.1017/S0954579408000588.

Defoe, I.N., Dubas, J.S., Figner, B., Van Aken, M.A.G., 2015. A meta-analysis on age differences in risky decision making: adolescents versus children and adults. Psychol. Bull. http://dx.doi.org/10.1037/a0038088.

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. J. Clin. Exp. Neuropsychol. 1–8. http://dx.doi.org/10.1080/13803395.2014.918091.

van Duijvenvoorde, A.C.K., Jansen, B.R.J., Visser, I., Huizenga, H.M., 2010. Affective and cognitive decision-making in adolescents. Dev. Neuropsychol. 35 (5), 539–554. http://dx.doi.org/10.1080/87565641.2010494749.

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. Dev. Psychol. 48 (1), 192–203. http://dx.doi.org/10.1037/a0025601.

Ellsberg, D., 1961. Risk, ambiguity, and the savage axioms. Q. J. Econ. 75 (4), 643. http://dx.doi.org/10.2307/1884324.

Eshel, N., Nelson, E.E., Blair, R.J., Pine, D.S., Ernst, M., 2007. Neural substrates of choice selection in adults and adolescents: development of the ventrolateral prefrontal and anterior cingulate cortices. Neuropsychologia 45 (6), 1270–1279. http://dx.doi.org/10.1016/j.neuropsychologia.2006.10.004.

Figner, B., Mackinlay, R.J., Wilkening, F., Weber, E.U., 2009. Affective and deliberative processes in risky choice: age differences in risk taking in the Columbia Card Task. J. Exp. Psychol.: Learn. Mem. Cogn. 35 (3), 709–730. http://dx.doi.org/10.1037/a0014983.

Galván, A., Hare, T.A., Parra, C.E., Penn, J., Voss, H.U., Glover, G.H., Casey, B.J., 2006. Earlier development of the accumbens relative to orbitofrontal cortex might underlie risk-taking behavior in adolescents. J. Neurosci. 26 (25), 6885–6892. http://dx.doi.org/10.1523/JNEUROSCI.1062-06.2006.

Galván, A., 2010. Adolescent development of the reward system. Front. Hum. Neurosci. 4 (6), 6. http://dx.doi.org/10.3389/neuro.09.006.2010.

Gardner, M., Steinberg, L., 2005. Peer influence on risk taking, risk preference, and risky decision making in adolescence and adulthood: an experimental study. Dev. Psychol. 41 (4), 625–635. http://dx.doi.org/10.1037/0012-1649.41.4.625.

Harbaugh, W.T., Krause, K., Vesterlund, L., 2002. Risk attitudes of children and adults: choices over small and large probability gains and losses. Exp. Econ. 5, 53–84.

Heron, M., 2013. Deaths: leading causes for 2010. Natl. Vital Stat. Rep. 62 (6).

Hertwig, R., Erev, I., 2009. The description-experience gap in risky choice. Trends Cogn. Sci. 13 (12), 517–523. http://dx.doi.org/10.1016/j.tics.2009.09.004.

Huizenga, H.M., Crone, E.A., Jansen, B.J., 2007. Decision-making in healthy children, adolescents and adults explained by the use of increasingly complex proportional reasoning rules. Dev. Sci. 10 (6), 814–825. http://dx.doi.org/10.1111/j.1467-7687.2007.00621.x.

Keulers, E.H.H., Stiers, P., Jolles, J., 2011. Developmental changes between ages 13 and 21 years in the extent and magnitude of the BOLD response during decision making. Neuroimage 54 (2), 1442–1454. http://dx.doi.org/10.1016/j.neuroimage.2010.08.059.

Knoll, L.J., Magis-Weinberg, L., Speekenbrink, M., Blakemore, S.-J., 2015. Social influence on risk perception during adolescence. Psychological Science 26 (5), 583–592. http://dx.doi.org/10.1177/0956797615569578.

Lejuez, C.W., Read, J.P., Kahler, C.W., Richards, J.B., Ramsey, S.E., Stuart, G.L., Strong, D.R., ... Brown, R.A., 2002. Evaluation of a behavioral measure of risk taking: the balloon analogue risk task (BART). J. Exp. Psychol.: Appl. 8 (2), 75–84. http://dx.doi.org/10.1037//1076-898X.8.2.75.

van Leijenhorst, L., Crone, E.A., Bunge, S.A., 2006. Neural correlates of developmental differences in risk estimation and feedback processing. Neuropsychologia 44 (11), 2158–2170. http://dx.doi.org/10.1016/j.neuropsychologia.2006.02.002.

van Leijenhorst, L., Gunther Moor, B., Op de Macks, Z.a., Rombouts, S.A.R.B., Westenberg, P.M., Crone, E.A., 2010a. Adolescent risky decision-making: neurocognitive development of reward and control regions. NeuroImage 51 (1), 345–355. http://dx.doi.org/10.1016/j.neuroimage.2010.02.038.

van Leijenhorst, L., Zanolie, K., Van Meel, C.S., Westenberg, P.M., Rombouts, S.A.R.B., Crone, E.A., 2010b. What motivates the adolescent? Brain regions mediating reward sensitivity across adolescence. Cereb. Cortex 20 (1), 61–69. http://dx.doi.org/10.1093/cercor/bhp078.

Levin, I.P., Weller, J.A., Pederson, A.A., Harshman, L.A., 2007. Age-related differences in adaptive decision making: sensitivity to expected value in risky choice. Judgm. Decis. Making 2 (4), 225–233.

Li, R., Brannon, E.M., Huettel, S.A., 2015. Children do not exhibit ambiguity aversion despite intact familiarity bias. Front. Psychol. 5 (January), 1–8. http://dx.doi.org/10.3389/fpsyg.2014.01519.

Li, R., Roberts, R.C., Huettel, S.A., Brannon, E.M., 2017. Five-year-olds do not show ambiguity aversion in a risk and ambiguity task with physical objects. J. Exp. Child Psychol. 159, 319–326. http://dx.doi.org/10.1016/j.jecp.2017.02.013.

Mata, R., Josef, A.K., Samanez-Larkin, G.R., Hertwig, R., 2011. Age differences in risky choice: a meta-analysis. Ann. N. Y. Acad. Sci. 1235, 18–29. http://dx.doi.org/10.1111/j.1749-6632.2011.06200.x.

O'Brien, L., Albert, D., Chein, J.M., Steinberg, L., 2011. Adolescents prefer more immediate rewards when in the presence of their peers. J. Res. Adolesc. 21 (4), 747–753. http://dx.doi.org/10.1111/j.1532-7795.2011.00738.x.

Padmanabhan, A., Geier, C.F., Ordaz, S.J., Teslovich, T., Luna, B., 2011. Developmental changes in brain function underlying the influence of reward processing on inhibitory control. Dev. Cogn. Neurosci. 1 (4), 517–529. http://dx.doi.org/10.1016/j.dcn.2011.06.004.

Paulsen, D.J., Platt, M.L., Huettel, S.A., Brannon, E.M., 2011. Decision-making under risk in children, adolescents, and young adults. Front. Psychol. 2 (April), 72. http://dx.doi.org/10.3389/fpsyg.2011.00072.

Paulsen, D.J., Carter, R.M., Platt, M.L., Huettel, S.A., Brannon, E.M., 2012. Neurocognitive development of risk aversion from early childhood to adulthood. Front. Hum. Neurosci. 5 (January), 1–17. http://dx.doi.org/10.3389/fnhum.2011.00178.

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 1–10. http://dx.doi.org/10.1016/j.neuropsychologia.2014.07.006.

Pfeifer, J.H., Allen, N.B., 2012. Arrested development? Reconsidering dual-systems models of brain function in adolescence and disorders. Trends Cogn. Sci. 16 (6), 322–329. http://dx.doi.org/10.1016/j.tics.2012.04.011.

Pfeifer, J.H., Allen, N.B., 2016. The audacity of specificity: moving adolescent developmental neuroscience towards more powerful scientific paradigms and translatable models. Dev. Cogn. Neurosci. 17, 131–137. http://dx.doi.org/10.1016/j.dcn.2015.12.012.

Poldrack, R.A., 2015. Is efficiency a useful concept in cognitive neuroscience? Dev. Cogn. Neurosci. 11, 12–17. http://dx.doi.org/10.1016/j.dcn.2014.06.001.

Prencipe, A., Kesek, A., Cohen, J., Lamm, C., Lewis, M.D., Zelazo, P.D., 2011. Development of hot and cool executive function during the transition to adolescence. J. Exp. Child Psychol. 108 (3), 621–637. http://dx.doi.org/10.1016/j.jecp.2010.09.008.

Rakow, T., Rahim, S.B., 2010. Developmental insights into experience-based decision making. J. Behav. Decis. Making 23 (1), 69–82. http://dx.doi.org/10.1002/bdm.672.

Richards, J.M., Plate, R.C., Ernst, M., 2013. A systematic review of fMRI reward paradigms used in studies of adolescents vs. adults: the impact of task design and implications for understanding neurodevelopment. Neurosci. Biobehav. Rev. 37 (5), 976–991. http://dx.doi.org/10.1016/j.neubiorev.2013.03.004.

Schiebener, J., García-Arias, M., García-Villamisar, D., Cabanyes-Truffino, J., Brand, M., 2014. Developmental changes in decision making under risk: the role of executive functions and reasoning abilities in 8- to 19-year-old decision makers. Child Neuropsychol. 1–20. http://dx.doi.org/10.1080/09297049.2014.934216.

Schlottmann, A., Anderson, N.H., 1994. Children's judgments of expected value. Dev. Psychol. 30 (1), 56–66. http://dx.doi.org/10.1037//0012-1649.30.1.56.

Shulman, E.P., Harden, K.P., Chein, J.M., Steinberg, L., 2016a. The development of impulse control and sensation-seeking in adolescence: independent or interdependent processes? J. Res. Adolesc. 26 (1), 37–44. http://dx.doi.org/10.1111/jora.12181.

Shulman, E.P., Smith, A.R., Silva, K., Icenogle, G., Duell, N., Chein, J.M., Steinberg, L., 2016b. The dual systems model: review, reappraisal, and reaffirmation. Dev. Cogn. Neurosci. 17 (1), 103–117. http://dx.doi.org/10.1016/j.dcn.2015.12.010.

Simpson, H.M., 2003. The evolution and effectiveness of graduated licensing. J. Saf. Res. 34 (1), 25–34.

Smith, D.G., Xiao, L., Bechara, A., 2012. Decision making in children and adolescents: impaired Iowa Gambling task performance in early adolescence. Dev. Psychol. 48 (4), 1180–1187. http://dx.doi.org/10.1037/a0026342.

Smith, A.R., Chein, J.M., Steinberg, L., 2014.. Peers increase adolescent risk taking even when the probabilities of negative outcomes are known. Dev. Psychol. 50 (5), 1564–1568. http://dx.doi.org/10.1037/a0035696.

Smith, A.R., Steinberg, L., Strang, N., Chein, J.M., 2015. Age differences in the impact of peers on adolescents' and adults' neural response to reward. Dev. Cogn. Neurosci. 11, 75–82. http://dx.doi.org/10.1016/j.dcn.2014.08.010.

Somerville, L.H., Jones, R.M., Casey, B.J.J., 2010. A time of change: behavioral and neural correlates of adolescent sensitivity to appetitive and aversive environmental cues. Brain Cogn. 72 (1), 124–133. http://dx.doi.org/10.1016/j.bandc.2009.07.003.

Steinberg, L., Icenogle, G., Shulman, E.P., Jason, B., Dario, C., Lei, B., Emma, T.S., 2017. Around the world, adolescence is a time of heightened sensation seeking and immature self- regulation. Dev. Sci. 1–13. http://dx.doi.org/10.1111/desc.12532.

Steinberg, L., 2007. Risk taking in adolescence: new perspectives from brain and behavioral science. Curr. Dir. Psychol. Sci. 16 (2), 55–59. http://dx.doi.org/10.1111/j.1467-8721.2007.00475.x.

Steinberg, L., 2010. A dual systems model of adolescent risk-taking. Dev. Psychobiol. 52 (3), 216–224. http://dx.doi.org/10.1002/dev.20445.

Steinberg, L., 2013. The influence of neuroscience on US Supreme Court decisions about adolescents' criminal culpability. Nat. Rev. Neurosci. 14 (July), 513–518. http://dx.doi.org/10.1038/nrn3509.

Substance Abuse and Mental Health Services Administration, 2013. Results from the 2012 National Survey on Drug Use and Health: Summary of National Findings. NSDUH Series H-46, HHS Publication No. (SMA), Rockville, MD, pp. 13–4795.

Trautmann, S.T., van de Kuilen, G., 2015. Ambiguity attitudes. In: Keren, G., Wu, G. (Eds.), The Wiley Blackwell Handbook of Judgment and Decision Making. John Wiley & Sons, Ltd, West Sussex, UK, pp. 89–116.

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. Proc. Natl. Acad. Sci. U. S. A. 109 (42), 17135–17140. http://dx.doi.org/10.1073/pnas.1207144109.

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. Proc. Natl. Acad. Sci. 21, 1–6. http://dx.doi.org/10.1073/pnas.1309909110.

Weber, E.U., Shafir, S., Blais, A.-R., 2004. Predicting risk sensitivity in humans and lower animals: risk as variance or coefficient of variation. Psychol. Rev. 111 (2), 430–445. http://dx.doi.org/10.1037/0033-295X.111.2.430.

Weigard, A., Chein, J.M., Albert, D., Smith, A.R., Steinberg, L., 2013. Effects of anonymous peer observation on adolescents' preference for immediate rewards. Dev. Sci. 17 (1), 71–78. http://dx.doi.org/10.1111/desc.12099.

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 Cogn. 83 (3), 315–323. http://dx.doi.org/10.1016/j.bandc.2013.09.008.