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Review

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

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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, non-linearly 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

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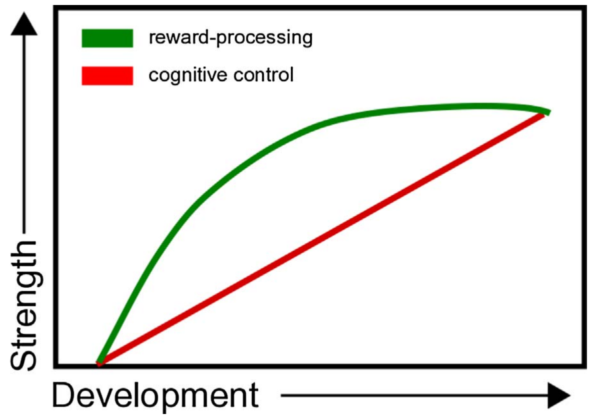

Fig. 1. The classic dual-systems imbalance model, in which cognitive control develops linearly while reward-processing peaks in adolescence. Adapted from Casey et al. (2008).

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