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The link between cognitive control and decision-making across child and adolescent development

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Understanding the neurocognitive mechanisms of decision-making is crucial to titrate and optimize opportunities for learning in childhood and adolescence. The development of prefrontal cortex and associated cognitive control has been shown across various studies to be especially important for decision-making in development. While future-oriented and social decisions in children are best accounted for by improvements in inhibitory control, during adolescence this is predicted by an increased ability to flexibly integrate contextual information and adapt decisions and behavior accordingly. Taking into account distinct neurocognitive mechanisms and aspects of cognitive control for specific developmental periods is the beginning for integrating the neuroscience of decision-making and education.

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Introduction

In recent years tremendous progress has been made in understanding one of the core skills that enables children to cope with an ever changing world: the ability to make complex decisions taking multiple factors into account. Such factors include for instance trade-offs between current desires and future goals or one's own versus another's needs. For children to make appropriate decisions is a skill of increasing importance in the context of education. This relates to their striving and perseverance in pursuing academic goals as well as creating positive social environments within which learning can take place.

Developmental brain imaging studies have successfully unraveled the underlying neural substrates important for making these kinds of decisions, but have largely ignored a key cognitive process, which is cognitive control. Yet, cognitive control may be the most important factor distinguishing *between* individuals, and may also be an important *predictor* for successful long-term outcomes. In this review, we synthesize the current literature on the development of decision-making across two domains, namely future-orientation and social decisions. We present a new perspective on decision-making by showing how cognitive control, and the prefrontal cortex as its neural substrate, influences how children and adolescents make decisions.

A role for cognitive control in decision-making

Value-based decision-making is a pervasive aspect of our daily lives. It occurs each time we have to make a choice between available options based on the values that we assign to each of them [1]. A critical scientific endeavor is to understand how and why certain decisions are made during childhood and how these change with age. This is especially important given that decisions can have far reaching consequences. Conceptual frameworks of value-based decision-making propose that decisions involve several stages, which require different value computations [2,3•]. Picture exam time and an adolescent torn between chatting with friends on Facebook and studying. While chatting brings instant gratification such procrastination will usually lead to poorer exam performance. Studying on the other hand is less enjoyable but ensures good grades. The ability to delay gratification early in life has been shown as a critical predictor of later scholastic success [4]. But how do children and adolescents make decisions in which the relative costs and benefits of present and future outcomes are weighed?

To reach a decision between two or more available options, first the value of each option is evaluated by itself. This occurs as a function of prior experience and is instantiated by activity in the orbitofrontal cortex [OFC; 5] as well as the striatum [5]. Such a process involves simultaneously weighing up associated costs of choosing either of the available options. As a result, each potential choice is assigned a value that integrates all anticipated values and costs into a common scale and a single entity, which is then interpreted to make a choice. Much research has implicated a subregion of the OFC, the ventromedial prefrontal cortex (vmPFC) to make such computations at the time of decision-making [6]. Understanding how decisions are made and moreover how individual differences in decision-making arise has focused primarily on these stages of valuation [7]. How aspects of cognitive control play a role in decision-making has been a neglected area of research [but see 8 for recent approaches to integrate the two research strands]. We argue that this link is especially critical when wanting to understand the development of decision-making.

Cognitive control refers to the ability to bring thoughts and actions into alignment with one's intentions, goals, and values [9]. This comprises a relatively broad class of mental operations, such as the representation of current goals, allocating one's attention to important aspects of the environment to achieve such goals and implementing actions and behaviors in line with goals across a range of different contexts [10]. In terms of a role in decision-making this means that cognitive control is critical in order to remember what the goal is (i.e. to get a good grade), to bias attention toward aspects of a held goal (i.e. ignoring distractors such as an incoming Facebook message) and to implement a course of action for achieving the goal (i.e. actually sitting down to prepare for exams). Importantly, cognitive control encompasses a variety of different processes, such as inhibition, working memory and cognitive flexibility early in development [11] and into adulthood [9]. It is thus feasible that distinct subprocesses of cognitive control may play a specific role for distinct developmental stages. Here we explore this possibility in the context of decision-making.

While many agree that cognitive control requires a multitude of processes represented in distinct brain regions [10,12–14], it is established that lateral portions of the prefrontal cortex (PFC) are critically involved for actively maintaining task goals, biasing attention and implementing behaviors [15]. One recent study demonstrates such a role of dorsolateral PFC (DLPFC) in decision-making in the context of dieters' choices between healthy and tasty foods [16]. Dietary choices between food-stimuli that varied in their taste and health properties were measured. While activity in the OFC encoded the stimulus values independent of the choice, health information of stimuli had a greater influence on OFC signal and subsequent choice when portions of left DLPFC were activated. Connectivity analyses revealed that when choosing healthy foods there was greater coupling between OFC and DLPFC. In other words, DLPFC was critical in maintaining dieters' goal relevant information of eating healthily and biasing signals that encode the value of available options thereby increasing choices of healthy foods.

Development of prefrontal cortex function and cognitive control

Cognitive control develops extensively throughout childhood and adolescence [11,17]. Prominent theories argue that these developments are marked by i) an increasing ability to overcome habits through engaging cognitive control in response to environmental signals; ii) engaging increasingly in proactive as opposed to reactive control; and iii) becoming increasingly self-directed in its deployment [18]. Importantly, robust cognitive control allows for responding with increased flexibility to the specific demands of the environments, something particularly crucial in the context of decision-making. Developmental cognitive neuroscience has made great strides in linking these cognitive changes to the maturation of underlying brain systems [19]. For instance, lateral PFC is one of the brain regions undergoing the most protracted age-related loss of gray matter volume throughout childhood and adolescence [20]. Further, linear age-related increases in structural connectivity are also among the most delayed in white matter bordering prefrontal cortex [21], which in turn impacts the extent of functional connectivity [22]. There is much evidence for slowly developing lateral PFC activity when performing tasks that require cognitive control such as working memory or inhibition [23,24], comprising both ventral as well as dorsal portions of PFC [25]. Given the considerable changes in cognitive control and underlying development of prefrontal cortex it is likely that these changes account for concomitant age-related changes in decision-making during childhood and adolescence. Below we present evidence from two decision-making domains in support of such a notion; weighing present and future rewards (future-oriented decision-making), and weighing benefits for other and self (social decision making).

Future-oriented decisions — intertemporal choice

The choice between small immediate rewards and larger delayed rewards as posed by our introductory example has classically been taken as a reliable indicator of patience [26]. Also known as delay discounting, such an ability to delay gratification and wait for larger rewards in the future has been linked to future scholastic aptitude and is therefore an important predictor of future well-being [4]. It has been shown that both during childhood as well as during adolescence decisions to wait for a larger reward increase with age [27,28,29••].

Childhood

Going beyond a mere description of developmental changes recent research has tried to identify the specific mechanisms of why such age-related changes in intertemporal choice arise. For instance developmental changes could occur due to age-related changes in the valuation of rewards in the immediate or distant future, or because cognitive control improves and enables temptations to be overcome. In a recent study this question was addressed directly in children [29••]. Children aged 6–13 years were given two tasks, a choice task and a valuation task. In the choice task children were presented with a small immediate and a large delayed reward and had to choose. In the valuation task children were presented individual reward options varying in both reward magnitude and reward delay (i.e. size of the reward and when it would be paid out). Children were asked to rate the attractiveness of each presented option. In addition children performed a stop-signal reaction time task (SSRT), which measures inhibitory control. Steinbeis *et al.* [29••] hypothesized that if younger children choose immediate options more frequently than older children because they value them more this should become apparent in the valuation task. If however age-related differences emerge as a function of changes in cognitive control then this should be indicated by a correlation of choices and inhibitory control. The latter hypothesis was confirmed. Analysis of the fMRI data indicated further that functional coupling between the ventromedial prefrontal cortex and the DLPFC increased as a function of choosing delayed rewards, age and inhibitory control.

Adolescence

A recent study also tested the role of cognitive control in intertemporal choice in adolescence [28]. Specifically, two competing hypotheses were assessed namely if age-related changes in delay discounting were accounted for by changes in present hedonism or future orientation. Future orientation refers to the ability to bias attention away from immediate rewards and to focus on future goals and thus encompasses a core feature of cognitive control [30]. It was found that with increasing age adolescents chose delayed rewards more often as a function of future orientation.

Finally, previous studies have linked delay discounting with structural connectivity between frontal and striatal brain regions [31,32••]. Importantly, developmental increases in structural connectivity strength in a tract of right DLPFC were correlated with increased negative functional coupling between right DLPFC and the striatum, which in turn accounted for the age-related increase in delay discounting, a finding that has been recently replicated in a longitudinal study [33]. Interestingly, inhibitory control as measured with the SSRT showed no relationship with delay discounting in adolescence [28]. Thus, the processes that explain future-oriented decisions changed during childhood and adolescence from inhibitory control to future orientation.

Social decisions — sharing and reciprocity

Changes in social decisions during childhood and adolescence are frequently observed, however systematic study using more sophisticated experimental approaches has only recently begun. Here we focus on developmental changes in how outcomes for oneself and others are weighed, as indicated by decisions to share and reciprocate altruistic or selfish acts. Such decisions have been studied extensively within a game theoretical framework using resource allocation paradigms [34]. For instance, children have been shown to be increasingly willing to share over the course of childhood [35]. Further children become increasingly inequity averse between ages 3–8 years [36] and into late childhood [37]. Social behavior during adolescence is marked by an increasing awareness of social context. This is illustrated by a heightened sensitivity to the mere presence of peers in the context of risky decision-making, compared to children and adults [38]. During adolescence the preference for equity appears to decrease, shifting toward choosing outcomes which maximize benefits for all parties involved and taking contextual variables increasingly into account [39••]. Finally, while children increasingly reciprocate unkind acts such as poor offers in an Ultimatum Game with a rejection [40,41] this appears to undergo further changes in during adolescence demonstrating an increased sensitivity for contextual cues and variables such as who one is interacting with [42–44].

Childhood

There is a well-documented link between sharing and cognitive control across childhood [45–47]. Inhibitory control in particular has been argued to play an important role in bringing behavior and action into alignment with explicitly held norms and beliefs (also known as closing the knowledge-behavior gap) [48]. In adults acting on endorsed fairness norms relies critically on functions of right DLPFC [49] and this should therefore improve with age. It was recently shown that the explicit endorsement of an equal split and the extent to which this is enacted becomes increasingly aligned during childhood [50].

More direct evidence for a role of inhibitory control in the knowledge-behavior gap comes from a recent study in which inhibitory control was temporarily taxed [51]. This study exploited a key feature of the cognitive system namely that regulating oneself in some form (i.e. inhibiting prepotent responses) can have deleterious effects on subsequent tasks requiring the same mental operations [52]. Studying children aged 6–9 years of age it was shown that after engaging in inhibitory control, children were subsequently less willing to share and more willing to accept unfair offers compared to previously engaging in a mere reaction time task. Importantly, there were no group differences in judgments of fairness norms, and this discrepancy in explicitly endorsed fairness norms and behavior increased after inhibitory control resources were temporarily depleted. These findings strongly imply that cognitive control is crucial for bringing about sharing and reciprocity in childhood.

Adolescence

Developmental neuroimaging studies have provided consistent evidence for a role of DLPFC in age-related increases in social decision-making. This is well illustrated in studies that manipulated contextual conditions. For instance the second mover's extent of reciprocation during a Trust Game was influenced by whether the first mover took on a big or a small risk in trusting the second mover [44]. Equally, the extent of rejection of unfair offers in the Ultimatum Game depended increasingly on whether more or less fair alternative offers could have been made [42,43]. Crucially, it was shown that taking these contextual factors into account progressed across childhood and adolescence and was associated with increased activity in DLPFC. The ability to increasingly take contextual factors into account and to rely less on social heuristics (i.e. always reciprocate) suggests greater cognitive flexibility and therefore cognitive control [53].[3] It has been argued that developmental changes in adjusting one's behavior flexibly to the changing demands of the environment is a hallmark of adolescent development in response to unexpected and emotionally salient events [55]. We propose that this developmental mechanism also accounts for observed changes in a variety of decision-making contexts. Thus, developmental changes in cognitive control such as inhibitory control and cognitive flexibility seem to mediate observed changes in social decisions such as sharing and reciprocity in childhood and adolescence respectively.

A unified account of cognitive control in decision-making during childhood and adolescence

While cognitive control clearly plays an important role in the development of decision-making both during childhood and adolescence, different facets of cognitive control seem to be important at each developmental period. For instance inhibitory control as measured by the stop-signal reaction time task plays an important role for decisions to share, reciprocate and delay gratification in children [29••,51]. On the other hand during adolescence it is more aspects of cognitive flexibility and orienting toward important goals that account for developmental changes in social and future-oriented decisions respectively [28,42,43]. It has been argued that a key transition in the development of cognitive control during childhood is the shift away from relying on environmental signals to self-directed control [18], while development during adolescence is marked by an increasing ability to adjust behavior to meet contextual demands [55]. The differential correlations between delay discounting and motor inhibition and future orientation during childhood and adolescence respectively illustrate this shift well. Thus, successful inhibition on the stop-signal task indicates the reactive ability to inhibit a prepotent response to an external stop signal, while orienting to contextual aspects away from the immediacy of the situation measures the inward shift in attention away from the lure of the present to achieve a future goal (i.e. reward maximization during intertemporal choice).

[3] Of course, there are also other factors that account for developmental changes in social decision-making. For instance it has been shown that deciding whether to trust another or not is dependent on developmental changes in perspective-taking during adolescence [54].

Cognitive control is clearly crucial for various aspects of decision-making both during childhood and during adolescence. Understanding which aspects of cognitive control are relevant to future-oriented and social decision-making at various points in development is critical to potentially shape both the individual and the environment in such ways as to produce optimal learning outcomes. This is especially important when devising interventions that impact cognitive control to improve decision-making with long-lasting effects on academic achievement.

Conflict of interest

Nothing declared.

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