

## Opinion

## Adolescent Development of Value-Guided Goal Pursuit

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**Adolescents are challenged to orchestrate goal-directed actions in increasingly independent and consequential ways. In doing so, it is advantageous to use information about value to select which goals to pursue and how much effort to devote to them. Here, we examine age-related changes in how individuals use value signals to orchestrate goal-directed behavior. Drawing on emerging literature on value-guided cognitive control and reinforcement learning, we demonstrate how value and task difficulty modulate the execution of goal-directed action in complex ways across development from childhood to adulthood. We propose that the scope of value-guided goal pursuit expands with age to include increasingly challenging cognitive demands, and scaffolds on the emergence of functional integration within brain networks supporting valuation, cognition, and action.**

### Letting Value be your Guide

As individuals transition from childhood to adulthood, dramatic changes occur on physical, psychological, and neurobiological levels to impact how individuals orchestrate their actions in a given moment. During **adolescence** (see [Glossary](#)), individuals begin to navigate increasingly complex daily challenges with more autonomy than ever before. However, all challenges are not created equal: some have more consequential outcomes than others, based on the goal at hand and the **value** of what is at stake.

Psychological theory and experiments in adults have underscored the importance of letting value guide goal-directed behaviors [1–4]. Indeed, we do not choose how to devote our energy and cognitive resources randomly; we use cues from the environment about what is important (or holds value) to guide the prioritization of resources toward actions most relevant to our goals. We use this framework as a lens to evaluate how value-guided goal pursuit develops from childhood to adulthood. Based on a new wave of research, we propose that this ability is continuing to fine-tune into the adolescent years. We will demonstrate that adolescents are highly attuned to identifying value in the environment, which in certain contexts can benefit their performance. However, ongoing neurodevelopment ([Box 1](#)) also imposes constraints on processes that integrate value signals with those that guide overt cognitions and actions. Therefore, adolescence marks a developmental period in which value guides goal pursuit in complex ways, underpinned by neurodevelopmental change in the functioning of brain systems that represent value, actions, and goals.

In this paper, we consider developmental changes in constituent and integrative processes that shape the use of value to guide two different forms of goal-directed behavior: cognitive control and learning. These functional domains are crucial because: (i) ongoing brain development shapes the normative development of these processes through adolescence, (ii) rich theoretical work in adults propose mechanistic routes for the modulatory influence of value, and (iii) they are functional domains that adolescents face with increasing independence.

### Highlights

Research is increasingly focused on identifying how integrated brain function across large-scale networks changes across development to support the emergence of complex behaviors.

There is growing evidence to suggest that although adolescents are capable of sophisticated forms of cognitive control and learning, the extent to which these processes are ‘tuned’ to value is undergoing continued developmental change.

Developmental research is increasingly turning to computational tools to isolate constituent subprocesses that contribute to sophisticated goal pursuit.

It is of growing importance to consider how ‘what is valuable’ differs across the child-to-adult ontogeny so that future research can deepen its consideration of ‘value’ across development.

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**Box 1. Evolution of the Study of Neurodevelopment**

The study of brain development has evolved greatly since the foundational observations of Huttenlocher [83], Goldman-Rakic [84], and others whose work revealed the progression of synaptic production followed by pruning that characterizes early life. Common use of noninvasive human brain imaging ushered in a new wave of research revealing complex dynamics of brain development and its progressions, primarily from middle childhood onwards. While this work has built a substantial knowledge base, it tells a somewhat complicated story.

For one, the 'growth curve' of neurodevelopment is not unitary across the brain or across measures of brain development. While the structural volume of the brain's gray matter progressively declines through late childhood and adolescence (thought to reflect synaptic pruning) [85], white matter shows progressive growth through these stages and well beyond [86,87]. These regressive and progressive patterns occur at different timelines across the brain's gross topology, meaning that some regions lag behind others in neurodevelopment. Of particular importance to this paper's themes is the protracted structural development of the PFC, which is continuing to develop well beyond the teenage years (e.g., [86]).

Layered atop the structural trajectories is the development of complex brain function, which is thought to be underpinned by increasing connectivity and functional coordination of brain networks (see [88] for commentary). Here, we focus on human brain imaging work that can chart functioning and coordination of distributed subcortical–subcortical and subcortical–cortical pathways that integrate information about value, action, and regulatory demands. However, it is important to recognize that functional integration over brain networks is just one of the many 'markers' of a mature brain.

**Value Assignment across Development**

A crucial building block to value-guided goal pursuit is the ability to detect and assign value to cues in the environment. The value attributed to a given action signifies the benefits that are expected to follow from it [5]. Being attuned to value in the environment allows an individual to evaluate the potential positive and negative outcomes of their actions. Although value cannot be measured directly, higher value can be inferred from indirect assessments: higher subjective ratings of positive valence and importance, more invigoration of physical speed, higher response rate, and greater effort exertion [6].

Based on research in children, adolescents, and adults, individuals at a wide variety of ages detect and assign value to environmental inputs. For example, young children (aged 3–6 years) can readily distinguish between high-value and low-value rewards and can indicate their preference for high-value options [7,8]. When asked to provide self-reported subjective value ratings, children, adolescents, and adults similarly rank monetary outcomes according to their relative value [9–11]. Further, children and adults alike often exhibit faster motor response to cues predictive of higher magnitude rewards [12]. While most research manipulating value uses monetary incentives of varying quantities, this approach might be subject to important limitations, as described in Box 2.

Brain imaging research assesses valuation processes by measuring neural responses to the expectation or receipt of valued incentives, and to cues predictive of them. Prior work has demonstrated that value coding is subserved by a collection of brain regions, including the ventral striatum and ventromedial prefrontal cortex (VMPFC) (Box 3) [13–16]. Developmental research has shown that even children show robust activity in this suite of brain regions during reward processing [12,17]. Further, many studies have shown that the ventral striatum response to the anticipation and receipt of rewards is elevated during adolescence [18–21], although it should be noted that this pattern is not always observed [9,22]. Whereas these findings focus on passive reward processes, few studies have linked age-related differences in striatal activity to value-relevant behaviors [23]. In this review, we extend beyond considering indices of reactivity to focus on how value may orchestrate strategic behavior and integrate with cognitive processes in an age-dependent manner.

**Glossary**

**Adolescence:** phase of the lifespan beginning with the onset of physical puberty and ending with the assumption of adult roles.

**Computational model:** a mathematical formalization of the interactions among assumed underlying cognitive processes required to perform a task, which allows for estimating contributions of component processes in complex cognition.

**Context monitoring:** a cognitive control process that involves selectively attending to the environment for relevant cues to determine the contextually appropriate action to select.

**Model-based learning:** acquiring a contingent or transitional structure of the environment to represent sequences of choices or actions to maximize valuable outcomes through incremental reinforcement.

**Model-free learning:** acquiring the structure of associations between choices or actions and valuable outcomes through incremental reinforcement.

**Proactive control:** form of cognitive control that allows an individual to maintain goal-related information in anticipation of an imminent cognitive challenge, so they can orchestrate behavior with less interference.

**Probabilistic learning:** learning from feedback (e.g., positive or negative outcomes) that is reinforced at a rate less than 100% of the time (e.g., fixed rate of 80%, drifting rate that changes over time).

**Reinforcement learning:** incremental learning from feedback such as rewards or punishments, or other valenced outcomes, which depends on the detection of value signals and their integration over repetitions.

**Value:** predicted or experienced benefits of an outcome, given the individual's internal and external state.

**Box 2. What Holds ‘Value’ to Children, Adolescents, and Adults?**

When using experimental approaches to examine the effect of value on related processes, one must pause to ask what is valuable to the individuals under investigation. The most common way to manipulate value in experiments is to use variable monetary outcomes. While money sits on a linear objective scale, humans do not interpret the value of money linearly (i.e., [89]). Likewise, money could ‘mean’ different things to children, adolescents, and adults given they have differential access to money and use money for different purposes in daily life. As such, it is crucial to consider whether the subjective value of money differs across development. If it does, it could present a crucial confound to age-related tests. For example, the failure of an infant to improve their performance on a task because monetary outcomes are at stake would not be construed as a motivation deficit, but rather due to the fact that experimenter-defined value mismatches with that of the experimental participant.

Rather than needing to assume that participants judge something as equivalently valuable, one can incorporate collateral measurements to quantify subjective value [90]. Prior research has asked participants of different ages to report whether different amounts of money seem like a little or a lot, and largely have found that adolescents and adults judge money consistently on these scales [10,11,91]. One can also measure subjective value in terms of the amount of energy or time an individual is willing to expend to obtain that outcome, or the tendency for a given outcome to be selected over others. Future research on the development of goal-directed behavior should avoid presuming equivalence in subjective value across age and incorporate collateral measures to check these assumptions.

Although prior work has shown that a common set of computational processes represent the value of diverse stimulus types (e.g., money and social cues [92,93]), these cues might be assigned different levels of goal relevance at different developmental stages. Indeed, while money is a convenient experimental tool for manipulating valuation processes, future research could move its focus to defining and interrogating what is ontogenetically valuable at different ages. While children’s goals tend to focus on family life, learning, and skill-building activities [94], adolescents exhibit a focused attention on social relationships [95], and young adults face important challenges establishing independence and choosing vocational and academic paths [96]. By considering what unique goals individuals hold at different ages, one can extend research on value and goal-directed behavior toward the most relevant domains of children’s and adolescents’ experiences.

**Value-Guided Cognitive Control**

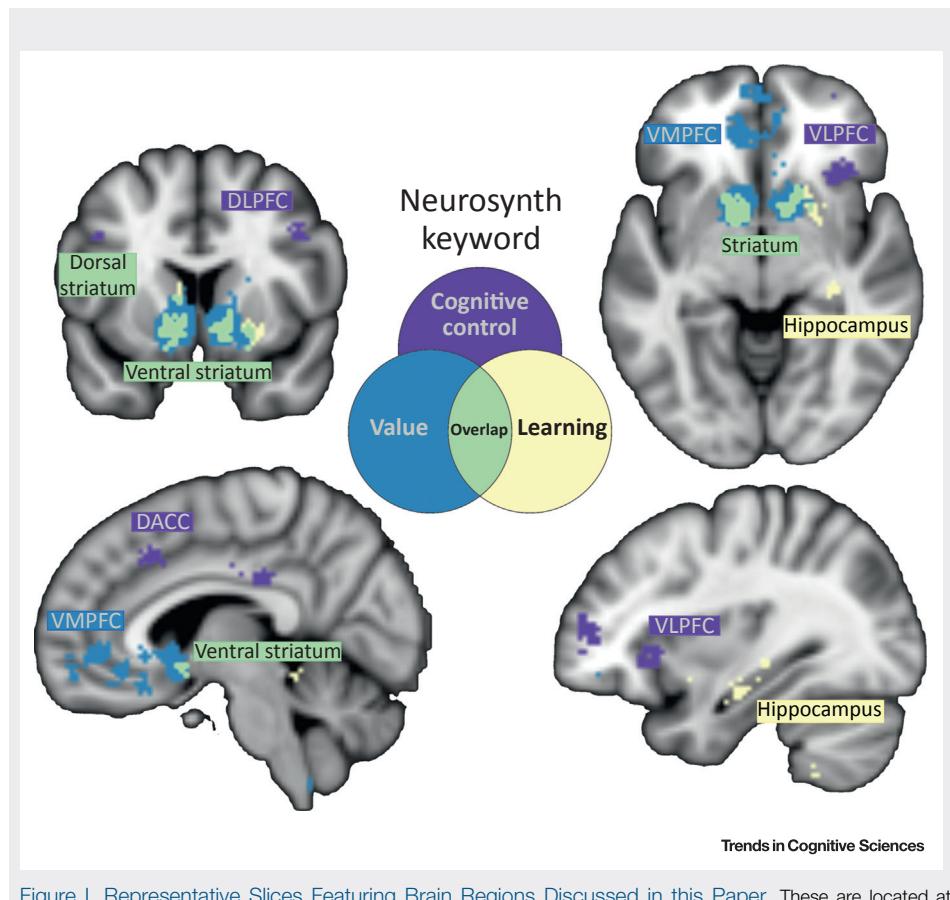
Cognitive control represents a collection of mental processes that allow individuals to select contextually appropriate behavior to pursue superordinate goals [24]. Recent work in adults has focused on how the value of a goal influences the execution of cognitive control [25,26]. Converging evidence demonstrates that when high-value goals are at stake, adults selectively improve their goal-directed actions (e.g., [10,27,28]). For example, young adults are more likely to improve control performance when pursuing high-value relative to low-value rewards, resulting in faster performance and higher accuracy [29].

Contemporary models of motivation-cognition interactions posit that value can enhance cognitive control by selectively coordinating integration between the striatum and prefrontal cortex (PFC) (Box 3), which are linked via complex, distributed connections [30–33]. The ventral striatum codes the motivational value of prospective incentives [34], and the dorsal striatum plays a crucial role in

**Box 3. Neural Reference Space for Value, Cognition, and Learning**

To characterize the neural reference space supporting value, cognition, and learning processes, we conducted a reverse-inference analysis in Neurosynth [97], a large-scale automated meta-analysis tool. This analysis extracts functional coordinate localization based on keyword search of a large bank of published papers, which predominantly include adult participants. The reverse-inference analysis generates spatial maps that contain brain regions that are more likely to appear related to the input keyword than other keywords (false discovery rate  $P < 0.01$ ). We further thresholded these maps to only include clusters of ten or more voxels, and binarized the remaining images.

The resulting figure (Figure 1) color-codes brain regions reliably and selectively observed in articles that use the keywords ‘cognitive control’, ‘value’, and ‘learning’, respectively. There is also overlap, such that more than one process of interest is associated with activity in particular brain regions. For example, the ventral striatum (extending into caudate and putamen) is observed in the maps for both ‘value’ and ‘learning’. However, there is also specificity; for example, the VMPFC only appears for ‘value’; whereas the hippocampus only appears in ‘learning’. Finally, ‘cognitive control’ results in a map with no meaningful overlap with ‘value’ or ‘learning’ (three voxels shared with ‘value’; not shown).



**Figure 1. Representative Slices Featuing Brain Regions Discussed in this Paper.** These are located at (clockwise from coronal slice)  $y = 10$ ,  $z = -6$ ,  $x = 34$ , and  $x = 6$ , respectively. DACC, Dorsal anterior cingulate cortex; DLPFC, dorsolateral prefrontal cortex; VLPFC, ventrolateral prefrontal cortex; VMPFC, ventromedial prefrontal cortex.

coordinating motor actions [35]. Key regions, including the ventrolateral PFC (VLPFC) and dorsolateral PFC (DLPFC), subserve effortful cognitive control processes and guide goal-directed action selection [36]. Theoretical frameworks propose that the striatum relays value-related information to the PFC to select contextually appropriate behavior and maximize the attainment of high-value outcomes [37]. Consistent with this model of corticostriatal circuit function, multiple studies have demonstrated that adults increase functional recruitment of the lateral PFC [2] and increase functional connectivity between the striatum and lateral PFC when pursuing high-value goals [10,38]. Together, this work in adults serves as a foundation to understand how value successfully guides the allocation of cognitive effort in a goal-directed manner.

### Cognitive Control Development

The maturation of cognitive control follows a protracted developmental trajectory, improving from childhood through adolescence [39–41]. It is important to recognize that adolescents can successfully exert cognitive control and, in many situations, they achieve adult-like levels of performance [42,43]. However, continued gains in cognitive control through adolescence are nonetheless observed when measuring the speed and consistency of performance, and when challenging the system with difficult task demands. In addition, adolescents' cognitive control is especially susceptible to disruption by emotionally evocative contexts [44,45]. Thus, while adolescents' cognitive control is robust to a variety of cognitively demanding tasks, it is nonetheless undergoing continued refinement.

This ongoing refinement of cognitive control through adolescence is paralleled by emerging functional development of brain systems that subserve effortful cognition, including the pre-frontal and parietal cortices. For example, age-related improvements in working memory accuracy from childhood to young adulthood are mediated by developmental increases in functional recruitment of PFC networks [46]. Further, trial-by-trial working memory accuracy and reaction times become more consistent with age. This emerging behavioral pattern is associated with age-related increases in the stability of task-related functional activity across multiple cortical networks [47].

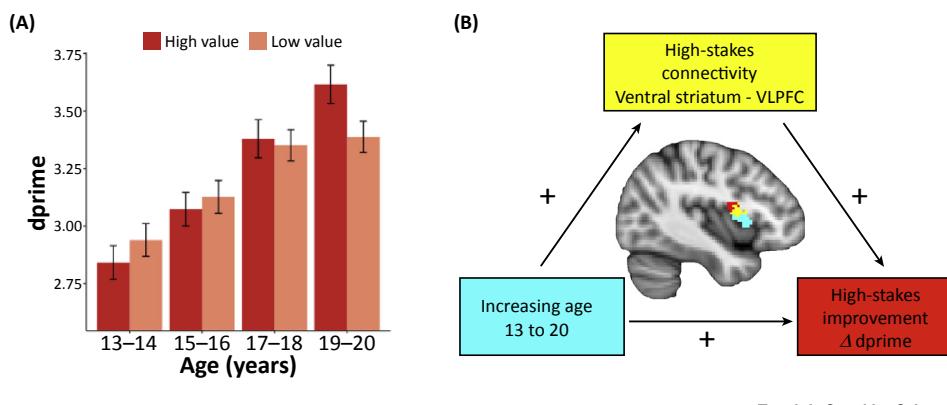
In addition, age-related differences in PFC recruitment during cognitive control may reflect developmental shifts in cognitive strategy implementation [42,48]. Older adolescents and young adults are more likely to implement optimal strategies to enhance the precision of control [49], such as the engagement of **proactive control**, a preparatory process that allows individuals to recruit prefrontal control systems in anticipation of an upcoming cognitive demand. This strategic shift is supported by increased connectivity between the striatum and PFC with age [50]. Together, these findings suggest that across adolescence, recruitment of control-related brain systems becomes increasingly stable and strategic, and these developmental shifts ultimately promote successful and efficient control performance.

### The Development of Value-Guided Cognitive Control

In this section, we propose that when faced with increasing cognitive control demands, the beneficial effects of value on cognitive performance continues to emerge throughout adolescence. Here, we highlight a set of studies supporting this perspective. One study testing children, adolescents, and young adults examined the influence of value on selective attention [51]. Participants completed a visual search task that invoked **context monitoring** (e.g., [52]). The task consisted of trials that included low-value or high-value cues (stimulus color signaled 1 cent versus 5 cents trials) denoting the payout for accurate performance. Results showed that young adults (aged 20–29 years) responded more consistently to high-value compared with low-value incentives, indicative of a value-specific enhancement of selective attention. In contrast, the child (aged 8–11 years) and adolescent (aged 14–16 years) groups did not selectively change response consistency across low-value and high-value trials. The young adult group also responded significantly faster for high-value trials relative to low-value trials as compared with children and adolescents. Notably, children and adolescents also sped up responses to high-value cues, but to a lesser degree than adults. These findings demonstrate that younger individuals detected high-value cues in the environment and were invigorated by them, but valuation differences did not translate into better performance for these age groups.

Similar developmental trends were reported in a study examining the effects of value on selective attention during memory encoding [53]. In this study, participants were given lists of words to remember, which were associated with varying value levels; participants would then be rewarded for accurate recall at a later test. Children (aged 5–9 years), adolescents (aged 10–17 years), and young adults (aged 18–23 years) recalled significantly more high-value words. However, this effect was the most pronounced in young adults (aged 18–23 years), who exhibited greater value-selective memory. Together, these findings suggest that the ability to flexibly enhance performance to high-value cognitive challenges continues to improve through adolescence and into early adulthood.

Recent work has also identified the neurodevelopmental processes that emerge through adolescence to support value-guided behavioral control, indicating that the late refinement of corticostriatal network connectivity fosters successful value-driven upregulation of cognitive



Trends in Cognitive Sciences

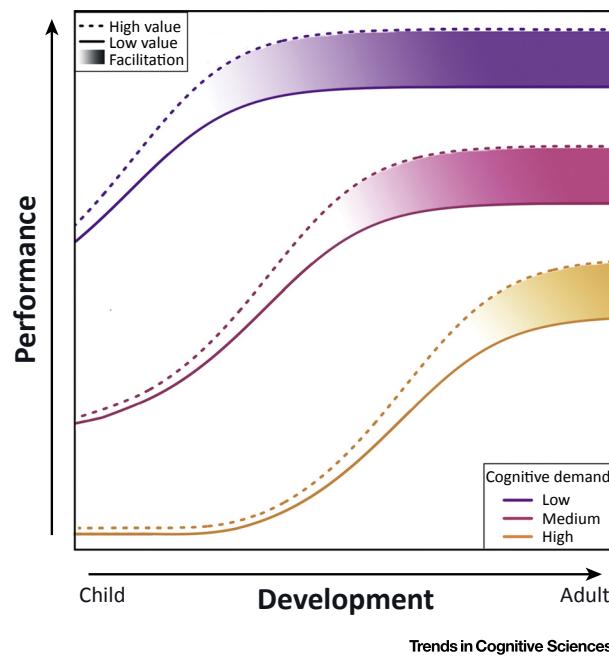
**Figure 1. Corticostratial Connectivity Mediates the Relationship between Age and Value-Guided Cognitive Control Performance.** (A) When performing a cognitive control task for low-value and high-value incentives, older participants (19–20 year olds) selectively improved performance ( $d'$  on y-axis) when high-value incentives were at stake, whereas younger participants performed similarly for low-value and high-value conditions. (B) Functional connectivity analyses were seeded in the ventral striatum and identified connectivity with VLPFC that was increased for high-value relative to low-value trials. Value-selective connectivity increased with age and was associated with improved performance on high-value trials. This pattern of corticostratial connectivity mediated the relationship between age- and value-selective performance [as shown in (A)].  $\Delta$   $d'$  denotes the difference score between high-value and low-value performance. VLPFC, ventrolateral prefrontal cortex. + denotes positive relationship between variables. Figure adapted with permission from [10].

control [10]. In this neuroimaging study, participants aged 13–20 years completed a go/no-go task in which accurate performance yielded either low-value or high-value payouts. Behavioral results demonstrated that performance improvements for high-value trials emerged in late adolescence. Participants aged 19–20 years exhibited a significant improvement in cognitive control performance for high-value trials, whereas participants aged 13–18 years performed similarly for low-value and high-value trials (Figure 1A). Individuals who selectively improved performance for high-value incentives exhibited increased functional connectivity between the ventral striatum and VLPFC during high-value trials (Figure 1B). This pattern of corticostratial functional connectivity also increased with age, and this value-specific connectivity profile mediated age-related increases in value-guided control.

These findings are consistent with models of adult value-guided cognitive control, proposing that connectivity between the ventral striatum and VLPFC enables the striatum to propagate value-related information to the VLPFC to selectively enhance control and maximize performance to obtain high-value goals [29,41]. Extending this framework to account for age-related changes, we suggest that younger adolescents may not coordinate value information with cognitive control demands to strategically adjust behavior as a product of neurodevelopmental constraints. Thus, we propose that late refinement of corticostratial connectivity sets the stage for successful value-guided goal-directed behavior.

### Development of Value-Guided Control: Constraints and Hypotheses

These recent studies suggest that value-guided control improvements continue to emerge throughout adolescence. Here, we turn to evidence from studies of adults to interpret this developmental trajectory. While work on adults has demonstrated the helpful effects of value on cognitive control, there is evidence that the beneficial effects of value diminish when a cognitive demand exceeds an individual's capacity [54]. Further, the beneficial effects of value disappear when participants are taxed with additional cognitive load, such as a secondary task, which can divert attention away from value cues and interfere with goal-directed actions [51,55]. These



**Figure 2. Value-Guided Improvements Scaffold on Emerging Gains in Cognitive Control Abilities.** This framework proposes that the ability to utilize value to improve performance emerges with age, scaffolding on cognitive development. This schematic illustrates how value differentially guides cognitive control performance (y-axis) with age (x-axis) across varying levels of cognitive demand. Low, medium, and high signify the demand level of a cognitive control challenge. Dashed lines indicate relative improvement for value-guided performance in a high-value context, and unbroken lines indicate baseline performance in a low-value context. While older aged individuals are capable of using value to boost performance under high cognitive demands, younger individuals improve for high-value conditions only when cognitive control abilities mature and reach the point of developmental stability, as denoted by the asymptote in low-value performance. Shading indicates the magnitude of value-selective improvements in performance, such that darker shading signifies strengthening of value-selective improvements. Note that this schematic does not showcase ceiling effects, which could arise from maximal performance in a low-value context, and subsequently limit the magnitude of the high-value effect.

findings imply that value can help performance when the cognitive challenge is matched to an individual's cognitive capacities, but value fails to facilitate performance past a certain difficulty threshold.

Applying this logic to a developmental framework, we propose that value-based facilitation scaffolds on ongoing cognitive control development. Baseline cognitive control performance continues to improve across adolescence, which gives rise to a command over a wider variety of cognitive challenges. We posit that the beneficial effects of value emerge when a given cognitive control ability reaches a point of stable maturation. As shown in Figure 2, value might improve cognitive control earlier in development when task difficulty and cognitive demands are low. By contrast, when faced with a difficult task taxing cognitive processes that are undergoing continued maturation, adolescents may face capacity limits that prevent value from bolstering performance. Thus, value facilitation effects (Figure 2, shaded areas) may emerge in tandem with the emerging capacity to meet more and more challenging cognitive demands. As a consequence, increasing age brings an expansion in the range of cognitive challenges for which value improves performance.

Consistent with this idea, there are circumstances when children and adolescents do use value to adjust control performance. For example, young children (aged 4–5 years) can use value to improve performance when promised a reward for accurate performance on a developmentally appropriate response inhibition task, but value does not benefit performance for a more difficult

cognitive flexibility task [56]. Moreover, if cognitive difficulty is titrated to an individual's ability, children, adolescents, and adults improve control accuracy for rewarding versus neutral outcomes [57]. Finally, if participants can anticipate imminent control demands, such as during an anti-saccade task which signals the upcoming need to implement control, children and adolescents can improve control when pursuing performance-contingent rewards [58,59]. These effects contrast with work described earlier, in which adolescents do not adjust performance in a value-selective fashion when performing control tasks that require flexible action selection [10], a skill that continues to develop into early adulthood [60]. Further evidence suggests that value may interfere with adolescent cognitive control when introduced as a distractor [49].

In sum, we propose that adolescents use value to improve performance if a task is cognitively tractable, but value is less beneficial when individuals are faced with challenging cognitive demands. While we have primarily suggested this trajectory scaffolds on cognitive development, it is also possible that strategic shifts with age could influence cost-benefit calculations that guide decisions of when to engage control processes [61–63]. For example, if a cognitive challenge is more difficult for younger individuals, and thus more subjectively costly to perform, they may be less likely to choose to engage in that process. An alternative possibility is that because cognitive demands are more taxing at younger ages, higher rewards might be required to motivate performance improvements. Future developmental work is needed to identify how these cost-benefit calculations for cognitive effort allocation change with age (see Outstanding Questions). Next, we consider whether this framework extends to the development of learning, a second functional domain for which value can guide goal pursuit.

### The Development of Value-Guided Learning

Whether in school, vocational settings, or social environments, individuals of all ages face the need to prioritize learning of certain information to maximize pursuit of goals in the moment and in the future. Using value to guide what and when to learn is thus a second core process underpinning mature goal-directed behavior. Experimentally, learning to associate stimuli or actions with valued outcomes is inferred when a participant chooses the highest-value stimuli or actions based on feedback history. Studies of this kind generally define selecting the option with the highest value (trained through extrinsic reinforcement like money, positive feedback, or 'correct' feedback) as optimal performance. In this way, **reinforcement learning** is inherently tied to value, and thus more optimal performance is thought to reflect the greater influence of value.

Basic forms of value-driven learning are available early in childhood [64]. Several studies show comparable overall performance on such learning tasks in adolescents and adults [65,66]. One such study tested adolescents (aged 12–16 years) and adults (aged 20–29 years) in a **probabilistic learning** task using monetary gains and losses as reinforcement. Individuals learned to select one of two cues that was reinforced with 80% probability [65]. This relatively high reinforcement rate rendered learning fairly easy, and resulted in similar accuracy for adolescents and adults. However, learning demands can be intensified by increasing the number of cues to learn [67,68], reducing the reinforcement probability [67], or increasing the complexity of the feedback given [68,69]. These more complex learning situations can challenge adolescents' learning abilities. For example, one study tested adolescents (aged 12–17 years) and adults (aged 18–32 years) in a probabilistic learning task with four cue pairs (i.e., eight total items), using gain or loss of points as reinforcement [68]. Further, they manipulated feedback to either reveal outcome information about both the chosen and unchosen cue in a pair, or the chosen cue alone. Through comparison of alternative **computational models**,

they found that adults employed more complex learning strategies than adolescents. Adults incorporated reinforcement valence (gain/loss) and outcome information for both chosen and unchosen cue options, and were more accurate overall than adolescents. In contrast, adolescents learned according to a simple value updating rule and did not integrate the complex feedback. Hence, age-related improvements in learning from adolescence to adulthood emerge when learning environments are particularly complex.

These age-related shifts in integrating complex feedback parallel work on the emergence of **model-based learning** strategies (i.e., representation of the transitional structure in a decision space acquired through reinforcement experience [70]). Recent work has shown that young adults (aged 18+ years) typically exhibit a ‘mixture’ of model-based and **model-free learning** strategies (i.e., purely feedback-driven) [71]. In children (aged 8–12 years) accuracy data suggest that learning is predominantly model-free, whereas adolescents (aged 13–17 years) show an increasing contribution of model-based strategies, resulting in a pattern intermediate between model-free and mixture [72,73]. Reaction times, from this work and others, suggests that the representation of structure in the environment may emerge in childhood [51,72]. However, the strategic implementation of that knowledge, such as sequences of actions to take to obtain valuable outcomes, emerges during adolescence and is increasingly applied into adulthood. Thus, even if younger individuals are capable of using valued feedback to guide learning, greater complexity of learning demands elucidate the continued developmental gains in strategy and optimization of learning.

Finally, recent work has revealed that there are some learning situations in which adolescents outperform adults. In a probabilistic learning study, adolescents (aged 13–17 years) formed reinforced stimulus–stimulus associations better than adults (aged 20–30 years) [74], suggesting enhanced learning from experience. Relatedly, when presented with a false instruction, adolescents (aged 13–17 years) prioritized learning from actually experienced feedback by discounting the false instruction, whereas adults (aged 18–34 years) persisted longer on the false instruction [67]. At a later test, adolescents showed less residual influence from the false instruction than adults, further suggesting that they had better integrated their experienced feedback over time [67]. Together, these studies suggest there are conditions that can be leveraged to reveal key learning advantages during adolescence.

### Development of Value-Guided Learning: Constraints and Hypotheses

When does value help or hinder learning over development? Research on the development of reinforcement learning is still generating and testing predictive models to answer this question. Here, we highlight considerations for future work in this area.

Computational learning models afford the opportunity to reveal the underlying component cognitive processes (e.g., learning rate, expected value) that contribute to learning within an individual. Importantly, model parameters can differ even when overall learning is comparable, indicative of latent strategy differences across individuals or age groups. In this way, model parameters can identify the underlying cognitive mechanisms that explain age-related learning differences [75]. For example, recent studies have demonstrated that similar feedback-based learning accuracy in adults and adolescents is supported by different underlying use of information to guide learning: adolescents have exhibited higher learning rates for negative reinforcement than adults [65,76] but have shown similar learning rates for positive reinforcement. By teasing apart component processes that give rise to learning, these studies show how and when age-related differences in learning emerge. More work using computational approaches is needed to evaluate the generalizability of inferences derived within a given

learning context, as factors such as the stability and probability of reinforcement can influence optimal learning strategies [77]. Nevertheless, this approach lays the foundation for constructing theoretical models to predict when adolescents' learning performance is helped or hindered by value relative to adults.

Secondly, component processes that give rise to learning may depend upon the differential development and functional integration of multiple learning systems in the brain. While the striatal learning system guides slow, incremental learning from feedback, learning systems within the medial temporal lobes, such as the amygdala [1] and hippocampus (Box 3), can accomplish learning rapidly [78]. In adults, the hippocampus and striatum can functionally couple to spread value information [79–81], allowing value learned in one context to transfer into a novel context, without requiring relearning. Such generalization informs preferences and helps for first-time decision making [81], a tool which could greatly benefit adolescents as they encounter unfamiliar situations. Whether, and when, adolescents can benefit from such neural coordination is important for understanding how value can influence goals via alternative routes of learning beyond the corticostriatal value circuit. For example, greater coactivation between striatum and hippocampus during learning led to stronger learning and memory associations in adolescents (aged 13–17 years) when compared with adults (aged 24–30 years), and may have contributed to adolescent's superior overall learning [74].

Finally, recent studies have revealed a shift with age from greater subcortical–subcortical functional connectivity [10,74], to increased subcortical–frontal [10,76,82] functional connectivity. The stronger subcortical–frontal connectivity that is observed in adults in these studies [10,76,82] is thought to facilitate sophisticated goal-directed performance. We propose that future studies should investigate the integrative roles of these functional brain networks. Doing so will allow crucial advances in understanding when different forms of learning abilities have stabilized and hence can be modulated by value (Figure 2). If so, it may be possible to leverage relatively more mature learning systems during adolescence to facilitate goal-directed learning and action.

### Concluding Remarks

As a product of their emerging independence, adolescents are challenged by the need to make increasingly complex decisions of how to act and what to learn. Here we present a framework that explains the age-related expansion in the range of cognitive challenges for which value improves performance. This account draws a key distinction between detecting value in the environment, a process which even young children are capable of, and using that information to guide the orchestration of goal-directed behavior. We propose that the latter is crucially yoked to cognitive and neurodevelopmental processes that continue to mature through adolescence. Moreover, the improvement of cognitive performance from adolescence to adulthood fosters an expansion in the range of challenges which can be enhanced by value. These ideas, which build on foundations from literature on value-guided cognition in adults, generate several questions that can guide future research (see Outstanding Questions). Ultimately, understanding what environmental contexts are more or less optimized for value integration during adolescence can inform educational and societal policies that bring out the best in adolescents.

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### Outstanding Questions

As complex processes continue to refine from childhood to adulthood, how is the subjective cost of exerting effort impacted? If effort is more 'costly' at younger ages, how does this impact decisions to engage in goal-directed behavior?

How can developmental research on value-guided goal pursuit test alternative accounts from research on adults? For example, recent work highlights effort-cost calculations as a form of cost-benefit decision making. Could adolescents' emerging use of value cues to guide goal pursuit result from biased cost-benefit processing rather than developmental constraints on value-cognition integration?

As cognitive control is an overarching concept encompassing a variety of specific cognitive subprocesses, can the field gain a more precise understanding of the difficulty of these processes in children, adolescents, and adults?

How can studies of value-guided goal pursuit reduce reliance on assumptions that convenient experimental manipulations of value (like money) are of equivalent subjective value in children, adolescents, and adults?

How does value guide other complex cognitive operations during adolescence, including exploratory behaviors, emotional regulation, decision making, and reasoning?

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## Trends in Cognitive Sciences

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